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WAVESHAPES OF CONTINUING CURRENTS FROM NEGATIVE AND POSITIVE CLOUD-TO-GROUND FLASHES OBSERVED IN SOUTHERN ARIZONA

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1. INTRODUCTION

It is widely known that there are three possible modes of charge transfer to the ground associated with lightning discharges: the return stroke, the continuing current (CC) and the M-component (Rakov et al., 2001; Rakov and Uman, 2003). The latter mode has not been reported in positive lightning until recently (V. A. Rakov, personal communication, 2006; Campos et al., 2007a, 2008).

1.1 Continuing Current – General

The CC is a continuous mode of charge transfer to the ground. Regarding its duration, three categories of CC were defined in previous studies. 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. Shindo and Uman (1989) defined “short” CC as indicated by a similar field change with a duration between 10 ms and 40 ms, and “questionable” lasting 1 to 10 ms. Ballarotti et al. (2005), based on data from a high-speed video system and avoiding contamination from what could just be return stroke pulse tails, introduced the term “very-short” defining continuing currents with a duration less than or equal to 10 ms but greater than 3 ms. Recently, Saba et al. (2006b) found that negative strokes with peak current higher than 20 kA are never followed by CC durations greater than 40 ms, while negative strokes with peak currents lower than 20 kA are followed by CC of any duration.

CC are responsible for most serious lightning damage associated with thermal effects, such as burned-through ground wires and optical fiber ground wires (OPGW) of overhead power lines, blowing fuses used to protect distribution transformers, holes in the metal skins of aircraft, etc (Chisholm et al., 2001; Fisher and Plummer, 1977; Rakov and Uman, 1990).

The value of the CC is usually estimated to be 100 A, with a range from 30 to 200 A and the charge transfer is typically between 10 and 20 C (Shindo and Uman, 1989). These parameters (commonly reported and used in lightning protection applications) are calculated assuming a constant current value for the CC (IEC, 2006).

1.2 Continuing Current – Waveshapes

Fisher et al. (1993) did the first study on the temporal development of continuing currents based solely on direct measurements from triggered lightning. They analyzed 30 CC having durations exceeding 10 ms and found that they exhibited a variety of waveshapes that were grouped into four categories. Campos et al. (2007b) presented the first results for negative CG based on data from a high-speed video system. They analyzed 63 negative long CC recorded in southeastern Brazil, grouping part of them (34 out of the 63) into the four categories observed by Fisher et al. (1993) but also noticing the need to create two additional categories that allowed the characterization of the remaining 29 cases. Differently from what was reported by Fisher et al. (1993), the presence of M-components (first described by Malan and Collens, 1937) were observed to occur in any period of all the six types.

Campos et al. (2007a,b, 2008) used the same method for high-speed video recordings for 21 positive CG observed in southern and southeastern Brazil and compared their statistical analysis to the one presented in Campos et al. (2007b) for negative CG. They found that positive CC presented a very distinctive statistical distribution; also two of the six types have not been observed in the +CG dataset (one from the original four by Fisher et al., 1993, and another from the additional two

Figure 1. Example of (a) flash and (b) calibration areas of a high-speed video frame that recorded a long CC (considered in this study).

presented in the same work). These features combined to those pointed out by Saba et al. (2006b) strongly suggest that the CC in positive CG flashes has an entirely different physical description.

The aim of this work is to present a similar analysis of CC high-speed video recordings obtained in southern Arizona. The same instrumentation and method will be used in order to find eventual geographical differences in the types distribution and also to increase the statistical data obtained previously in Brazil (Campos et al., 2007a,b, 2008).

2. INSTRUMENTATION AND METHOD

2.1 High-speed camera

A Photron FASTCAM 512 PCI and a Red Lake 8000S Motion Scope high-speed cameras working at a frame rate of 4,000 fps (exposure time of 250 µs) and 1000 fps (exposure time of approximately 1 ms), respectively, were used in the observations of the present study. For both cameras the triggering mode was set to record 1 second prior to and 1 second after the trigger button is pressed by the operator. Each frame is GPS time-stamped, allowing an accurate correlation with data from a lightning locating system. For a more detailed discussion on the accuracy of high-speed camera for lightning observation please refer to Saba et al. (2006a, 2008) and Campos et al. (2007b).

2.2 Video analysis

A computational algorithm was developed in order to obtain relative luminosity variations from the recorded video frames. For each CC, a channel area and a calibration area are defined; the averaged pixel value is calculated for each area. The calibration average is subtracted from the channel average frame by frame; the results (relative values of channel luminosity) are plotted versus time. This strategy allowed us to considerably reduce the effects of external sources of light (e.g., a cloud flash that occurred visually close to the studied CC channel). Figure 1 shows an example of channel and calibration area in a frame from one of the high-speed videos considered in the present study. Diendorfer et al. (2003) analyzed the brightness and the current of the initial continuous current in upward initiated flashes to the Gaisberg tower. They used a highspeed video system to measure the brightness of the channel from distances of a few hundred of meters from the discharge and made direct current measurements at the point of impact. They found an excellent linear correlation (r^2 =0.96) between brightness and current in the range of 10 to 250 A. Based on the fact that continuing current values in CG flashes are usually in this range, we assumed that the variations observed in the brightness of the channel are proportional to variations in the current that flows along the channel (Fisher et al., 1993; Campos et al.,

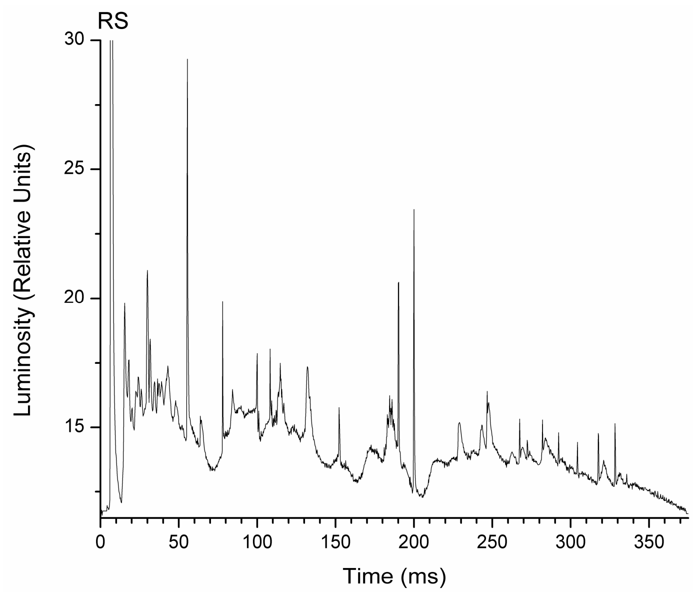


Figure 2. Example of a luminosity-versus-time graph obtained for the present study; this case was considered as Type V.

2007a,b, 2008). Figure 2 shows the luminosity-versus-time graph of one of the CC studied in this paper. A detailed description and validation of the applied method is presented by Campos et al., 2007b.

3. DATASET AND RESULTS

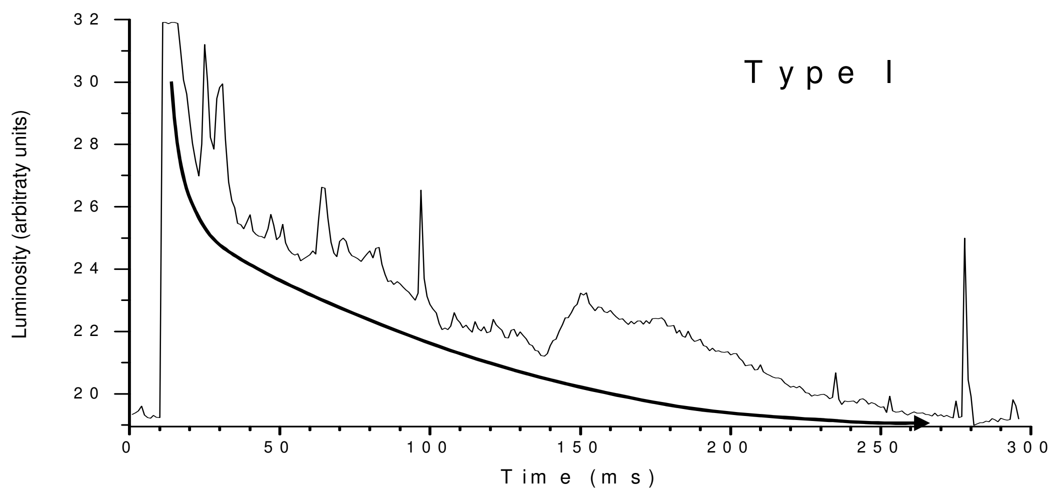
From 266 flashes recorded with a high-speed camera during July and August 2007 a total of 34 negative and 5 positive long CC were selected. All these flashes occurred in the southern Arizona region and were observed from the Physics-Atmospheric Sciences Building in the University of Arizona campus (32.230°N, 110.953°W, altitude: 735 m) in Tucson. The area is well covered by the NLDN – National Lightning Detection Network™ (Biagi et al., 2007; Cramer et al., 2004; Cummins et al., 1998, 2006).

Luminosity versus time graphs were obtained for all the selected CC and were classified into the six waveshape types (Fisher et al., 1993, Campos et al., 2007b). Figure 3 illustrates each type and Table 1 presents the textual descriptions. Figure 4 shows occurrence statistics for southern Arizona (Figure 4c) compared to triggered-lightning (Figure 4a; Fisher et al., 1993) and to negative and positive natural flashes recorded in Brazil (Figure 4b; Campos et al. 2007b, 2008). General statistics, combining the datasets for Brazil (Campos et al., 2007b, 2008) and southern Arizona (present study) are shown in Figure 4d. Within the dataset, 3 flashes presented more than one CC considered in this study; we have analyzed how the waveshape Type varies from one stroke to the other within the same flash and the results are summarized in Table 2. All the listed strokes followed the same channel for each flash.

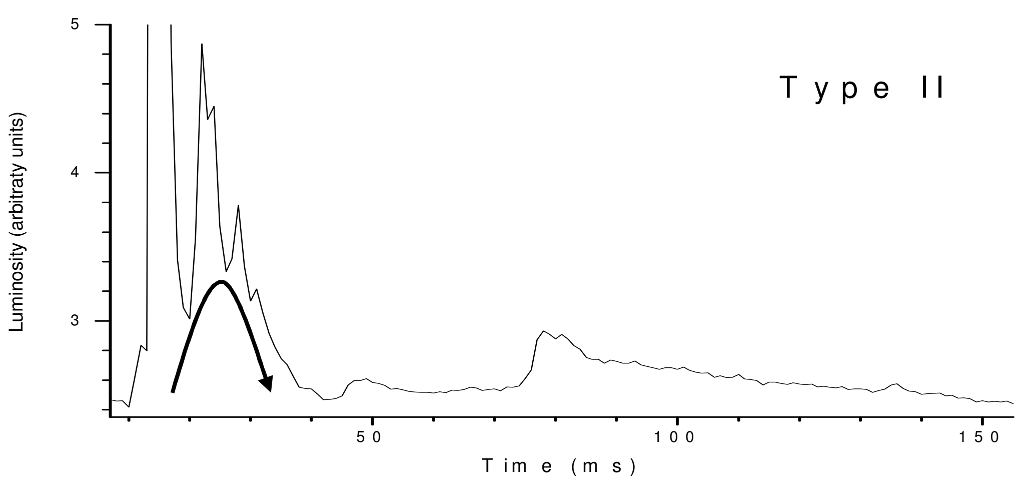
One could argue that the occurrence of each type may be influenced by the distance from the camera to the stroke event (given by the NLDN data). For example, a very distant stroke could be mistakenly considered as Type VI due to the very low intensity of its luminosity. On the contrary, it is possible to observe from Figure 5 that nearly all events occurred at distances smaller than 50 km (only 2 exceptions in 39) and that there is no substantial difference in the distance distribution for each Type.

Table 1. Textual description of each of the six waveshape Types considered in this study.

Type	Textual Description
I	More or less exponential decay
II	Hump followed by a gradual decay
III	Gradual increase and decrease
IV	Hump followed by a long-lasting steady plateau
V	Two or more humps
VI	Low intensity plateau

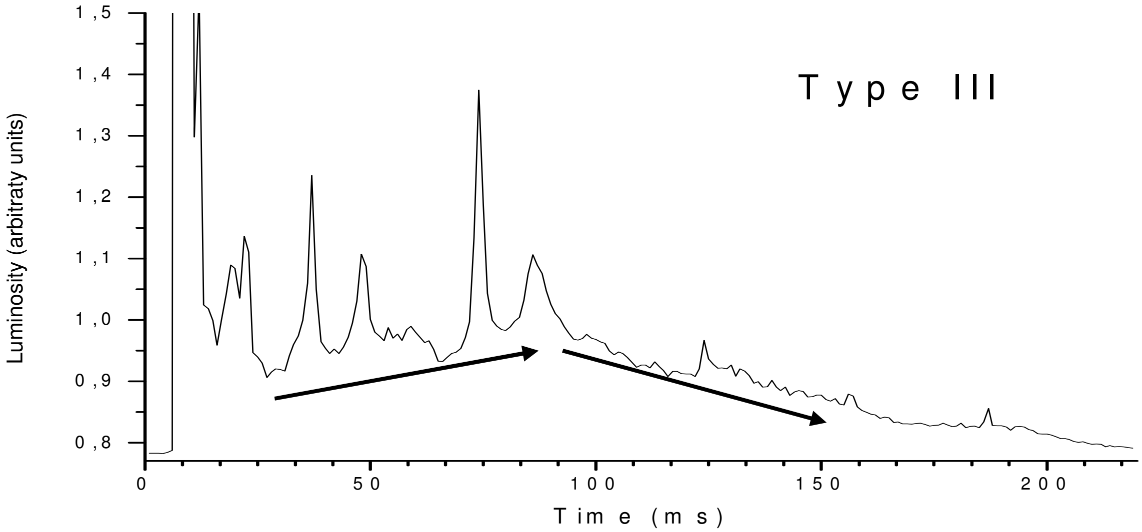


(a)

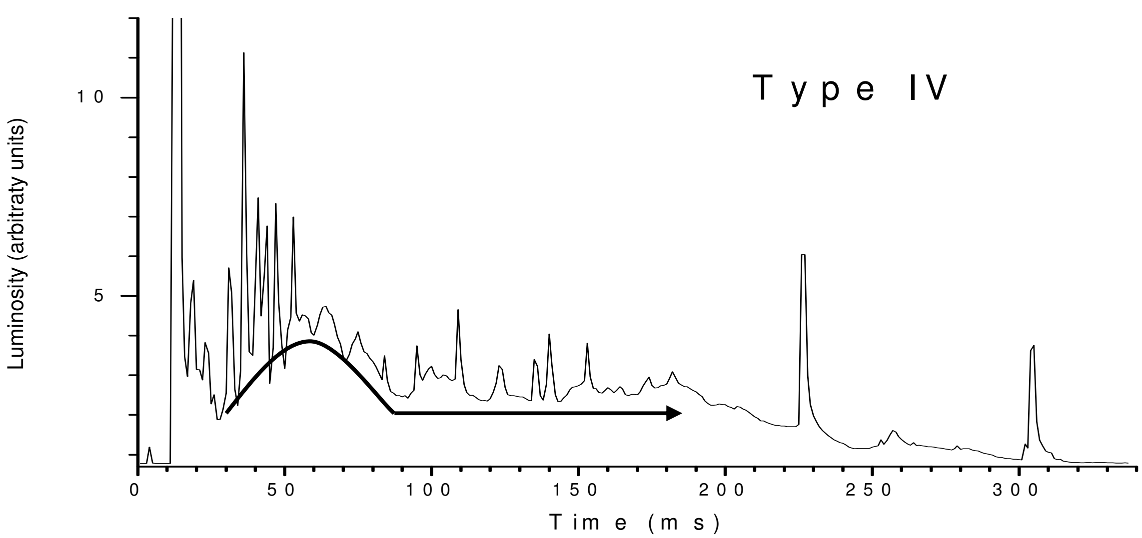


(b)

Figure 3. Examples of continuing current waveshapes of (a) Type I, (b) Type II, (c) Type III, (d) Type IV (Fisher et al., 1993), (e) Type V and (f) Type VI (Campos et al., 2007b). Each arrow highlights general characteristics of each Type (described in Table 1).

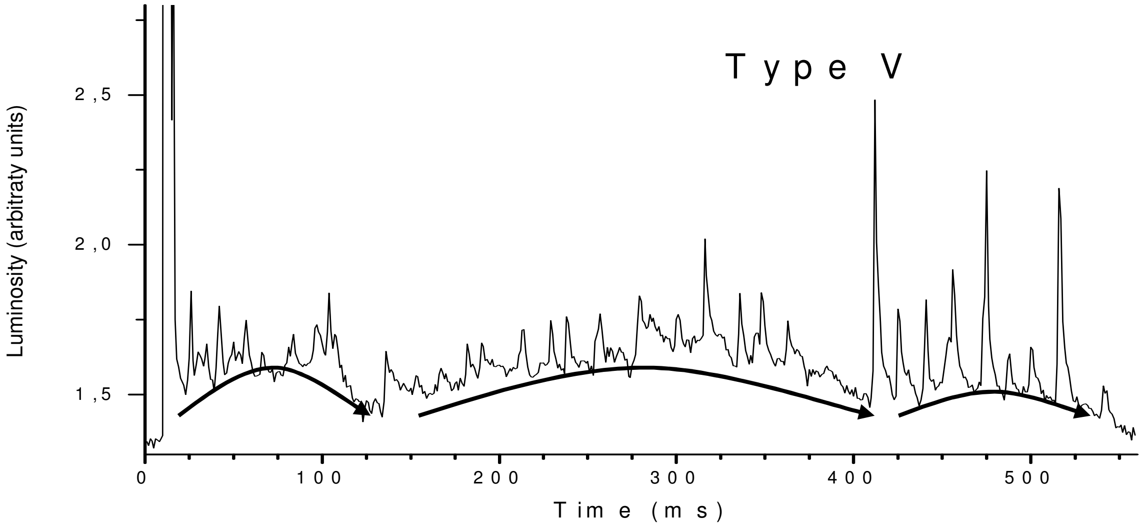


(c)

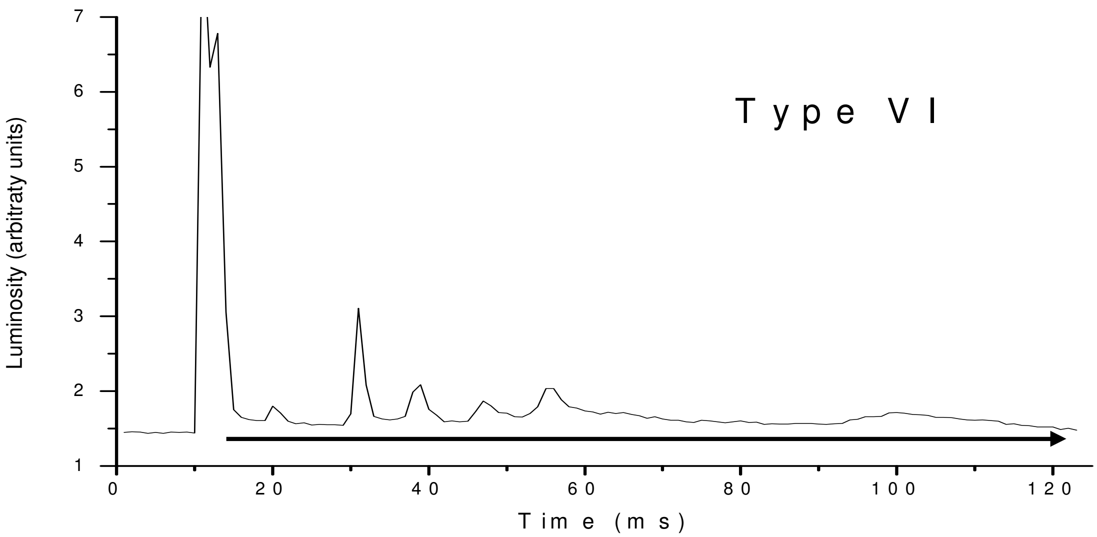


(d)

Figure 3 (continued).



(e)



(f)

Figure 3 (continued).

4. SUMMARY AND DISCUSSION

This paper has presented a statistical analysis of the occurrence of CC waveshape Types in southern Arizona from high-speed video observations. The results on the analyzed topics are presented in Figure 4 and discussed in detail in the following sections.

4.1 Statistical comparison between Brazil and southern Arizona

For negative flashes (34), the most common waveshape Type observed in southern Arizona was VI (50%, Figure 4c) similarly to Brazil (Figure 4b; Campos et al., 2007b). There was no report of Type IV cases, relatively uncommon also in Brazil (8% according to Campos et al., 2007b).

Regarding positive flashes (5), similarly to Brazil (Figure 4b; Campos et al., 2008), Types III and V were not observed, reinforcing the possibility of their non-existence in positive CC (Figure 4c). No Type IV case was found (only 9% of the cases in Brazil). Contrary to Campos et al. (2008) that reported Type VI as being the most common for positive CC in Brazil(43%), it was not observed in the southern Arizona dataset, possibly due to its limited size (only 5 cases).

4.2 Analysis of the general combined dataset

Figure 4d shows the combined datasets for natural CG flashes of both polarities from Brazil (Campos et al., 2007b, 2008) and southern Arizona. Regarding negative flashes (97), Type VI was still the most frequent (39%) and Type I was the second most frequent (18%). The occurrence percentages of Types II, III and V had no significant difference (11-13%) while Type IV is the rarest (5%).

Positive flashes (26) presented no cases of Types III and V, reinforcing the hypothesis presented by Campos et al. (2008), who suggested that its physical mechanism does not allow this kind of temporal development, knowing that both Types are very similar (Type III presents one "hump", a gradual increase and decrease in the CC level, while V presents two or more "humps"; see Figure 3c and 3e).

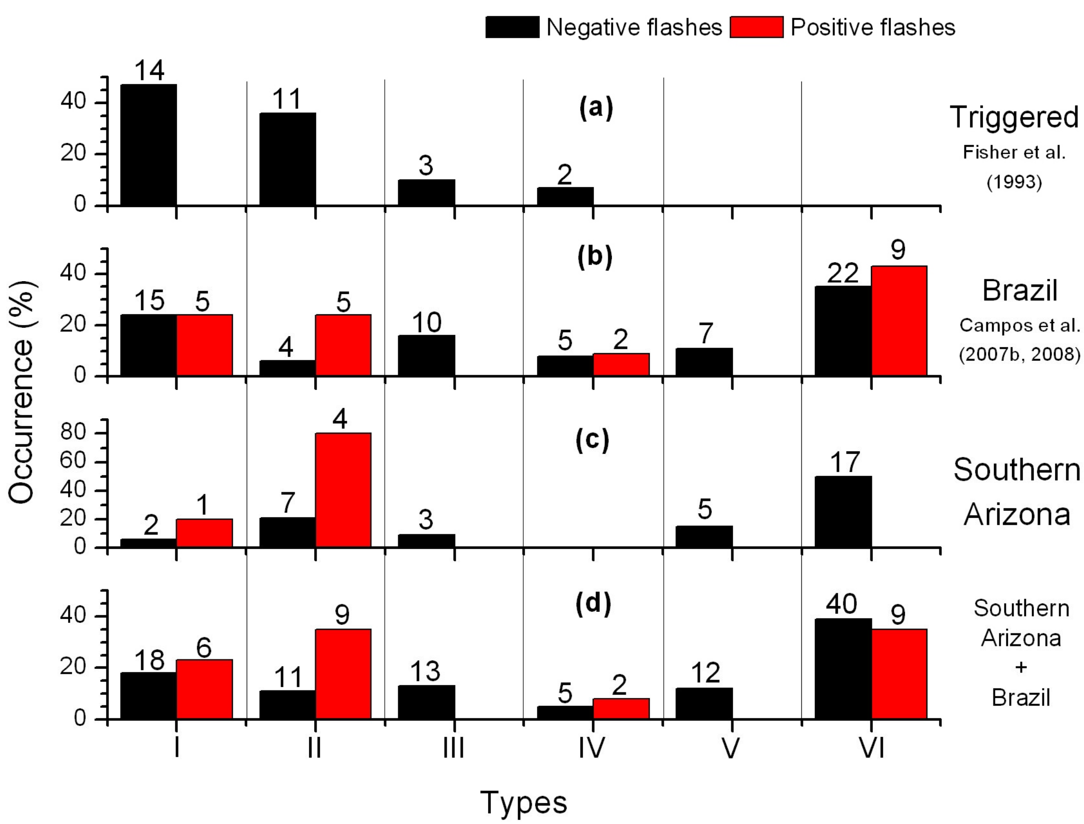


Figure 4. Histograms of the occurrence of waveshape types in (a) triggered flashes (Fisher et al., 1993); natural negative and positive flashes in (b) Brazil (Campos et al., 2007b, 2008), (c) southern Arizona (present study) and (d) southern Arizona and Brazil. Absolute numbers are placed on top of each bar.

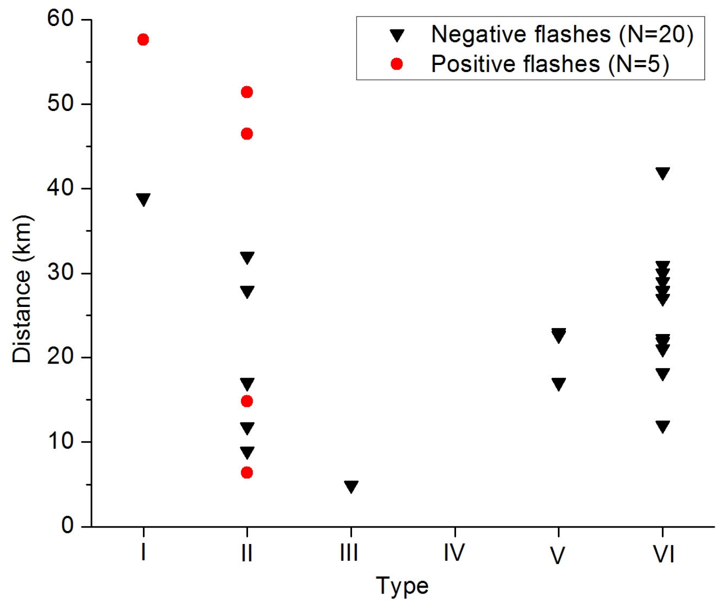


Figure 5. Distribution of stroke distance versus waveshape Type.

Table 2. Variation of waveshape Types among strokes within the same flash. All the listed strokes followed the same channel (for each flash).

Event	Stroke Order	Type	CC duration (ms)
2007-07-31 2h32min39s UT	6th	II	150
	7th	VI	85
	11th	VI	55
	13th	VI	30
2007-08-16 3h45min45s UT	1st	V	325
	3rd	II	145
2007-08-16 3h52min55s UT	2nd	I	160
	4th	III	165
	6th	VI	45

4.3 Waveshape Type variation within the same flash

In the CC data obtained in southern Arizona there are 3 flashes with more than one stroke considered in the waveshape statistics. Their detailed data (time, stroke order Type and CC duration) are presented in Table 2. All the listed strokes followed the same channel (for each flash). Note that different types of CC can occur within the same flash.

5. ACKNOWLEDGEMENTS

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