Relation between lightning return stroke peak current and following continuing current

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Received 17 July 2006; revised 25 October 2006; accepted 31 October 2006; published 7 December 2006.

[1] The magnitude of the return stroke peak current preceding continuing current (CC) in ground flashes was investigated. This study was performed using a high-speed camera (1,000 frames/s), an electric field flat-plate antenna and data provided by the Brazilian Lightning Detection Network (RINDAT). The observation of 454 negative strokes followed by CC with durations from 4 ms to 542 ms revealed that negative strokes combining both peak current greater than 20 kA and CC greater than 40 ms are highly unlikely to occur. However, this was found to be possible for positive strokes. In addition, we found that on average the longer the CC, the lower the return stroke peak current preceding it. Therefore, the average detection efficiency of RINDAT was found to decrease from 62% for negative strokes followed by very-short CC (less than 10 ms) to 36% for strokes followed by long CC, with an intermediate value of 57% for strokes followed by short (from 10 to 40 ms) CC. **Citation:** Saba, M. M. F., O. Pinto Jr., and M. G. Ballarotti (2006), Relation between lightning return stroke peak current and following continuing current, *Geophys. Res. Lett.*, *33*, L23807, doi:10.1029/2006GL027455.

1. Introduction

[2] Three categories of continuing currents (CC) were defined in previous studies on flashes containing CC. *Kitagawa et al.* [1962] and *Brook et al.* [1962] defined "long" CC as indicated by a steady electric field change with a duration in excess of 40 ms, which was the value then accepted for typical interstroke intervals. *Shindo and Uman* [1989] defined "short" CC as indicated by a similar field change with duration between 10 ms and 40 ms and "questionable" CC for durations between 1 and 10 ms. Considering that the maximum duration of the return stroke is often assumed to be about 3 ms [*Rakov and Uman*, 2003, p. 176], *Ballarotti et al.* [2005] recently introduced the term "very-short" to define continuing currents with a duration less than or equal to 10 ms but greater than 3 ms. This recent definition, based on high speed video data, avoids contamination of what could just be return-stroke pulse tails.

[3] In addition, the literature contains studies comparing electric field peak (Ep) and charge values for strokes initiating CC with those not initiating CC. *Brook et al.* [1962] reported that the charge transferred by return strokes followed by long CC is smaller than for strokes that do not. *Livingston and Krider* [1978] showed that electric field changes for strokes initiating CC are smaller in amplitude and slower in rise time than those due to the preceding return strokes. *Uman* [1987] concluded that there is something different about leaders and return strokes involved in initiating CC. *Shindo and Uman* [1989] using simultaneous single-station electric field and multiple-station TV measurements, also reported that, on average, the return stroke initial electric field peaks (and by inference peak currents) of strokes initiating short CC (mean = 2.6 V/m) and long CC (mean = 2.7 V/m) are smaller than those not initiating CC (mean = 4.0 V/m) or initiating "questionable" CC (mean = 3.9 V/m). Finally, *Rakov and Uman* [1990a] found the same behavior for one first return stroke (2.7 V/m) and 27 subsequent strokes (mean = 2.2 V/m) followed by long CC when compared with "regular" subsequent strokes (mean = 3.4 V/m). They used the term "regular" to denote strokes neither initiating long CC, nor preceding those doing so, nor following long CC intervals. More recently, *Biagi et al.* [2006] comparing the U.S. National Lightning Detection Network reports of CG strokes with those recorded on video and optical and electric field waveforms, found that a large fraction of low peak current intensity strokes of negative flashes were followed by long continuing currents.

[4] In this study, we investigate the relationship between peak current intensity (I_p) and the duration of CC in ground flashes in more detail. This relationship is analyzed for both positive and negative strokes and for first and subsequent strokes. As far as we know, we are presenting the first analysis of the detection efficiency of lightning location systems for return strokes followed by CC.

2. Instrumentation and Measurements

2.1. Methodology

[5] A high-speed digital video camera (Red Lake Motion Scope 8000S) with a resolution and exposure time of 1 ms was used by the Atmospheric Electricity Group (ELAT) to record images of cloud-to-ground flashes in Southeastern Brazil between January 2003 and April 2005. The sites used during the data acquisition are located in São José dos Campos (23.212°S; 45.867°W, altitude: 635 m) and Cachoeira Paulista (22.686°S; 44.984°W; altitude: 625 m). Both sites are located in a region that is well covered by the Brazilian Lightning Detection Network (RINDAT).

[6] The high-speed camera has a trigger system that detects a signal from an external source. We can set the trigger point to determine how many frames we want to record before the event. Each trigger pulse was initiated manually, depressing a hand-held switch when a flash occurred. All high-speed video recordings had a 1 s pre-trigger time and a total recording time of 2 seconds (2,000

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0094-8276/06/2006GL027455

frames). The pre-trigger time of 1 s proved to be long enough to prevent the missing of first strokes. Also, the total recording time of 2 s was long enough to capture the whole flash. All images were GPS synchronized, time stamped and without any image persistence. For more details on the accuracy of high-speed cameras techniques for lightning observations see *Saba et al.* [2006].

[7] It is important to note that the distance of observation varied from 1 to 100 km (based on RINDAT data). In some thunderstorms the duration of the CC was certainly underestimated by the high speed video data due to the large observation distance and the presence of rain. In order to reduce errors, we limited the present study to flashes occurring within 50 km from the camera. A similar underestimation (less than 20%) also occurs when determining the duration of CC from electric field records [*Shindo and Uman*, 1989]. In this study, we also used an electric field flat-plate antenna to observe CC in 19 flashes. The decay constant of the circuit was 11 sec. The durations of these 19 CC were compared with the durations given by the high-speed camera.

[8] In order to identify the stroke polarity and peak current, we used the RINDAT data (more information on the characteristics of the network is found in the work of *Pinto et al.* [2006]). The stroke matching between camera and network was done by GPS time synchronization (timing accuracy for each GPS system less than 1 millisecond). The detection efficiency (DE) of the network in the region was 88% for flashes and 55% for strokes [*Ballarotti et al.*, 2006]. One must bear in mind that peak current estimation by lightning detection networks such as RINDAT are inferred from the peak electric and/or magnetic radiation field. The relationship between peak current and peak field comes from triggered negative lightning strokes which are similar to natural negative subsequent strokes. Thus, the field-to-current conversion may not be accurate for converting first stroke fields or positive stroke fields into currents since the physics involved in these discharges may be different. Data from lightning detection networks are also subject to systematic and random errors. According to *Jerauld et al.* [2005] and *Rakov* [2005], who compared peak current values from the US National Lightning Detection Network (NLDN) with those obtained from direct measurements in triggered lightning, the NLDN underestimated peak current by about 18% (median value) for 70 strokes with peak currents below 50 kA.

2.2. Data

[9] A total of 311 negative flashes (1243 strokes) and 16 positive flashes (20 strokes) were recorded by the high-speed camera during 37 different thunderstorm days. The low number of positive flashes may be explained by the fact that the camera was usually pointed in the direction of maximum flash rates, which usually corresponds to regions producing negative flashes. The positive flashes were mostly single-stroke flashes. Nine positive first-strokes followed by some CC were detected by the lightning detection network.

[10] Almost 37% (454) of all negative strokes observed (1243 strokes) were followed by some kind of continuing luminosity longer than 3 ms. The lightning detection network estimated peak current intensity for 248 (55%) of these 454 strokes followed by CC. Within this subset of 248 strokes, 55 (22%) were first-strokes and 193 (78%) were subsequent-strokes.

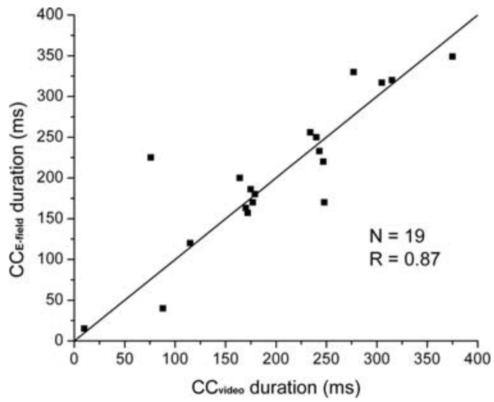

Figure 1. Values of CC duration from two different techniques. Linear fit through the origin ($CC_{E\text{-field}} = 0.99^* CC_{video}$) and correlation coefficient are also shown.

3. Results and Discussion

[11] The following results were obtained for negative flashes. Results for positive flashes are specifically indicated as such.

[12] Figure 1 shows the relationship between the duration of CC determined from high-speed images (CC_{video}) and from E field ($CC_{E\text{-field}}$) for 19 strokes for which both measurements were available. An average relative discrepancy ($100^*|CC_{E\text{-field}} - CC_{video}|/CC_{video}$) of 23% was found. This reasonable agreement between both techniques shows that, although they have different limitations, they are equally useful for short and long CC observations. Our experience shows that the high speed camera is more precise in determining the duration of very-short duration CC due to the fact that the signature of the slow electric field change is not clear in this range.

[13] The range of the values measured and the frequency distributions for peak current intensity and CC duration for first and subsequent strokes detected by RINDAT are presented in Figure 2. Figure 2 also shows that the mean I_p (CC duration) of first strokes is higher (lower) than the mean I_p (CC duration) of subsequent strokes.

[14] Some CCs classified as initiated by first strokes in this study could actually be initiated by the second stroke of the flash. Due to the finite video resolution of 1 ms, if two different strokes using the same path between cloud base and ground occur within the 1 ms framing interval, they will appear as a single stroke. Considering that *Rakov and Uman* [1994], using simultaneous electric field and TV measurements, reported only 2 first single-grounded strokes (in 76 flashes) that could actually be two distinct return-strokes occurring within a millisecond, we think that this misclassification, although possible, is unlikely.

[15] A scatter diagram in which I_p is plotted against the CC duration is given in Figure 3. Note that strokes with higher peak current are followed by shorter CC, while strokes followed by longer CC have lower peak currents. None of the 4 first strokes (7% of 55) and 36 subsequent

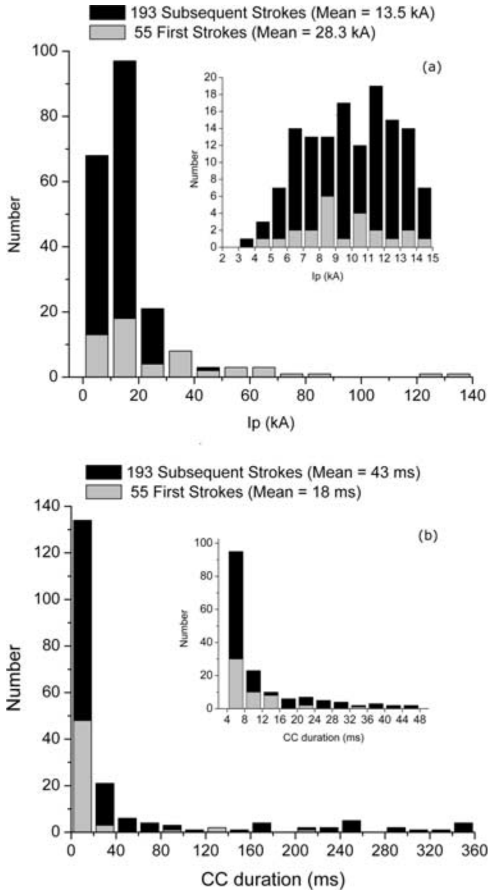

Figure 2. The distribution of (a) peak current and (b) CC duration at two different scales for 248 negative strokes followed by CC with durations ranging from 4 to 350 ms.

strokes (19% of 193) followed by long CC had peak current values higher than 20 kA. In contrast, any value of peak current is possible for strokes that are followed by CC less than 15 ms. In Figure 3, we can also observe that highest peak currents (above 50 kA) are associated with first stroke discharges.

[16] Figure 3 also includes nine positive strokes for comparison. They show that, contrary to the 248 negative strokes analyzed, positives strokes may combine high peak current with long CC duration (4 cases out of 9).

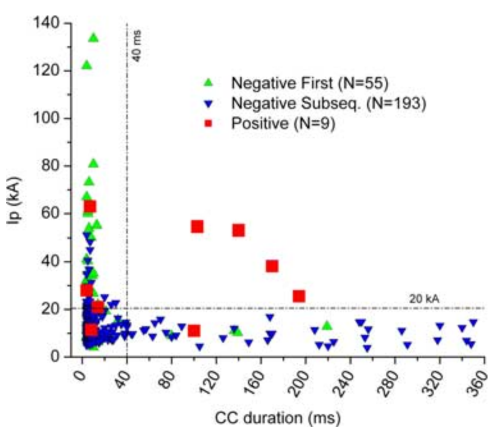

Figure 3. Peak current (I_p) versus CC duration for 248 negative strokes and 9 positive strokes.

[17] Figure 4 shows the average RINDAT DE and average I_p for 454 strokes with different ranges of CC. The average I_p for strokes initiating very-short CC (20 kA) is larger than the average I_p for strokes initiating short CC (14 kA) and long CC (10 kA). The DE for negative strokes followed by very-short, short and long continuing currents were respectively 62% (154 out of 248), 57% (54 out of 94) and 36% (40 out of 112). It is clear that the longer the CC is, the lower is the average I_p and, consequently, the DE.

[18] The average I_p for strokes initiating short CC and long CC are respectively 30% and 50% lower, than the average I_p of strokes initiating very-short CC. Using a smaller database and a different very-short CC range (from 1 ms to 10 ms, designated ‘‘questionable CC’’), *Shindo and Uman* [1989] found a similar behavior for average Ep of strokes preceding short CC, but found a smaller decrease for average Ep of strokes preceding long CC (see Table 1).

4. Concluding Remarks

[19] We found that negative strokes with peak current higher than 20 kA are never followed by CC durations greater than 40 ms, while negative strokes that have peak currents lower than 20 kA are followed by CC of any duration. Considering the high number of cases observed, these parameters determine an ‘‘exclusion zone’’ for negative strokes, which seems to indicate that high peak current negative strokes followed by long CC do not exist.

[20] Considering that on average, negative first strokes have larger peak fields and currents than subsequent strokes [*Rakov and Uman*, 1990b; this study], the reported rare occurrence of first strokes initiating long CC in this study and in previous studies [*Rakov and Uman*, 1990a; *Saba et al.*, 2006] is consistent with the existence of the ‘‘exclusion zone,’’ which occurs for both first and subsequent strokes.

[21] Taking into account the errors involved in the estimation of peak currents and CC durations, the apparent threshold values presented for the ‘‘exclusion zone’’ must be taken as approximate. Additional similar studies using more accurate techniques should be performed in order to improve and confirm the threshold values found in this work.

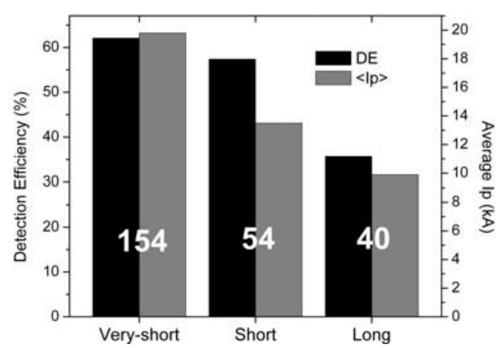

Figure 4. Detection efficiency (DE) and average peak current $\langle I_p \rangle$ for strokes with different ranges of CC. The numbers in white represent the number of strokes detected and used for calculating the average peak current.

Table 1. Average Ep and I_p Comparison

Study	Very-ShortCC	Short CC	Long CC	Decrease, %Very-Short to Short	Decrease, %Very-Short to Long
Shindo and Uman [1989] (Ep)	3.9 V/m N = 16	2.6 V/m N = 15	2.7 V/m N = 12	34	31
Present Study (I_p)	20 kA N = 154	14 kA N = 54	10 kA N = 40	32	50

[22] The "exclusion zone" found for negative strokes was not observed for positive strokes. As shown here, long continuing currents following high peak current strokes are present in 4 out of 9 of these discharges. This was somehow expected. Although there are very few data in the literature that give peak current values for strokes followed by CC, reports on the occurrence of high peak current strokes and long CC are very common for positive flashes [*Rust et al.*, 1985; *Rakov and Uman*, 2003, p. 219].

[23] Finally, as the efficiency of most of the existing lightning detection networks depends on the intensity of the return stroke, strokes followed by long CC are usually less detectable. Consequently, thunderstorms with a high percentage of strokes followed by long CC probably have a lower average I_p and lower percentage of detected strokes. Other detection techniques should be used in order to better detect strokes followed by this deleterious mode of discharge.

[24] **Acknowledgments.** We would like to thank L. Zanella, F. G. Cardoso, and R. Faria for their help in the data acquisition and processing; K. P. Naccarato for obtaining the RINDAT data; FAPESP for research grant 02/10630-7 and the Conselho Nacional de Desenvolvimento Científico (CNPq) for research grant 475299/2003-5; and also I. R. C. A. Pinto for helpful discussions.

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