Characteristics of Initial Continuous and Continuing Current Processes in Rocket-triggered Lightning

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ABSTRACT: Channel-base currents of ten rocket-triggered lightning measured in Conghua, Guangzhou, China in summer of 2011 are analyzed. Characteristic parameters and correlationship of 10 initial continuous currents (ICCs), 79 initial continuous current pulses (ICCPs) superposed on ICC, 8 continuing currents (CCs) after return stroke, and 35 M-components superposed on CC in the ten triggered lightning are analyzed statistically. The geometric mean values (GM) of duration, amplitude, and charge transfer for ICC are 298 ms, 192 A, and 57.2 C, respectively. The corresponding parameters for CC are 37 ms, 202 A, and 7.4 C, respectively. The amplitude of ICC is slightly smaller than the CC. The values of duration and charge of ICC are about 8 times bigger than CC.

Current waveforms of ICCPs and M-components are all approximate symmetry. The GM of magnitude, charge transfer, half peak width, rise time (10-90%), duration, preceding ICC level, and interpulse interval are 142 A, 148 mC, 928 μs, 466 μs, 2.88 ms, 186 A and 12.3 ms for ICCPs, respectively. The corresponding parameters for M-components are 308 A, 179 mC, 628 μs, 369 μs, 1.95 ms, 243 A and 7.8 ms, respectively. As a whole, the current waveforms of M-components are steeper, narrower and bigger than ICCPs; the distribution of M-components is more intensive than ICCPs.

There are significant correlations between the duration of ICC and half peak width, rise time, duration, magnitude of ICCP, the correlation coefficients are 0.77, 0.76, 0.77 and -0.87, respectively. While the correlation coefficients of duration of CC after return stroke and half peak width, rise time, duration, magnitude of M-component are 0.53, 0.49, 0.52 and -0.79, respectively.

INTRODUCTION

Continuing current (CC) in cloud-to-ground lightning is a continuous mode of thundercloud charge transfer to the ground along lightning channel after lightning stroke. The ground electric field waveform of CC changes slowly within a broad range. Meanwhile, the lightning channel below the cloud in CC process shines continuously. Hagenguth and Anderson [1952] firstly discovered CC when observed lighnting to the Empire building. CC changes with a duration between a few milliseconds and a few hundred milliseconds. According to the duration, CC can be grouped into three categories: long CC,

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greater than 40 ms; short CC, between 10 ms and 40 ms; very short CC, less than 10 ms [Kitagawa et al. 1962; Shindo and Uman 1989; Ballarotti et al. 2005]. The amplitude of CC is mostly dozens to hundreds of Ampere [Brook et al. 1962; Shindo and Uman 1989]. Brook et al [1962] calculated charges transfer for CC and found that the average charge of long CCs (average duration 150 ms) is 12 C.

The phenomenon of lightning channel brightness bump up in channel faint light phase after lightning stroke was first described by Malan and Collens [1937], which was termed M-component. Thottappillil et al [1990, 1995] measured the characteristic parameters of M-components in close cloud-to-ground lightning flashes and triggered lightning, geometric mean values (GM) of duration and interpulse interval of M-components in ground lightning are 0.9 ms and 2.1 ms, respectively. The peak currents are between 100 A to 200 A, rise times from 10% to 90% peak are between 300 μs to 500 μs, charges transfer are between 0.1 C to 0.2 C for M-components in triggered lightning. The geometric mean values of peak current, risetime from 10% to 90% peak, half peak width and charge transfer for ICCPs and M-components given by Qie et al. [2014] are 0.09 kA、437μs、712μs、0.10 C, and 0.28 kA、251μs、242μs、0.10 C, respectively.

The initial stage (IS) of negative rocket-triggered lightning can be viewed as composed of an upward positive leader (UPL) followed by an intial continuous current (ICC). The ICC usually includes impulsive processes which are referred to as ICC pulses or IS pulses. The detailed information on IS and ICC pulses is found in the work of Wang et al. [1999], Miki et al. [2005], and Flache et al. [2008]. The transition from the UPL to the ICC isn't identified by examining channel-base current records. So, the total IS is regarded as ICC in this paper.

EXPERIMENT DATA AND PARAMETER DEFINITION

Experiment data

The Guangdong Comprehensive Observation Experiment on Lightning Discharge (GCOELD) has been conducted since 2006 in Conghua, Guangdong, China. More detail about GCOELD was introduced in [Zhang et al. 2014]. There were total 13 negative lightning triggered in May to August in 2011, the channel base currents of ten triggered lightning were measured and recorded by a shunt with a resistance of 1mΩ and oscilloscope. Sample rate of the oscilloscope was set to be 10 MSa/s, and the recording length was 2 s. Some informations of the ten triggered lightning are shown in Table 1.

Table 1 Some informations of ten triggered lightning studied in this paper

Triggered lightning	Data of lightning	Triggered way	Number of return strokes	Number of ICCs	Number of ICCPs	Number of CCs	Number of M-components
T201102	June 7	Classical triggering	1	1	4	1	5
T201103	June 7	Classical triggering	0	1	11	0	0
T201105	June 11	Classical triggering	1	1	21	1	0

T201106	June 11	Classical triggering	0	1	18	0	0
T201107	June 11	Classical triggering	1	1	2	1	4
T201108	June 29	Classical triggering	8	1	0	4	21
T201110	June 29	Altitude triggering	1	1	18	1	5
T201111	July 16	Classical triggering	0	1	3	0	0
T201112	July 16	Classical triggering	0	1	2	0	0
T201113	July 30	Classical triggering	0	1	0	0	0
Total			12	10	79	8	35

Parameter definition

Current waveforms of typical ICC and CC (Fig.1) are both changing slowly and continuously. ICC duration (T_{ICC}) is the time interval between the time of current begin to greater than noise current level to the time of current begin to submerging in the noise level. CC duration (T_{CC}) is the time interval between the end time of waveform falling fast after return stroke to the time of current begin to submerging in the noise level. Charge transferred for ICC (Q_{ICC}) or CC (Q_{CC}) is the time integral of ICC or CC current. ICC or CC amplitude (A_{ICC}, A_{CC}) is result of the amount of charge (Q_{ICC}, Q_{CC}) divided by the duration (T_{ICC}, T_{CC}).

As shown in Figure 1, there are some current pulses superposed on ICC and CC. In this paper, only the ones which have obvious corresponding pusles in fast and slow electric field change waveforms are analyzed as ICCPs and M-components. The current waveforms of typical ICCP and M-component of triggered lightning T201102 and T201107 shown in Figure 1 are depicted in Figure 2. The current waveforms of ICCPs and M-components both exhibit approximate symmetry. Some current parameters of ICCP and M-component are defined in Figure 2. In this paper, the parameters definitions of ICCP are as same as M-component's, and they are all as same as the definition of other researchers' [Thottappillil et al. 1995]. Preceding M-component level (I_{CC}) is the value of the continuing current immediately preceding the M-component. M current magnitude (A_M) is the difference between the peak of M-component current pulse and the preceding continuing current level. M current duration (Td_M) is the time interval measured from the behinning of the wave front to the somewhat subjectively selected point at which the trailing edge of the M-component becomes indistinguishable from the overall continuing current waveform. M current half-peak width (Th_M) is the time interval between the 50% values of the magnitude on the wave front and on the falling portion of the M pulse. M current rise time from 10% to 90% (Tr_M) is the time interval on the wavefront between the 10% and 90% values of the magnitude. M charge (Q_M) is the time integral of the M current above the continuing current. M interval (Ti_M) is the time interval between the

peak values of successive M-components. The corresponding parameters symbols of ICCP are A_{ICC}, I_{ICC}, A_{ICCP}, Td_{ICCP}, Th_{ICCP}, Q_{ICCP}, and Ti_{ICCP}.

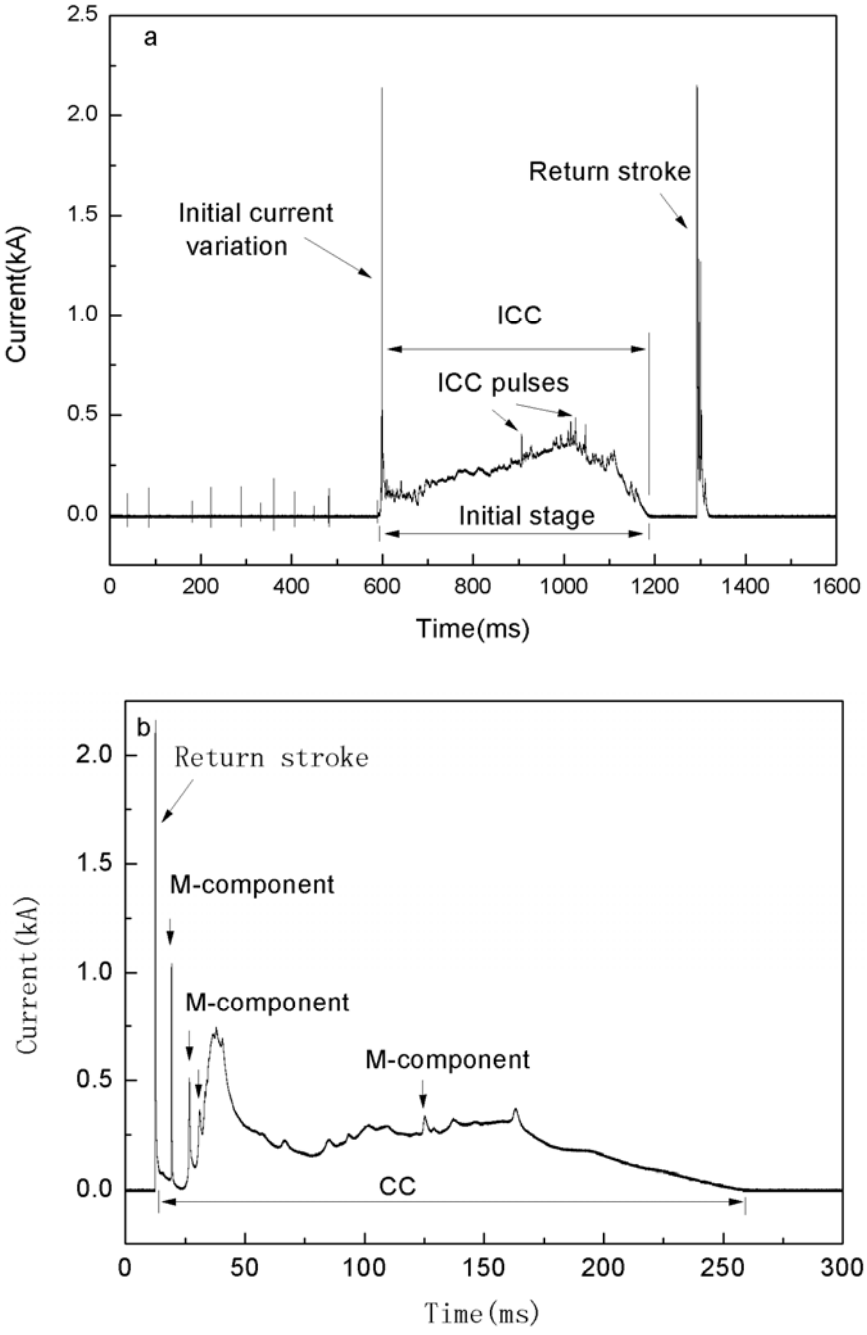


Figure 1 Current waveforms: a, initial continuous current (ICC) in triggered lightning T201102; b, continuing current (CC) in triggered lightning T201107

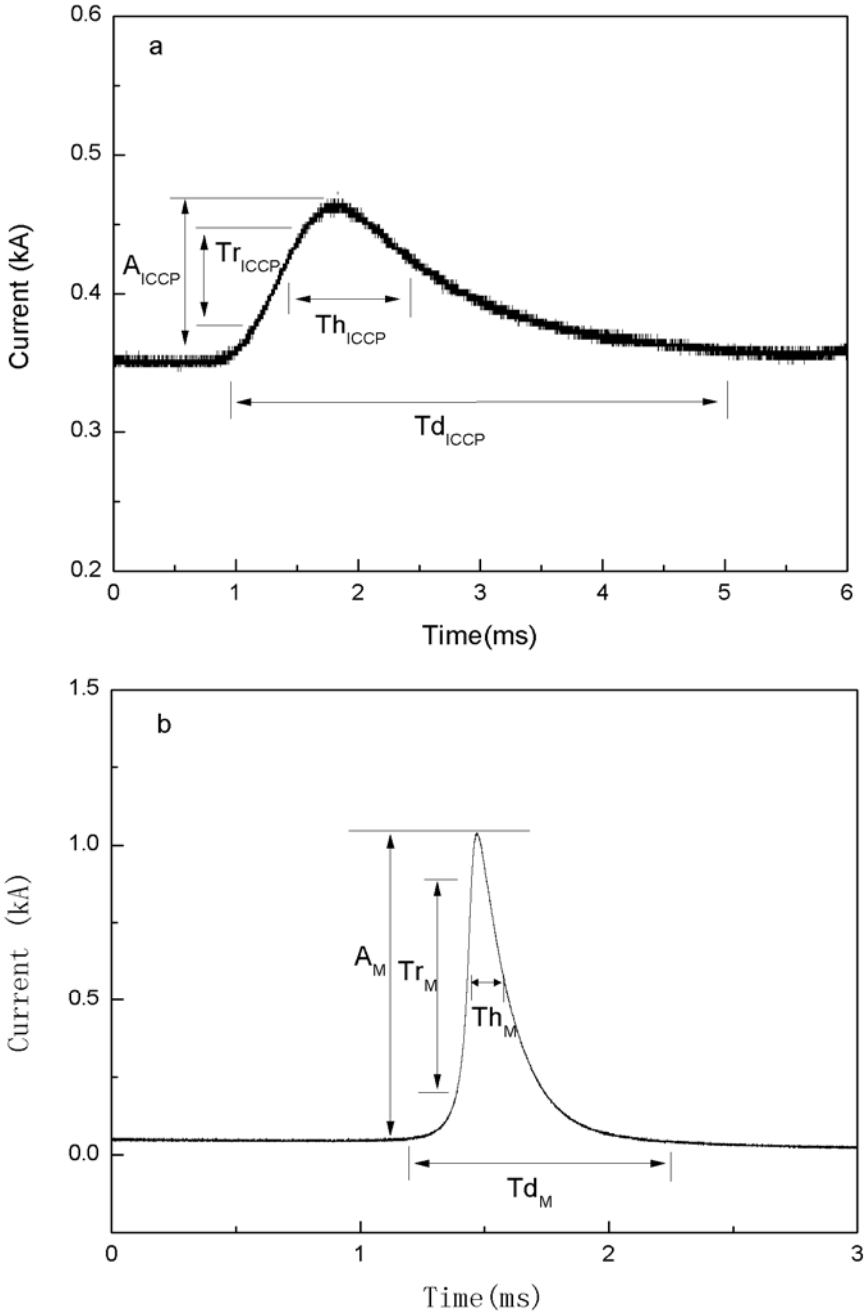


Figure 2 Current waveforms: a, initial continuous current pulse (ICCP) in triggered lightning T201102; b, M-component in triggered lightning T201107

RESULTS

Characteristic parameters of ICC and CC

The characteristic parameters of the ten ICCs are shown in Table 2. Great differences occur in different ICCs. The durations of ICCs vary between 39 ms and 693 ms, of which the geometric mean value (GM) is 298 ms. Charges transfer for ICCs are between 11.6 C and 184.6 C with a GM of 57.2 C. The amplitudes of ICCs change from 70 A to 666 A with a GM of 192 A.

Table 2 Statistical results of parameters of initial continuous currents (ICC) in triggered lightning

Triggered lightning	T_{ICC}(ms)	Q_{ICC}(C)	A_{ICC}(A)
T201102	593	142.5	240
T201103	693	184.6	266
T201105	443	61.6	139
T201106	653	80	123
T201107	39	25.9	666
T201108	165	11.6	70
T201110	452	88.6	196
T201111	240	54.0	225
T201112	277	60.0	217
T201113	239	33.8	141

Table 3 showes the characteristic parameters of CCs after return strokes in triggered lightning. Return stroke order is the order of return stroke which is followed CC in a lightning. As shown in Table 3, the CC durations range form 3 ms to 591 ms with a GM of 37 ms. Charges transfer for CCs are between 0.3 C and 79.4 C with a GM of 7.4 C. The amplitudes of CC change from 107 A to 667 A, and the GM is 202 A. The amplitude of ICC is slightly smaller than the CC. The values of duration and charge of ICC are about 8 times bigger than CC.

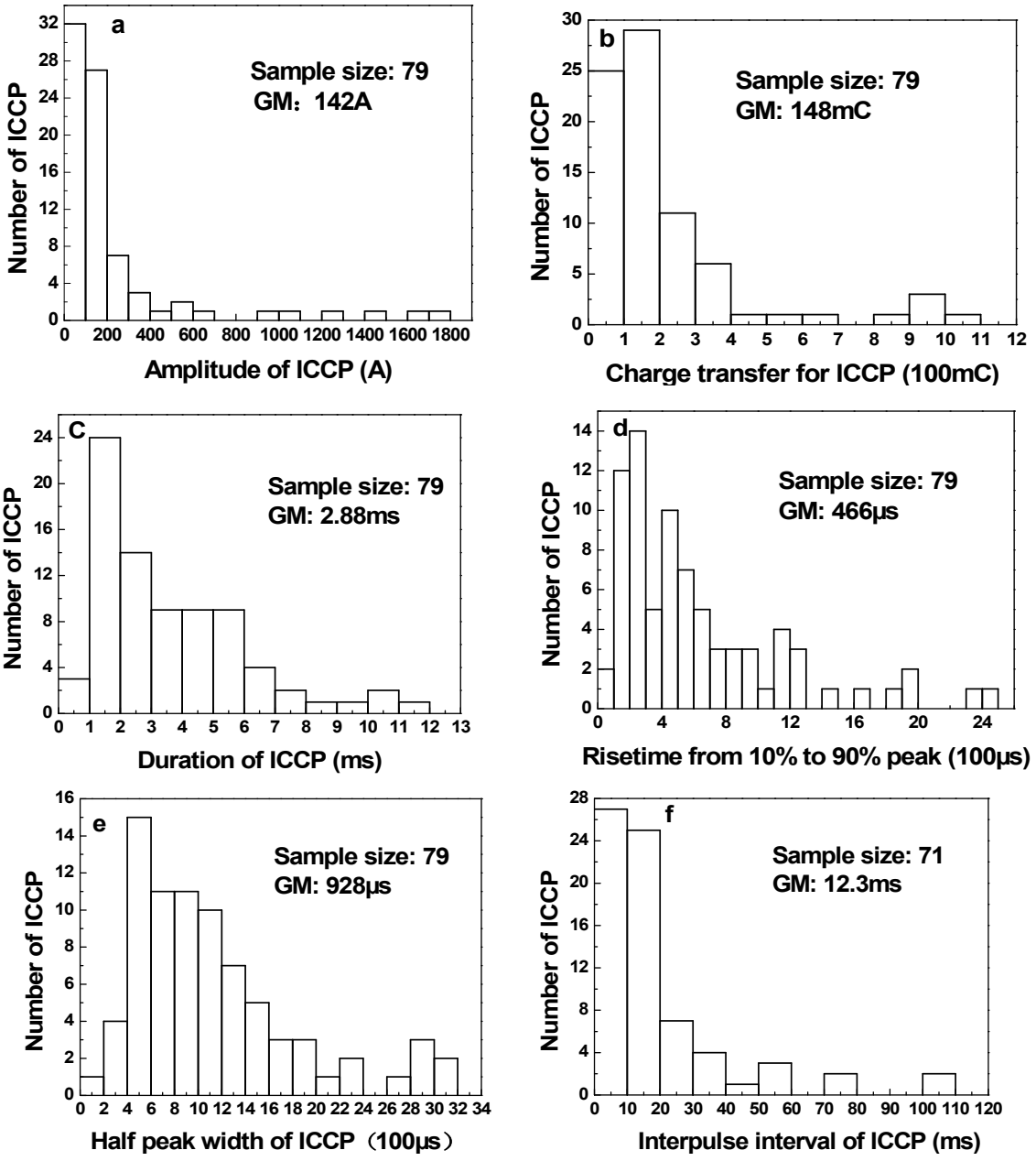
Table 3 Statistical results of parameters of continuing currents (CC) in triggered lightning

Triggered lightning	Return stroke order	T_{CC}(ms)	Q_{CC}(C)	A_{CC}(A)
T201102	1	27	5.1	189
T201105	1	3	0.3	107
T201107	1	249	52.3	210
T201108	4	3	0.5	153
T201108	6	591	79.4	135
T201108	7	27	17.8	667
T201108	8	36	11	307
T201110	1	99	15	153

Characteristic parameters of ICCP and M-component

Figure 3 show the characteristic parameters of 79 ICCPs. As shown in Figure 3, the magnitudes of ICCPs range from 32 A to 1.75 kA with a GM being 142 A, magnitudes of 72% ICCPs are less than 200 A. Charges transfer for ICCPs vary from 17 mC to 1.03 C, with the GM being 148 mC, 78 of 79 ICCPs are less than 1 C, and 89.9% of the total ICCPs are less than 400 mC. ICCP durations range from 177 μs to 11.48 ms with a GM of 2.88 ms, and the number of ICCPs between 1 ms and 2 ms is biggest. The rise

times (10%-90%) of most ICCPs are between 100 μs and 700 μs, the minimum value of rise time is 69 μs, the maximum value of rise time is 2.44 ms, and the GM of rise time is 466 μs. The half peak widths of most ICCPs are between 200 μs and 1.6 ms, the range of variation of half peak widths is from 68 μs to 3.18 ms, with the GM being 928 μs. Interpulse intervals of ICCPs range from 1.5 ms to 108 ms with a GM of 12.3 ms, most of them are less than 20 ms. The overwhelming majority of preceding ICC level of ICCPs are less than 400 A, the range of variation of preceding ICC level is from 26 A to 2.5 kA, wiht the GM being 186 A.



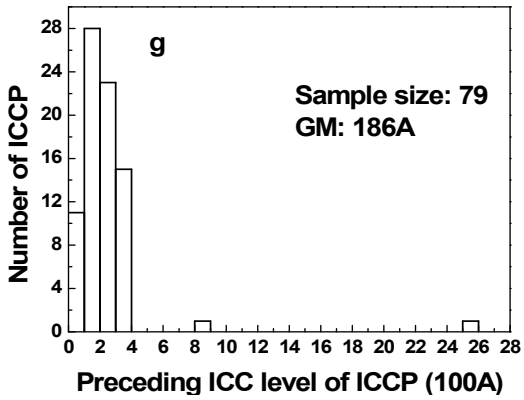
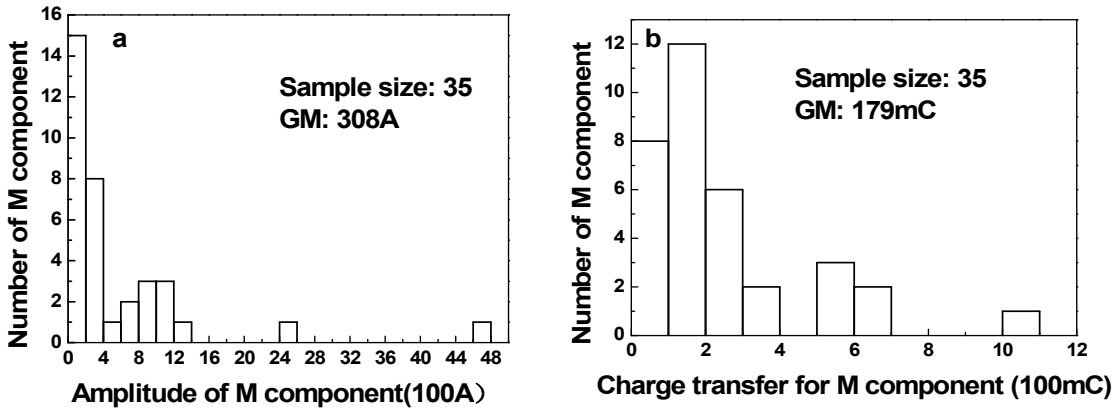


Figure 3 Distributions of characteristic parameters of initial continuous current pulse (ICCP) in triggered lightning: a, magnitude; b, charge transfer; c, duration; d, rise time from 10% to 90% peak; e, half peak width; f, interpulse interval; g, preceding ICC level

The characteristic parameters of 35 M-components in CCs after return strokes in triggered lightning are shown in Figure 4. The number of M magnitude less than 200 A is biggest, 200 A to 400 A takes the second place; the range of variation of M magnitudes is from 79 A to 4.6 kA, with the GM being 308 A. The overwhelming majority of charges transfer for M-components are less than 1 C, the minimum value is 3 mC, the maximum value is 5.11 C (not depicted), and the GM is 179 mC. M-component durations range from 313 μs to 15.3 ms with a GM of 1.95 ms. The distributions of rise time (10%-90%) and half peak width of M conmponents are both well-distributed relatively, the GM of them are 369 μs and 628 μs, respectively. More than half of interpulse intervals of M-components are less than 10 ms, the GM is 7.8 ms. The preceding CC level vary from 13 A to 1.6 kA, and the GM of preceding CC level is 243 A.



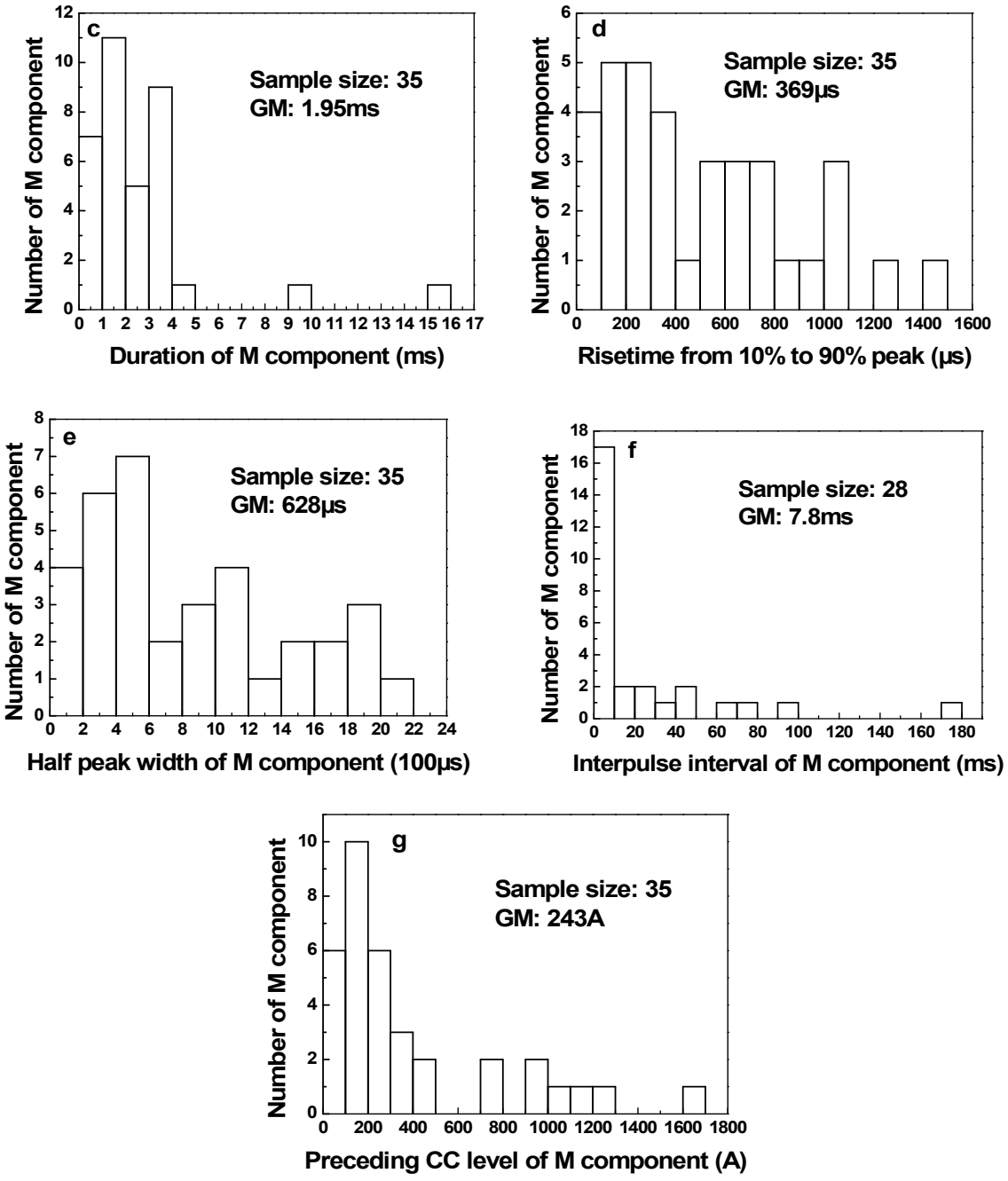


Figure 4 Distributions of characteristic parameters of M-components in triggered lightning: a, magnitude; b, charge transfer; c, duration; d, rise time from 10% to 90% peak; e, half peak width; f, interpulse interval; g, preceding CC level

Most of ICCs and CCs are superposed by ICCPs and M-components. Table 4 is the comparison of the GM of characteristic parameters of ICCP and M-component. As shown in Table 4, magnitude, preceding ICC level, and charge transfer of ICCP are both less than M-component's, rise time (10%-90%), half peak width and duration of ICCP are all more than M-component's. The current waveform of M-component is

steeper, narrower and bigger than ICCP; the distribution of M-component is more intensive than ICCP.

Table 4 Geometric mean values of current parameters of ICCP and M-component

	Magnitude (A)	Charge transfer(mC)	Duration(ms)	Rise time(μs)	Half peak width(μs)	Interpulse interval (ms)	Preceding ICC or CC level (A)
ICCP	142	148	2.88	466	928	12.3	186
M-component	308	179	1.95	369	628	7.8	243

Relationship between characteristic parameters of ICC and ICCP

Table 5 is correlation coefficients of characteristic parameters of ICC and ICCP. There are significant positive correlation between the duration of ICC and half peak width, rise time, duration of ICCP, the correlation coefficients are 0.77, 0.76, and 0.77, respectively. The duration of ICC has significant negative correlation with the magnitude of ICCP and the correlation coefficient is -0.87. These correlation coefficients are all through the verification of significance level 0.05.

Table 5 Correlation coefficients between characteristic parameters of ICC and ICCP

	A_{ICCP}	Q_{ICCP}	Th_{ICCP}	Tr_{ICCP}	Td_{ICCP}	I_{ICC}	Ti_{ICCP}
T_{ICC}	-0.87	-0.63	0.77	0.76	0.77	-0.61	0.42
Q_{ICC}	-0.61	-0.48	0.32	0.43	0.39	-0.33	0.52
A_{ICC}	0.69	0.16	-0.61	-0.46	-0.63	0.98	-0.41

Relationship between characteristic parameters of CC and M-component

Table 6 is correlation coefficients of characteristic parameters of CC and M-component. As shown in Table 6, the relationships between the CC duration and CC charge transfer with characteristic parameters of M-component are the same. There are significant positive correlations between CC duration and interpulse interval of M-component, between CC charge transfer and interpulse interval of M-component, the correlation coefficients are 0.92 and 0.97, respectively. The significant negative correlation coefficients between CC duration, charge transfer and M magnitude are -0.79 and -0.76, respectively. These correlation coefficients are all through the verification of significance level 0.05.

Table 6 Correlation coefficients between characteristic parameters of CC and M-component

	A_M	Q_M	Th_M	Tr_M	Td_M	I_{CC}	Ti_M
T_{CC}	-0.79	-0.24	0.53	0.49	0.52	-0.43	0.92
Q_{CC}	-0.76	-0.09	0.59	0.59	0.57	-0.36	0.97
A_{CC}	0.56	0.72	0.52	0.54	0.13	0.83	-0.35

CONCLUSION AND DISCUSSION

The characteristic parameters and correlations of 10 ICCs, 79 ICCPs, 8 CCs and 35 M-components are statistically analyzed by using rocket-triggered lightning channel base currents. The geometric mean values (GM) of duration, amplitude, charge transfer for ICC are 298 ms, 192 A, 57.2 C, respectively. The corresponding parameters for CC are 37 ms, 202 A, 7.4 C, respectively. The amplitude of ICC is slightly smaller than the CC, and the duration of ICC are about 8 times longger than CC, so ICC charge is 8 times bigger than CC.

Current waveforms of ICCPs and M-components both exhibit approximate symmetry. The current waveform of M-component is steeper, narrower and bigger than ICCP; the distribution of M-component is more intensive than ICCP. The GM of magnitude, charge transfer, half peak width, rise time (10-90%), duration, preceding ICC level, interpulse interval are 142 A, 148 mC, 928 μs, 466 μs, 2.88 ms, 186 A and 12.3 ms for ICCP, respectively. The corresponding parameters for M-component are 308 A, 179 mC, 628 μs, 369 μs, 1.95 ms, 243 A and 7.8 ms, respectively. These results all supported the conclusion of Wang et al. [1999] and Qie et al. [2014] that the physical processe of ICCP is similar to M-component.

Kitagawa et al. [1962] research finding indicated that M-component can superpose on long CC, also can superpose on short CC. The research of Fisher et al. [1993] showed clearly that M-component is the necessary condition to form a long continuous current. Zhao et al. [2011] studied that M-component maybe plays an important role in maintaining lightning channel after return stroke and keeping continuous current. The correlations between ICC and ICCP, between CC and M-component are analyzed in this paper, the results indicate that there are significant positive correlation between the duration of ICC and half peak width, rise time, duration of ICCP, the correlation coefficients are 0.77, 0.76, and 0.77, respectively. The duration of ICC has significant negative correlation with the magnitude of ICCP and the correlation coefficient is -0.87. There is significant positive correlation between CC duration and interpulse interval of M-component, the correlation coefficient is 0.92. The significant negative correlation coefficient between CC duration and M magnitude is -0.79. These correlation coefficients are all through the verification of significance level 0.05.

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