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PRESENCE OF CONTINUING CURRENT IN NEGATIVE CLOUD-TO-GROUND FLASHES

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1. INTRODUCTION

One of the important ways to transfer charges during the flash occurrence is the presence of continuing current (CC). In previous works, images from high-speed video cameras showed the persistence of the channel brightness after the return stroke (RS) for up to 40 ms (Ballarotti et al, 2005; Saba et al, 2006b). Kitagawa et al. (1962) correlated photographic and electric field observation for CC. It is possible to observe LCC by video cameras and to obtain some properties just by analyzing video records or by studying their slow electric field, as done by Shindo and Uman (1989). They are classified as long continuing current (LCC) if longer than 40 ms. If their duration is between 10 and 40 ms they are named Short Continuing Current (SCC). and Very Short Continuing Current (VSCC) for durations between 3 and 10 ms (Ballarotti et al. 2005; Shindo and Uman, 1989).

The LCC was mentioned in literature as apparently responsible for most serious heating damage due to lightning, e.g. burned-through ground wires of overhead power lines (Rakov and Uman, 1990), and the production NOx (Cooray et al, 2009).

This study summarizes some properties of CC from recordings of negative cloud-to-ground flashes in southeastern Brazil during the summer seasons between 2003 and 2011. It presents the methodology and information about the observation site, followed by statistics on CC occurrence, the analysis of the estimated current for 10 events and the detection efficiency for strokes followed by LCC.

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1.1 Instrumentation and data

The data used for the analysis were derived from high-speed video recordings. For the present study we have used two different high-speed digital video cameras: Red Lake Motion Scope 8000S, with exposure times between 1 ms and 2 ms (500 to 1,000 frames per second), and a Photron Fastcam 512 PCI, with exposure times between 125 and 250 microseconds (8000 to 4000 frames per second). For more information about the techniques or the accuracy of high-speed cameras for lightning observations, see Ballarotti et al. [2005] and Saba et al. [2006a].

All flashes were recorded between March 2003 and April 2011 in southeastern Brazil. This region is well covered by the Brazilian Lightning Location System (BrasilDat) which has provided data on stroke polarity and estimated peak current, inferred from the electric and/or magnetic radiation fields. More information on the characteristics of the network is provided by Naccarato and Pinto Jr. [2009]. The stroke distance from the sensor was also estimated by BrasilDat. When more than one stroke from a given flash followed the same channel and the distance were estimated, the flash distance was assumed to be the arithmetic mean between the estimated distances for all strokes.

1.2 Methodology

The dataset used was limited to flashes occurring at a maximum distance of 30 km. The distances were limited to 30 km in order to minimize possible errors produced by low visibility. Following the criterion suggested by Ballarotti et al. [2005], when the luminosity of the channel after the return stroke lasted 3 ms or less, we have not considered that this luminosity was due to the CC itself.

From the video analyses we have obtained information about the time of return stroke, the flash multiplicity, new channel formation, LCC presence and its duration (Δt). All videos were time-stamped and GPS-synchronized. All the strokes occurrences were compared with strokes detected by BrasilDat, which provides polarity, estimated peak current and location.

The waveform provided by a slow electric field sensor for 10 return stokes followed by LCC were analyzed in order to estimate the transferred charge and the average value for current according to equations (1) and (2), respectively (Uman, 1987). Figure 1 shows the scheme adopted to calculate the charge transfer. Charge transfer (ΔQ) was calculated from: ΔE, the electric field change due to continuing current, D, the distance of the stroke detected by LLS, H, the height of the negative charge center, which was estimated as the average height of the -10ºC and -20ºC temperature level obtained from radiosonde profiles. The main error in charge calculation was due to the error associated with the distance D which was assumed to be 1 km. For more details about this methodology see Medeiros (2011).

$$\Delta Q = \frac{2\pi\varepsilon_0 [H^2 + D^2]^{3/2}}{H} \Delta E_T \quad (1)$$

$$I_{avg} = \frac{\Delta Q}{\Delta t} \quad (2)$$

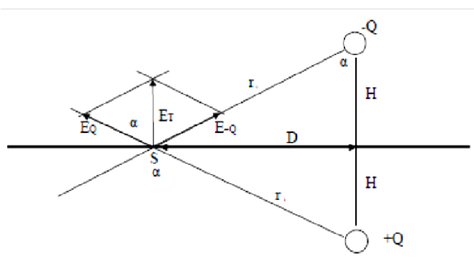

Figure 1 - Scheme adopted to calculate charge transfer.

2. ANALYSIS AND RESULTS

4495 strokes from 971 flashes were analyzed. The average stroke multiplicity of the dataset was 4.6; the average number of new channels per flash was 1.7 and the ratio between the average multiplicity and the number of channels was 2.7. Out of 971 flashes, 162 (17%) were single-stroke flashes. Figure 2 shows the percentage of return strokes (RS) followed by CC according their duration.

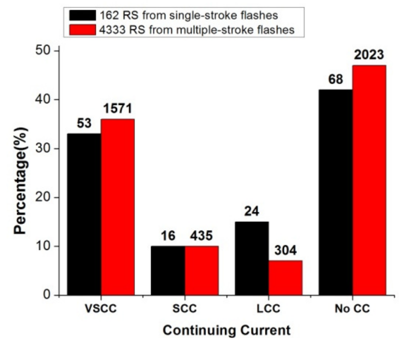

Figure 2- Percentage of RS for (a) single and (b) multi-stroke flashes according their duration. LCC for duration longer than 40ms, SCC between 10 and 40 ms and VSCC for duration between 3 and 10 ms. RS were considered without CC when their duration does not exceed 3 ms

2.1 Continuing Current duration

Table 1 summarizes the percentage of RS followed by continuing current longer than 3 ms and by LCC. The histogram of the duration of CC is given in Figure 3.

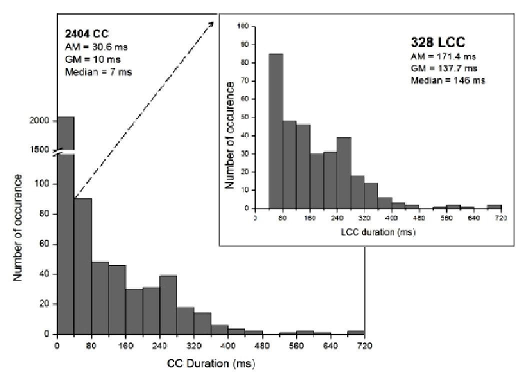

Figure 3-Histogram of CC and LCC duration.

About 80% of 328 LCC presented here were longer than 80 ms. The longest observed in this dataset was 714 ms.

Table 1- Percentage of RS in single and multiple-stroke flashes followed by any type of CC and LCC.

	# of flashes	# of RS	RS followed by CC	RS followed by LCC
Total	971	4495	2404 (53%)	328 (7%)
Single-stroke flashes	162 (17%)	162	94 (58%)	24 (15%)
Multiple-stroke flashes	809 (83%)	4333	2310 (53%)	304 (7%)

2.2 Presence of LCC according to stroke order

The probability of a return stroke to be followed by a LCC according to stroke order is given in the distribution diagram in Figure 4. The shaded area shows the presence of LCC ending a flash. First strokes rarely develop a LCC, while the fifth stroke presented the highest percentage of strokes with LCC.

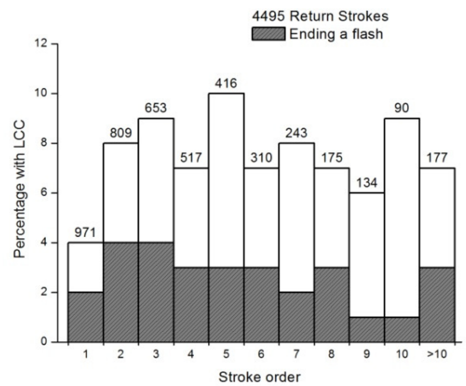

Figure 4 - Probability of a LCC following strokes of different order. The shaded area shows the presence of LCC ending a flash

2.3 LCC charge and current intensity

An analysis of 10 events and their electric field showed that there seems to be a relationship between the intensity of the continuing current and its ability to either end a flash or favor subsequent strokes that follow the same channel.

Table 2 shows the charge and current intensity for 10 events of LCC analyzed. The current intensity for flashes with higher multiplicity presented LCC lower than 50 A.

However, events in which the current intensity was greater than 50 A, presented multiplicities lower than or equal to 4 and most of them ended the flash.

Table 2 - Charge and current intensity calculated for LCC events.

	Multiplicity	Return stroke order	LCC duration (ms)	Current Intensity (A)	Charge (C)	Error (C)
1	9	7	207	19.4	4.0	0.9
2	10	5	120	26.9	3.2	0.8
3	10	10	44	26.3	1.1	0.3
4	5	4	92	20.3	1.9	0.4
5	2	2	157	122.7	19.3	4.2
6	3	3	293	153.4	45.0	8.2
7	2	2	188	55.6	10.5	2.3
8	10	7	298	23.1	6.9	1.5
9	2	1	281	165.1	46.4	9.8
10	4	2	281	116.6	32.8	5.5

It seems that a LCC with lower intensity is not enough to end a flash but it is important to maintain the channel through which subsequent dart leaders will produce new return strokes. The scatterplot of Figure 5 shows that the higher is the current intensity the lower is the number of strokes in a given flash.

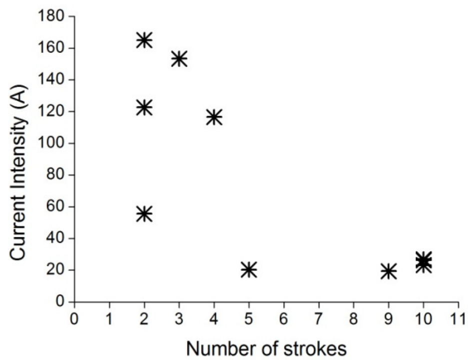

Figure 5 - Current intensity for LCC versus number of strokes in flash.

2.4 Detection efficiency for strokes containing CC

The detection efficiency (DE) (Figure 6) is lower for strokes with lower Ip, in agreement with the results presented by Saba el al. (2006b). Although the average Ip of return strokes followed by CC longer than 100 ms is lower than strokes with shorter CC, their DE is slightly higher.

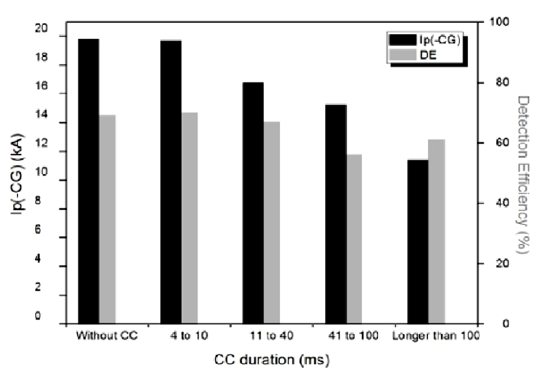

Figure 6- Peak current (Ip) and Detection Efficiency (DE) versus CC duration

Figure 7 shows a scatter plot distribution of estimated Ip versus DE for 8 different ranges of CC. There is an apparent tendency for strokes without CC or followed by short CC to have higher Ip and higher DE while strokes followed by CC longer than 20 ms to present a lower Ip and lower DE.

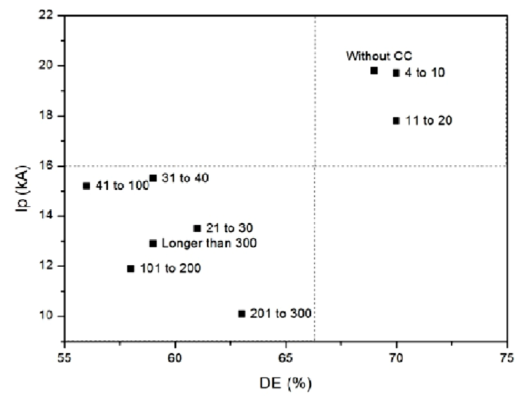

Figure 7- Scatter plot of Ip versus DE for 8 different ranges of CC.

3. DISCUSSION

The results allowed us to better understand the usual conditions that favor the occurrence of continuing current. The occurrence of long continuing current usually ends a flash or promotes another stroke in the same channel indicating that long continuing currents can be an important factor in establishing a channel. Long continuing current which have lower current intensity usually occurs in flashes with higher multiplicity. Long continuing current with higher current intensity usually ends the flash causing a lower multiplicity lightning flash. Strokes containing long continuing current were less detected when compared to those containing currents with shorter duration or without continuing currents.

Heckman (1992) suggested a relationship between current intensity, channel length and the occurrence of current cutoff when the channel was longer or the current intensity was lower than the necessary to maintain the channel active (Williams, 2006). During the LCC, leaders keep developing through the cloud collecting charge and sustaining the channel conductive (Mazur, 2002). If the current intensity is lower, the channel tends to be interrupted by current cutoff. When this occurs, the channel is still partially ionized so it is easier for dart leaders to initiate new strokes through the same channel. It is probable that the current intensity is not enough to keep the channel active until the end of the flash.

As the stroke order increases the channel grows longer and becomes more unstable. For a current of higher intensity, the channel is more stable and conductive. Thus, in flashes with lower multiplicity in which the LCC terminates the flash, the LCC is probably of higher current intensity in a shorter channel length.

The detection efficiency of a return stroke is related to the peak current value. Therefore, if the return stroke is followed by long continuing current and has a low value of Ip, the Detection Efficiency is reduced. On the other hand, cases with a CC longer than 100 ms presented a higher DE. Further investigations are necessary to resolve this question, especially a more detailed statistical analysis on the DE for different intervals of CC duration, minimizing the possibility of having statistical fluctuations bias in the observed results.

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