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Waveshapes of continuing currents and properties of M-components in natural positive cloud-to-ground lightning

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ABSTRACT

This work analyses the waveshapes of continuing currents and parameters of M-components in positive cloud-to-ground (CG) flashes through high-speed GPS synchronized videos. The dataset is composed of only long continuing currents (with duration longer than 40 ms) and was selected from more than 800 flashes recorded in São José dos Campos (45.864°W, 23.215°S) and Uruguaiana (29.806°W, 57.005°S) in Southeast and South of Brazil, respectively, during 2003 to 2007 summers. The videos are compared with data obtained by the Brazilian Lightning Location System (BrasilDAT) in order to determine the polarity of each flash and select only positive cases. There are only two studies of waveshapes of continuing currents in the literature. One is based on direct current measurements of triggered lightning, in which four different types of waveshapes were observed; and the other is based on measurements of luminosity variations in high-speed videos of CG negative lightning, in which besides the four types above mentioned two additional types were observed. The present work is an extension of the latter, using the same method but now applied to obtain the waveshapes of positive CG lightning. As far as the authors know, this is the first report on M-components in positive continuing currents. We also have used the luminosity-versus-time graphs to observe their occurrence and measure some parameters (duration, elapsed time and time between two successive M-components), whose statistics are presented and compared in detail to the data for negative flashes. We have plotted a histogram of the M-components elapsed time over the total duration of the continuing current for positive flashes, which presented an exponential decay (correlation coefficient: 0.83), similar to what has been observed for negative flashes.

1. Introduction and review

It is well known that there are three possible modes of charge transfer to ground associated with strokes from negative lightning discharges: the return stroke, the continuing current and the M-component (Rakov et al., 2001; Rakov and Uman, 2003). Previously, only the two former were already known to occur in the positive flash phenomenon (V. Rakov, personal communication, 2006). In this paper we present results from the observations of M-components in positive CG lightning. As far as the authors know, this is the first report on the presence of M-components in positive continuing currents. In the following a brief descriptions of the continuing current and M-component are presented.

1.1. Continuing current

The continuing current (CC) is a continuous mode of charge transfer to the ground. Three categories of CC were defined in previous studies of flashes containing CC. Kitagawa et al. (1962) and Brook et al. (1962) defined "long" continuing current (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"

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Table 1
Comparative summary review on CC and M-components recent and the present studies

Work (triggered or CG lightning)	Analyses		Number of CC	Number of M	Observation method	Distance range (km)
	CC waveshape	M-components				
Fisher et al. (1993) (triggered)	X		30	–	Channel base current	–
Campos et al. (2007) (natural negative)	X	X	63	345	High-speed video	2 to 53
Present study (natural positive)	X	X	21	190	High-speed video	9.5 to 96

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. As reported by previous works, 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 (e.g., Chisholm et al., 2001; Fisher and Plumer, 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). Fisher et al. (1993) published the first study on the waveshapes of CC, based solely on direct measurements from triggered lightning. They analyzed 30 CC having durations exceeding 10 ms and found that they exhibit a variety of waveshapes that were grouped into four categories. Campos et al. (2007) presented the first results for negative CG flashes based on data from a high-speed video system. They analyzed 63 negative long CC, 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.

In the present work an analysis similar to Campos et al. (2007) is done for CC of positive CG lightning. The study is based on video observation of the channel luminosity variation with time in a millisecond time scale and it is the first to present data on characterization of waveshapes of positive CG lightning CC. The data are compared to those for triggered lightning and negative CG lightning.

1.2. M-component

The M-component, first described by Malan and Collens (1937), is observed as an increase in luminosity of the channel during the occurrence of a continuing current event. The intensity of their light pulses as a function of time is more or less symmetrical. The increase in luminosity is associated with current pulses with amplitudes of typically some hundreds of amperes and rise times of some hundreds of microseconds as observed from triggered lightning measurements (Thottappillil et al., 1995). They are distinctly different from return

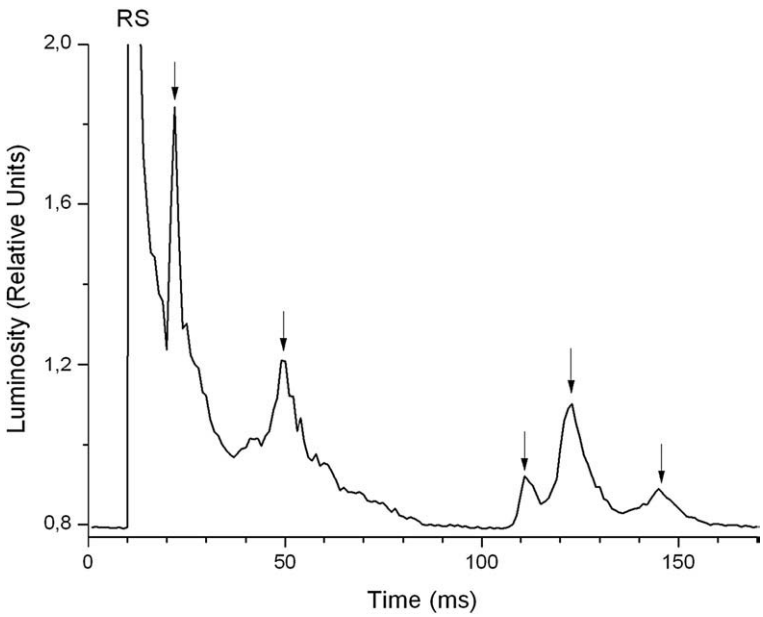

Fig. 1. Example of a luminosity-versus-time graph obtained for one of the positive flashes analyzed in this study. RS indicates the return stroke (cut here in order to enhance the visualization of the CC waveshape) and each arrow indicates an M-component.

Table 2
Statistics on negative (Campos et al., 2007) and positive CC waveshape types compared to the data for triggered lightning presented by Fisher et al. (1993)

Type	Description	Triggered (Fisher et al., 1993)	Negative flashes (Campos et al., 2007)	Positive flashes (present study)
I	More or less exponential decay	47% (14)	24% (15)	24% (5)
II	Hump followed by a gradual decay	36% (11)	6% (4)	24% (5)
III	Gradual increase and decrease	10% (3)	16% (10)	0% (0)
IV	Hump followed by a long-lasting steady plateau	7% (2)	8% (5)	9% (2)
V	Two or more humps	–	11% (7)	0% (0)
VI	Low intensity plateau	–	35% (22)	43% (9)
Total		100% (30)	100% (63)	100% (21)

stroke current pulses, which occur only after the cessation of any preceding current through the channel base and which typically exhibit submicrosecond rise times (Fisher et al., 1993). Most of these parameters were obtained through rocket-triggered or tower-initiated lightning. For CG flashes, few statistics on the characteristics of M-components were done and, most of them were based on electric field change techniques, which limits the observation to very close range ground flashes. Table 1 summarizes the previous recent works about these two subjects (Thottappillil et al., 1990; Rakov et al., 1992; Fisher et al., 1993; Thottappillil et al., 1995, and Campos et al., 2007) in comparison to the present study.

In the present study, statistical distribution for M-component characteristics is done for a larger number of positive CG flashes occurring from 9.5 up to 96 km from the observer. It is based on the variation of the channel luminosity with time on a millisecond scale. As far as we know, this is the first work reporting the occurrence of M-components in positive CG lightning (V. Rakov, personal communication, 2006).

Table 3
Summary of M-components statistics comparing the datasets for positive and negative (Campos et al., 2007) flashes

Parameter	Positive flashes (present study)			Negative flashes (Campos et al., 2007)		
	Sample size	GM	$SDlog_{10}$	Sample size	GM	$SDlog_{10}$
M elapsed time, Δt_{RM}, ms	190	52.5	0.44	345	42	0.55
M interval, Δt_M, ms	172	8.6	0.42	289	11	0.43
M duration, T_M, ms	190	3.4	0.28	345	4.8	0.23

GM is the geometric mean value and $SDlog_{10}$ is the standard deviation of the logarithms of the parameters.

2. Instrumentation and data collection techniques

For this study we used a Red Lake 8000S Motion Scope high-speed CCD camera set at a frame rate of 1000 frames per second. The triggering mode used recorded 1 s prior to and 1 s after the trigger button was pressed by the operator. The high-speed video recordings were stored in computer files, which can be retrieved and replayed at an adequate speed for a detailed analysis. Each video frame was GPS time-stamped with 1 ms accuracy.

In order to identify the stroke polarity and determine the distance from the camera, we used the BrasilDAT Lightning Location System data [more information on the characteristics of the network is found in Pinto et al. (2006a,b, 2007)]. The stroke matching between camera and network was done by GPS time synchronization (timing accuracy for each GPS system less than 1 ms).

More details on the site, equipment and accuracy of high-speed videos in lightning observation can be obtained in Campos et al. (2007) and Saba et al. (2006a, 2008).

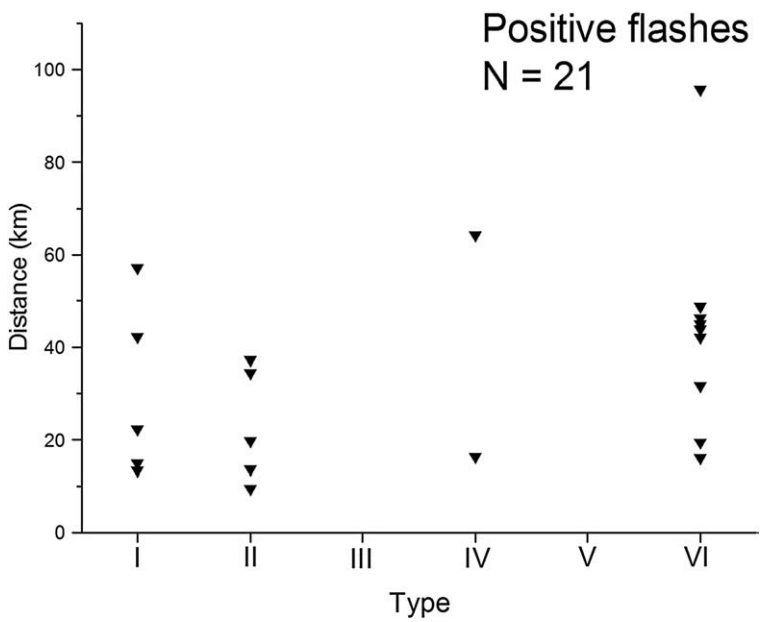

Fig. 2. Plot of positive stroke distances for each type; there is no distinctive distance distribution for any specific types.

2.1. Video analysis

In order to identify the M-components and to trace the waveshape of the CC events, a computational algorithm was developed to open and analyze pixels of each image obtained by the high-speed camera. Graphs showing luminosity-versus-time were then generated. As reported by Diendorfer et al. (2003) through tower measurements, the lightning channel luminosity is directly proportional to the current that flows through it, following a linear correlation in the range of 10 to 250 A. As this range is also the typical range observed for CC in natural flashes (e.g. Shindo and Uman, 1989), one could use the luminosity-versus-time graphs to infer how the continuing current intensity varies with time. Fig. 1 shows a luminosity-versus-time graph of one of the positive CC considered in the present study.

A more detailed description of the applied method is presented by Campos et al. (2007).

3. Data analysis and results

Our total dataset is composed of 63 negative and 21 positive long CC during which 345 and 190 M-components were observed, respectively. All the cases were selected from more than 800 flashes recorded in São José dos Campos (45.864°W, 23.215°S) and Uruguaiana (29.806°W, 57.005°S) in

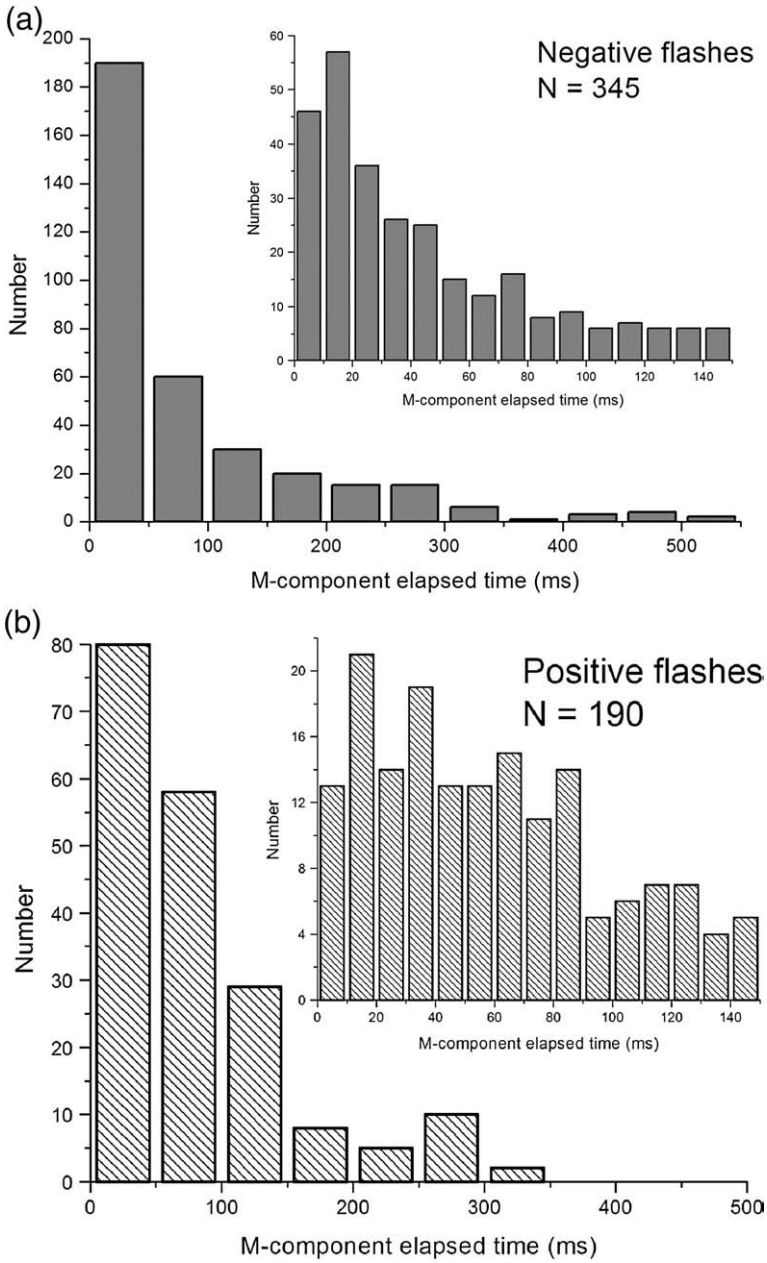

Fig. 3. Distribution of M-component elapsed time for (a) negative (Campos et al., 2007) and (b) positive cases.

southeast and south of Brazil, respectively, during the summers of 2003 to 2007. Both sites are located in regions covered by the Brazilian lightning locating system—BrasilDAT. A detailed study on the data for negative CC and M-components were already presented by Campos et al. (2007) and their data are reproduced here just for comparison purposes.

3.1. Continuing current waveshape

After applying the method described by Campos et al. (2007) to 21 events of long positive CC, we were able to identify three out of four types mentioned by Fisher et al. (1993) and one out of two other new types proposed by Campos et al. (2007) to better characterize cases that are not well covered by Fisher et al. (1993).

A total of 190 M-components were detected superimposed on the waveshapes of the positive CC. Having in mind the definition of an M-component, every increase in the luminosity shown in the generated graphs was visually inspected through the source videos to better discriminate M-components from spurious fluctuations.

The statistics of the occurrence of the different types of waveshapes in positive CG lightning is presented in Table 2 along with the data for negative CG (Campos et al., 2007) and triggered (Fisher et al., 1993) flashes. All types of waveshapes observed in positive CC has presented, in at least one case, M-components superimposed throughout the whole duration

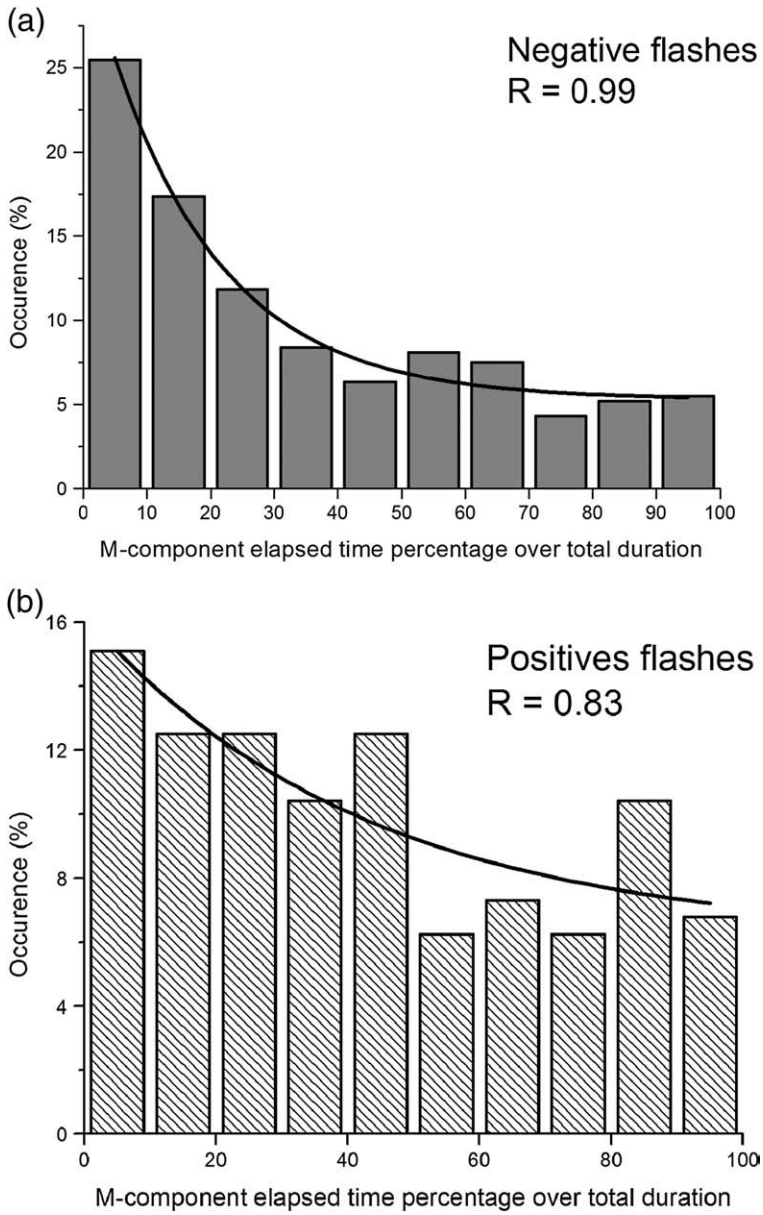

Fig. 4. Percentage occurrence of M-components elapsed time over CC total duration; both (a) negative (Campos et al., 2007) and (b) positive flashes datasets were fit to exponential decay curves with correlation coefficients of 0.99 and 0.83, respectively.

(similarly to that reported by Campos et al., 2007, for negative CC); Fisher et al. (1993) did not observe M-components of the waveshapes of Types II and IV during specific periods. Also the most frequent waveshape was not Type I, as observed by Fisher et al. (1993), but Type VI (not observed by them)for both positive and negative (Campos et al., 2007) flashes datasets.

The percentages for Types I and IV are almost identical for both positive and negative flashes (Campos et al., 2007) while Types II and VI were considerably more frequently observed in the positive CC. Types III and V were not observed in the entire positive flashes dataset. As they are very similar (Type III has one hump with M-components superimposed on it while V has two or more humps of the same kind), it is possible to argue that the physical mechanism of the positive CC does not allow this kind of temporal development.

One could argue that the occurrence of each type may be influenced by the distance from the camera to the stroke event (for example, a very distant case could be mistakenly considered as Type VI due to the very low intensity of its luminosity). On the contrary, it is possible to notice from Fig. 2 that nearly all events occurred within distances smaller than 60 km (2 exceptions in 21) to the observation site; there is also no substantial difference between the distance distributions for each Type. The same analysis was made by Campos et al. (2007) for the negative flashes dataset with similar conclusions.

3.2. M-component

Using the same method as Campos et al. (2007), a total of 190 M-components were identified during the CC phases of

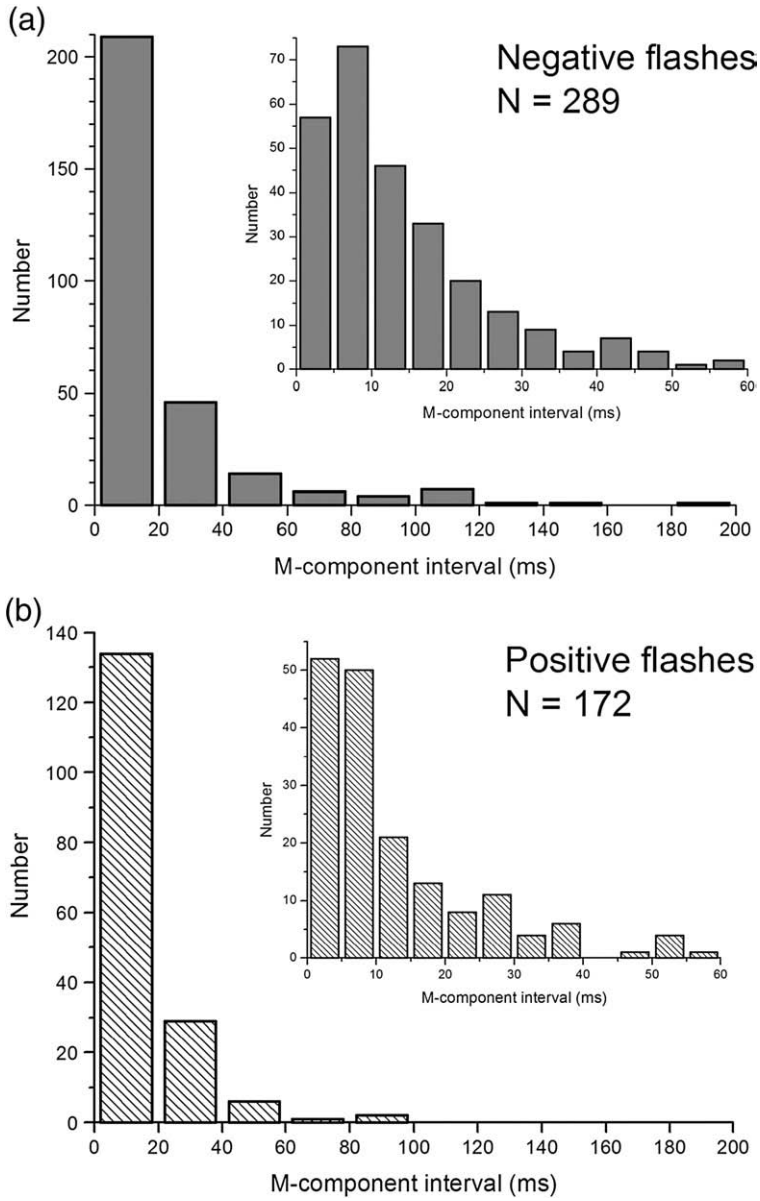

Fig. 5. Distribution of M-component intervals for (a) negative (Campos et al., 2007) and (b) positive CC.

21 positive flashes. The average number of M-components per continuing current was 9.0. Due to the 1-ms resolution of the videos, the minimum interval distinguishable between two consecutive M-components was 2 ms. As the exposure time of each frame is also 1 ms, even when a M-component lasts less than 1 ms, it is detected as a 2-ms duration M-component. This limitation however is not critical, since according to studies done by Thottappillil et al. (1995), 75% of the intervals between M-components is greater than 2 ms and about 80% of the M-components durations last longer than 1 ms.

The statistical results of the parameters discussed below are presented in Table 3 and compared to results for negative flashes.

3.2.1. M-component elapsed time

The distributions of all negative and positive M-components elapsed times are shown in Fig. 3 (negative distribution from the previous work by Campos et al., 2007). For both negative and positive flash datasets, the most frequent values occurred between 10 and 20 ms (57 cases in 281 for negative 21 in 167 for positive flashes).

We have normalized the M-component elapsed time absolute values in terms of percentage over the total duration of the CC, as shown in Fig. 4. This data was presented earlier by Campos et al. (2007), only for negative M-components (Fig. 4a). For negative CC, nearly 25% of M-components occur in the first 10% of the duration of the CC, and more than 75% occur in the first half of the CC (Campos et al., 2007). For the

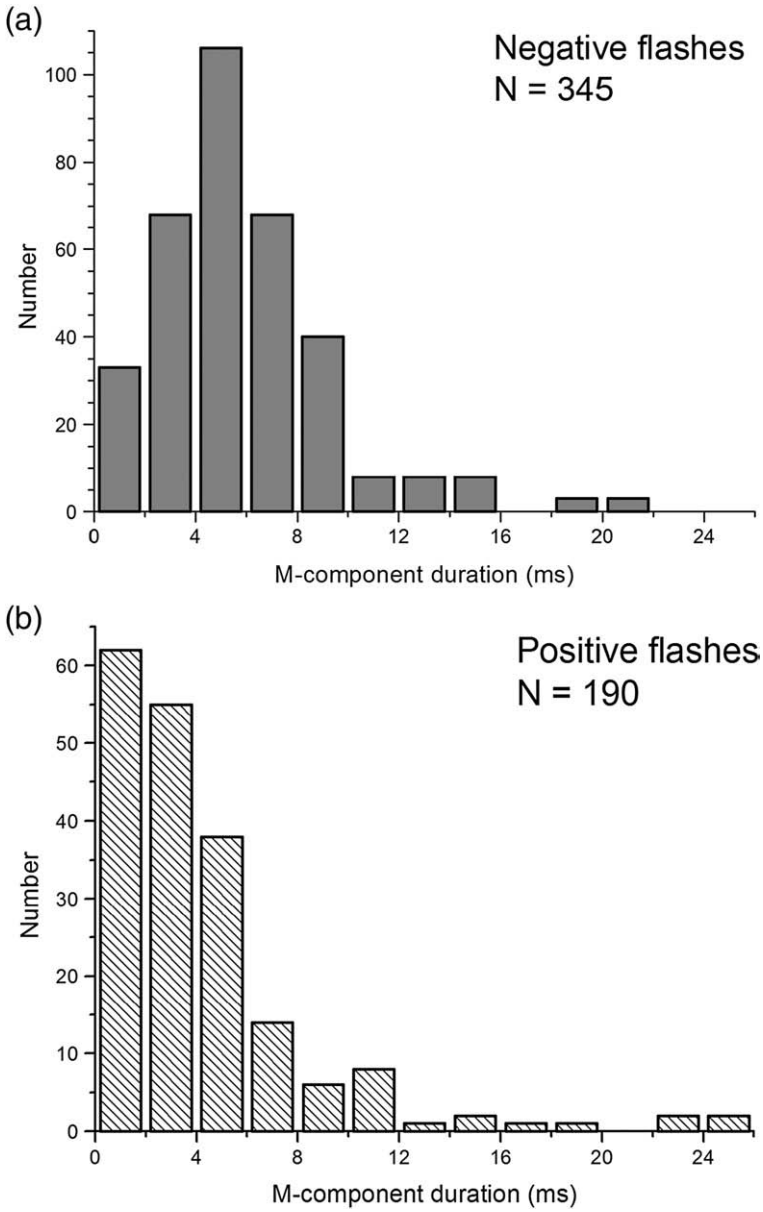

Fig. 6. Histograms of M-component duration for (a) negative (Campos et al., 2007) and (b) positive cases.

positive cases, only 15% of the M-components occur in the first 10% of the continuing current and only approximately 60% of the M-components occur in the first half of the CC extension. It is noticeable that M-components in negative flashes tend to group in the early periods of the continuing current while in positive flashes they are better distributed along the total duration. The occurrence for negative flashes follows an exponential decay with the time of the continuing current with very good approximation (correlation coefficient: 0.99, as obtained by Campos et al., 2007); the positive flash dataset also presented the same correlation but with a smaller confidence (correlation coefficient: 0.83).

Our geometric mean for M-component elapsed time was 52.5 ms for positive flashes whereas Campos et al. (2007) obtained 42 ms for negative flashes; both are very distinctive from the value presented by Thottappillil et al. (1995), who found 9.1 ms for triggered flashes. A possible explanation for this discrepancy is that although the present study and the one made by Campos et al. (2007) could not see elapsed times lower than 2 ms, both studies' datasets include some very long CC. The maximum value of elapsed time obtained was 318 ms (for positive flashes) and 538 ms for negative flashes (Campos et al., 2007). The maximum value of the elapsed time found by Thottappillil et al. (1995) was lower than 256 ms (retrieved from the maximum value of the elapsed time duration axis of their histogram).

3.2.2. Time interval between successive M-components

The distribution of the 172 time intervals between successive M-components during the CC of positive flashes is shown in Fig. 5. In the same figure the results for negative flashes is also shown (Campos et al., 2007). More than 90% of the negative M-components intervals and 99% of the positive ones are shorter than 60 ms (Fig. 5).

3.2.3. M-component duration

Fig. 6a,b shows the distribution of the duration of 345 negative (Campos et al., 2007) and 190 positive M-components. Although for both positive and negative M-components more than 90% of the cases lasted less than 10 ms, positive cases tend to be shorter: 30% lasted less than 2 ms while only 10% of the negative cases were included within this range. Also, more than 60% lasted less than 4 ms against only 30% of the negative M-components. For the negative flashes dataset, there is a peak of occurrence between 4 and 6 ms (about 30% of the negative dataset) and an extreme case lasting 21 ms (Campos et al., 2007); among the positive M-components the peak occurred for cases lasting less than 2 ms (also about 30% of the positive dataset) and an extreme value of 24 ms was observed. In both negative and positive flashes datasets, their extreme cases are longer than the maximum statistical range of 16 ms shown in the histograms presented by Thottappillil et al. (1995) for triggered lightning. Due to the temporal resolution of the camera it was not possible to determine with good precision the exact duration of M-components lasting less than 2 ms, although they could be observed and considered in the statistics as M-components with 2-ms duration; for further details on the instrument limitation for this work, please refer to the studies made by Saba et al. (2006a, 2008) and Campos et al. (2007). According to Thottappillil et al. (1995), 2-ms long or shorter M-components represent 50% of the cases in triggered lightning. But it was found that only 10% of the negative (Campos et al., 2007) and 30% of the positive cases were within this range, suggesting that natural M-components tend to be longer.

4. Summary

This paper reports the characteristics of long positive CC along with the associated M-components for positive CG lightning using the same method presented by Campos et al. (2007) (and briefly described in Section 2.1 of the present paper). It is the first work to report the occurrence of M-components in positive CC (V. Rakov, personal communication, 2006).

Contrary to the results presented by Fisher et al. (1993) for triggered flashes and Campos et al. (2007) for negative CG flashes, we have not observed any Type III or V cases in the positive flashes dataset. As both types have a very similar characterization (humps superimposed by M-components, one in Type III and two or more in V), one could argue that this pattern of temporal development of the CC is not possible in the physical mechanism of the positive CC. For both positive and negative flashes, Type VI was the most frequent and Types I and IV presented almost identical occurrence statistics. It is evident that the parameters for CG lightning of both polarities are very distinctive from the triggered lightning data presented by Fisher et al. (1993).

Even though both positive and negative M-components elapsed time have presented the same kind of exponential decay fit when normalized to the total duration of the CC, they have very distinctive temporal distributions; negative M-components tend to occur in the first moments after the return stroke (Campos et al., 2007) while the positive ones have a more homogeneous distribution along the CC duration.

There was no statistically significant difference between the negative and positive values for the time interval between two successive M-components. Positive M-components tend to present slightly smaller durations when compared to negative ones; despite this fact, more than 90% of the cases lasted less than 10 ms for both kinds.

The average number of M-components per CC found was 9.0 for positive CG lightning, while for negative cases it was 5.5 (Campos et al., 2007). This difference may be related to the very distinctive temporal distribution in each case.

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References

Ballarotti, M.G., Saba, M.M.F., Pinto Jr., O., 2005. High-speed camera observations of negative ground flashes on a millisecond-scale. Geophys. Res. Lett. 32, L23802. doi:10.1029/2005GL023889.

Brook, M., Kitagawa, N., Workman, E.J., 1962. Quantitative study of strokes and continuing currents in lightning discharges to ground. J. Geophys. Res. 67, 649–659.

Campos, L.Z.S., Saba, M.M.F., Pinto Jr., O., Ballarotti, M.G., 2007. Waveshapes of continuing currents and properties of M-components in natural negative cloud-to-ground lightning from high-speed video observations. Atmos. Res. 84, 302–310.

Chisholm, W.A., Levine, J.P., Chowdhuri, P., 2001. Lightning arc damage to optical fiber ground wires (OPGW): parameters and test methods, in 2001 Power Engineering Society Summer Meeting. Conference Proceedings, Vancouver, BC, Canada, vol. 1, pp. 88–93.

Diendorfer, G., Viehberger, M., Mair, M., Schulz, W., 2003. An attempt to determine currents in lightning channels branches from optical data of a high-speed video system, in Int. Conf. on Lightning and Static Electricity 2003. Conference Proceedings, CD-ROM, I03-8 PMY. Royal Aeronautical Society, Blackpool, UK.

Fisher, F.A., Plumer, J.A., 1977. Lightning Protection of Aircraft. NASA Ref. Publ.. NASA-RP-1008.

Fisher, R.J., Schnetzer, G.H., Thottappillil, R., Rakov, V.A., Uman, M.A., Goldberg, J.D., 1993. Parameters of triggered-lightning flashes in Florida and Alabama. J. Geophys. Res. 98, 22887–22908.

IEC, 2006. Protection against Lightning, Part 1: General Principles. IEC. 62305-1.

Kitagawa, N., Brook, M., Workman, E.J., 1962. Continuing currents in cloud-to-ground lightning discharges. J. Geophys. Res. 67, 637–647.

Malan, D.J., Collens, H., 1937. Progressive lightning, III, The fine structure of return lightning strokes. Proc. R. Soc. Lond., A Math. Phys. Sci. 162, 175–203.

Pinto Jr., O., Nacaratto, K.P., Saba, M.M.F., Pinto, I.R.C.A., Abdo, R.F., Garcia, S.A.M., 2006a. Recent upgrades to the Brazilian Integrated Lightning Detection Network. 19th International Lightning Detection Conference, Vaisala, Tucson, AZ, USA.

Pinto Jr., O., Naccarato, K.P., Pinto, I.R.C.A., Fernandes, W.A., Neto, O.P., 2006b. Monthly distribution of cloud-to-ground lightning flashes as observed by lightning location systems. Geophys. Res. Lett. 33, L09811. doi:10.1029/2006GL026081.

Pinto Jr., O., Pinto, I.R.C.A., Naccarato, K.P., 2007. Maximum cloud-to-ground lightning flash densities observed by lightning location systems in the tropical region: A review. Atmos. Res. 84, 189–200.

Rakov, V.A., Uman, M.A., 1990. Long continuing current in negative lightning ground flashes. J. Geophys. Res. 95, 5455–5470.

Rakov, V.A., Uman, M.A., 2003. Lightning: Physics and Effects. Cambridge Univ. Press, New York. 687 pp.

Rakov, V.A., Thottappillil, R., Uman, M.A., 1992. Electric field pulses in K and M changes of lightning ground flashes. J. Geophys. Res. 97, 9935–9950.

Rakov, V.A., Crawford, D.E., Rambo, K.J., Schnetzer, G.H., Uman, M.A., Thottappillil, R., 2001. M-component mode of charge transfer to ground in lightning discharges. J. Geophys. Res. 106, 22817–22831.

Saba, M.M.F., Ballarotti, M.G., Pinto Jr., O., 2006a. Negative cloud-to-ground lightning properties from high-speed video observations. J. Geophys. Res. 111, D03101. doi:10.1029/2005JD006415.

Saba, M.M.F., Pinto Jr., O., Ballarotti, M.G., 2006b. Relation between lightning return stroke peak current and following continuing current. Geophys. Res. Lett. 33, L23807. doi:10.1029/2006GL027455.

Saba, M.M.F., Cummins, K.L., Warner, T.A., Krider, E.P., Campos, L.Z.S., Ballarotti, M.G., Pinto Jr., O., Fleenor, S.A., 2008. Positive leader characteristics from high-speed video observations. Geophys. Res. Lett. 35, L07802.

Shindo, T., Uman, M.A., 1989. Continuing current in negative cloud-to-ground lightning. J. Geophys. Res. 94, 5189–5198.

Thottappillil, R., Rakov, V.A., Uman, M.A., 1990. K and M changes in close lightning ground flashes in Florida. J. Geophys. Res. 95, 18631–18640.

Thottappillil, R., Goldberg, J.D., Rakov, V.A., Uman, M.A., Fisher, R.J., Schnetzer, G.H., 1995. Properties of M components from currents measured at triggered lightning channel base. J. Geophys. Res. 100, 25711–25720.