NOTES AND CORRESPONDENCE

Characteristics of Cloud-to-Ground Lightning in Chinese Inland Plateau

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Abstract

Characteristics of cloud-to-ground (CG) lightning flashes in the Chinese inland plateau have been analyzed by using the data obtained from a broadband slow antenna system, with a time resolution of 1 microsecond in 1996, and a CG lightning location network from 1997 to 1998. It has been found that lightning discharges in a plateau summer thunderstorm usually present some special characteristics compared with the typical summer thunderstorm. On the average, positive CG flashes comprised 16% of total CG flashes in the Chinese inland plateau. After comparison with radar echo, it is found that some weak thunderstorms are conducive to positive CG flashes. The first return strokes are usually preceded by a long duration preliminary breakdown process which is characterized by discrete bipolar pulses for both positive and negative CG flashes. The mean duration of electric field change prior to first return stroke is about 126.1 ms, in which 23% exceeds 200 ms for negative CG flashes, and the corresponding value is 165.1 ms for positive CG flashes. The mean interval between 152 successive analyzed pulses is $211.0 \pm 148.0 \mu\text{s}$, and the total duration of the pulses is $32.0 \pm 20.0 \mu\text{s}$ for negative CG flashes, while the mean time interval between the 50 analyzed pulses is $165.0 \pm 120.0 \mu\text{s}$ and the total duration of pulses is $27.0 \pm 19.0 \mu\text{s}$ for positive CG flashes. Other discharge features, such as interstroke intervals, amplitude distribution of the subsequent return strokes and etc., are also analyzed in the paper.

1. Introduction

In the late 1980s, several unusual electrical features were observed for summer thunder-

storms in the Chinese inland plateau area. These features include: (1) when thunderstorms are overhead, the electric field at the ground are usually positive (defined as positive charge being overhead) (Wang et al. 1987); (2) nearly all cloud discharges appear to occur in the lower portion of the cloud to neutralize the main negative charge and the lower pocket positive charge (Liu et al. 1989; Qie et al. 2000b); (3) all rocket-triggered lightning are

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positive with only initial continuous current stages (Liu et al. 1994). These features suggest that the thunderstorms in the Chinese inland plateau may have some unique electrical structures. Therefore, the cloud-to-ground discharges that occurred there might also have some unusual characteristics compared with typical summer thunderstorms. This motivates us to conduct a simultaneous multiple-station measurement of cloud-to-ground lighting discharges near Lanzhou in Gansu province during 1996–1998. This paper reports our statistical results obtained from the measurements.

2. Instrumentation and data

The measurement of the electric field generated by CG lightning flash was conducted by using a broadband slow antenna system in 1996 in Zhongchuan ($103^{\circ}36'E$, $36^{\circ}36'N$) of Gansu province, which is located in the Chinese inland plateau. The elevation of the observation area is 1900 m above sea level. The time constant of the slow antenna system is 5 s with a frequency bandwidth of 2 MHz. The output of the slow antenna is digitized by a 12-bit A/D converter and recorded by a computer at a sam-

pling rate of 1 MHz. The recorded length is 1 s. The recorder was operated in pre-trigger mode, so that the events 250 ms prior to the trigger point can be well documented. The detection range of a slow antenna system is about 25 km. The wide bandwidth, the high sensitivity and the high time resolution of the slow antenna system make it possible to record the electric field waveforms even generated by faint discharges such as stepped leader and preliminary breakdown processes in CG flashes. Meanwhile, the fine structures of return strokes can also be recorded and well recognized.

A lightning location system was employed in 1997–1998 to provide the lightning location and polarity information. This system consisted of three direction finders (DFs) which were installed in the Pingliang area ($35^{\circ}57'N$, $106^{\circ}69'E$) of Gansu province, an area also located in the Chinese inland plateau. The elevation of this area is about 1630 m above sea level. The experiment area together with the observation sites are shown in Fig. 1. Three DFs are located in Pingliang, Liupan mountain and Pengyang with 40 km, 40 km, and 30 km apart, respectively. The detection range of one

Fig. 1. Map of the Chinese inland plateau, showing DF stations and observation sites. Also indicated are the major mountain, main river, main cities, as well as 1000 m, 1500 m and 2000 m elevation contours above sea level. The inserted box in the upper-right corner of the figure showing location of the experiment area.

Fig. 2. Ratio of positive CG flashes to total CG flashes for individual thunderstorm as a function of total number of CG flashes produced by the same thunderstorm.

DF system was about 200 km, and the detection efficiency was about 90%. The central position analyzer (PA) and 5 cm wavelength radar are installed in Pingliang. The triggering lightning experiment was conducted in the center of the DF network and in visual field of the radar during the summer of 1997.

3. Results

3.1 Ratio of positive CG flash number to total CG flash number

The data obtained with the lightning location system are used to study the ratio of positive CG flash number to total CG flash number in individual thunderstorm. Figure 2 shows the scatter plot of positive flash ratio versus the total flash number. Apparently, different thunderstorms show much different ratios of positive CG numbers. The more the total flashes in an individual thunderstorm, the less the positive flashes. The thunderstorm occurred on July 30, 1997 has the maximum flash number, 3005 and the corresponding ratio of positive CG flash is only 6.5%, while the thunderstorm occurred on August 8, 1998 has the minimum flash number, only 2 and its percentage of positive CG flashes is 100%. The ratio of positive CG flashes for different thunderstorms changes

from 6.5% to 100%. Totally, 8068 CG flashes were detected from 33 thunderstorms, in which 1237 were positive flashes and the resultant positive flash ratio is 15.3%.

The radar echo pictures both in PPI and RHI display manners for two thunderstorm processes on July 26 and July 30, 1997 are shown in Figs. 3a, 3b, 3c and 3d, respectively. All pictures correspond to the mature stage of the thunderstorm. The process on July 30, 1997 was the strongest one during the observation period, with the greatest reflectivity of more than 60 dBZ, and lasted more than three hours. This thunderstorm produced a maximum flash number, 3005, and a minimum positive CG flash ratio, 6.5%. The thunderstorm on July 26, 1997 is a typical one in the observation area with a greatest reflectivity of only 40 dBZ. It produced 69 CG flashes in total, and its percentage of positive CG flashes was 30. This kind of thunderstorm usually lasted not longer than one hour. Based on our observation, it seems that the stronger thunderstorm is conducive to produce negative CG flashes, while the weaker thunderstorm is conducive to produce positive CG flashes. Usually, The positive CG flashes are produced in developing and dissipating stage of an individual thunderstorm (Fuquay 1982; Orville et al. 1983). This indicates that weaker stage of a thunderstorm is conducive to produce positive CG flashes, and is in agreement to our result in some extents.

The total CG flash number and positive flash ratio during different hours of a day are plotted in Fig. 4. Both the total flash number and the positive flash ratio show obviously diurnal variation. From these two figures, again, we can see that the higher positive flash ratio relates to fewer total CG flashes corresponding to weaker or less active thunderstorm. Also seen in the figure, the positive flash number peak lags behind that of total flash number in time. If we consider that most of the CG flashes occurred in the mature stage of a storm, then this fact suggests that the positive CG flash is more likely to occur in later stages of a thunderstorm.

The data obtained with slow antenna system also allowed us to have a statistic study on the positive ground flash ratio. A total of 101 CG lightning flashes were recorded by the slow antenna system from 9 thunderstorms, and 18

Fig. 3. Radar echo pictures during the mature stage of two thunderstorms, (a) PPI display for the weaker thunderstorm on July 26, 1997, (b) RHI display for the same thunderstorm on July 26, 1997, (c) PPI display for the severest thunderstorm on July 30, 1997, (d) RHI display for the same thunderstorm on July 30, 1997.

among them are positive. The resultant positive flash ratio is 17.8%, which agrees well with that obtained from the lightning location system.

3.2 Processes just prior to the first return strokes

By analyzing the electric field data obtained with the slow antenna system, it was found that first return strokes are usually preceded by a long duration electric field change in both positive and negative CG flashes. A total of 83 negative CG flashes and 18 positive CG flashes were used to perform a statistic study on this

process. For negative CG flashes, the mean duration of electric field change prior to first return stroke is about 126.1 ms in which 23% exceeds 200 ms, and the corresponding value is 165.1 ms for positive CG flashes.

Examples of the electric field change preceding the first return stroke of a positive and a negative CG flash and the corresponding time-expanded waveforms are shown in Fig. 5 and Fig. 6, respectively. The preliminary breakdown process of negative CG flashes is characterized by discrete bipolar pulses as shown in Fig. 5b. The mean interval between the analyzed 152 successive pulses is $211.0 \pm 148.0 \mu\text{s}$

Fig. 4. Diurnal variation of total CG flash number (solid line) and ratio of the positive CG flash number to the total CG flash number (dotted line).

and the total duration of the pulses is $32.0 \pm 20.0 \mu\text{s}$. The stepped leader process occurred between the preliminary breakdown and the first return stroke can be clearly identified in Fig. 5c. Stepped leader is characterized by discrete monopolar pulses. The average time interval between the successive leader steps for 41 negative CG flashes is $26.0 \pm 14.0 \mu\text{s}$ and the mean width of pulse is $8.0 \pm 3.0 \mu\text{s}$. The preliminary process of positive CG flashes is also characterized by discrete bipolar pulses as shown in Fig. 6b. The mean time interval between the 50 analyzed pulses is $165.0 \pm 120.0 \mu\text{s}$ and the total duration of a preliminary breakdown pulse is $27.0 \pm 19.0 \mu\text{s}$. However, no stepped leader pulses can be apparently identified between the preliminary breakdown and the first return stroke process.

3.3 Interstroke intervals

Figure 7 shows the frequency distribution of the interstroke interval between 238 subsequent return strokes in 50 multiple-stroke negative CG flashes. The arithmetic and geometric means of the interstroke intervals are 64.3 ms and 46.6 ms with the largest and smallest being 328.5 ms and 4.8 ms, respectively.

Table 1 shows the statistic results of the interstroke interval obtained in America and Sweden since 1990's. The mean interstroke in-

terval obtained here is smaller than that obtained by Thottappillil et al. (1992) and Rakov et al. (1994) in Florida, but agrees well with that obtained by Cooray and Perez (1994) in Sweden, with the difference less than 3%.

In the course of our measurement, three positive CG flashes with two return strokes have also been recorded. The corresponding interval between subsequent return stroke and first return stroke was 57.2 ms, 109.6 ms and 109.6 ms, respectively.

3.4 Amplitude distribution of the subsequent return strokes

In lightning protection standards and design, the electric field of first return stroke in a multiple-stroke flash is generally regarded as the strongest one. However, this study shows that at least one subsequent stroke field peak in 54% of the total 50 CG flashes is larger than the first one. The geometric and arithmetic mean ratio of subsequent return stroke peak electric field to that of the first return stroke are 0.46 and 0.7 with the largest and the smallest values of 3.8 and 0.04, respectively. Figure 8 shows the frequency distribution of the ratio of subsequent return stroke peak electric field to that of the first return stroke. The percentage of subsequent strokes with peak amplitudes larger than the first return

Fig. 5. Relative electric field (E) of a negative CG flash, (a) before the first return stroke, (b) preliminary breakdown process with expanded time scale, (c) stepped leader process with expanded time scale. R represents the return stroke.

stroke peak amplitudes is about 22.6%. In fact, the amplitude of the electric field change by a return stroke also depends on the height of the charge, as well as the distance to a flash. According to Krehbiel et al. (1979) and Qie et al. (2000a), the CG discharge usually extends the channel horizontally. If a subsequent stroke extends the channel closing to the observation

Fig. 6. Same as Fig. 5 but for positive CG flash.

Fig. 7. Frequency distribution of the interstroke intervals in negative CG flashes.

station, the larger amplitude will also be possibly obtained.

For comparative purposes, the results obtained by other investigators are summarized in Table 2. Note that the percentage of flashes

Table 1. Statistics of time interval between return strokes.

	Total number of flashes	Total number of subsequent strokes	Arithmetic mean (ms)	Geometric mean (ms)
Thottappillil et al.(1992)	46	199		57
Cooray and Perez(1994)	271	568	65	48
Rakov et al.(1994)		270		60
This paper	50	238	64.3	46.6

Fig. 8. Ratio of the peak electric field amplitudes of subsequent return strokes to that of first return strokes for negative CG flashes.

in which at least one subsequent stroke field peak is larger than the first one and the percentage of subsequent strokes having amplitudes larger than the first stroke amplitude are much larger than the value measured in Florida by Thottappillil et al. (1992) and that observed in Sweden by Cooray and Perez (1994), while the ratio of subsequent return stroke peak electric field to that of the first return stroke is between the value reported by Thottappillil et al. (1992) and Cooray and Perez (1994). Chinese inland plateau thunderstorms appear to produce more flashes with at least one subsequent stroke field peak is larger than the first. Meanwhile, it was also found that more subsequent strokes here show larger amplitude than that of the first strokes.

3.5 Number of strokes per flash

The frequency distribution of the stroke number per flash is depicted in Fig. 9. Most of

Table 2. Ratio of the peak electric field amplitudes of subsequent return strokes to that of first return strokes for negative CG flashes in different region.

Reference	Total number of CG flashes	Percentage of flashes in which at least one subsequent stroke field peak is larger than the first (%)	Percentage of subsequent strokes whose field peak is larger than the first (%)	Total number of subsequent strokes	Ratio of subsequent stroke field peak to that of the first (%)	
					Arithmetic mean	Geometric mean
Thottappillil et al. (1992)	46	33	13	199		0.42
Cooray and Perez (1994)	271	24	15	314	0.63	0.51
This paper	50	54	22.6	238	0.70	0.46

Fig. 9. The number of return stroke for individual CG flashes.

the CG flashes are single-stroke flashes comprising 39.8% of the total CG flashes. The mean number of strokes per flash obtained here is 3.76 with the largest stroke number of 14. This result is between that reported by Thottapillil et al. (1992) and Cooray and Perez (1994), whose results are 3.5 and 3.9, respectively.

Only 3 out of 23 positive CG flashes had two return strokes comprising 13.0% of the total positive CG flashes. The percentage is much less than that of negative CG flashes.

4. Discussion

Table 3 gives a summary of the positive CG flash ratio reported by different authors during recent years. Note that the average positive flash ratio for summer thunderstorms in America is less than 10%, which is apparently smaller than that reported in this paper.

In literature, five types of conditions have been reported to be conducive to the occurrence of positive ground flashes. (1) Dissipating stage of an individual thunderstorm (Fuquay 1982; Orville et al. 1983). (2) Winter thunderstorms (Takeuti et al. 1978; Brook et al. 1982). (3) Shallow clouds such as trailing stratiform regions of mesoscale convective systems (Engholm et al. 1990). (4) Severe thunderstorms (Rust et al. 1981; MacGorman and Burgess 1994). (5) Thunderclouds formed over forest fires (Vonnegut and Orville 1988). Besides of

Table 3. Ratio of positive CG flashes to total CG flashes in different regions.

Reference	Season	Region	Method	CG flashes	Number of positive CG flashes	Percentage of positive CG flashes (%)
Brook et al. (1982)	Winter	Japan	ES, V	63 CG	26	41
Macgorman and Morgenstern (1998)	Summer	America	LLS	All CG flashes in 25MCSs		6.6
Orville and Huffines (1999)	Summer	America	LLS	All CG flashes in 10-year's MCSs		3-9
Qie et al. (1991)	Summer	Beijing	LLS	10548 CGs		1.7
This paper	Summer	Gansu	LLS	7221 CGs	1111	15.3
		Gansu	ES	106 CGs	23	17.8

Note: ES: slow antenna; V: video; CG: cloud-to-ground flash; MCS: mesoscale convective system

occasional very severe thunderstorms, most of them in the Chinese inland plateau are short in duration and usually have a small number of ground flashes. The severest thunderstorm analyzed in this paper only produced 3005 CG flashes. The higher positive CG flash ratio observed here may suggest that some weak thunderstorms are also conducive to positive flashes.

Electric field change preceding first return stroke has been studied by many authors, however the only statistical data of electric field preceding stepped leader were presented by Beasley et al. (1982). A total of 79 CG flashes were analyzed in their studies and the mean duration of stepped leader and preliminary process preceding first return stroke is 90 ms which is much smaller than that obtained in this study. The mechanism whereby first return stroke is preceded by such long duration electric field change has not been completely understood. Clarence and Malan (1957) attributed it to processes that initiate stepped leader, while Kitagawa and Brook (1960) and Thomson (1980) insisted that it should be regarded as independent intracloud processes. To some extent we agree to the latter. Because of the complexity of the problem we have discussed these processes in another paper (Qie et al. 2000b).

Ushio et al. (1998) analyzed the preliminary breakdown processes of positive CG flash in winter thunderstorms, and found that the mean time interval between successive preliminary breakdown pulses is 54.2 μ s and the total duration of the pulses is 18.8 μ s which is shorter than the value obtained in our study. Weidman and Krider (1978) found that the mean time interval between the successive preliminary breakdown pulses for summer thunderstorm is 130.0 μ s and the total duration of the preliminary breakdown pulses is 41.0 μ s. Above results are obtained in different places for different thunderstorms, so it is difficult to conclude that the differences resulted from the different flash polarity or different region. Our results indicate that although the time intervals between successive preliminary breakdown pulses and the total duration of preliminary breakdown pulses of positive and negative CG flashes are in the same order, but that of positive CG flash is larger than that of negative one.

5. Conclusions

A study on the characteristics of the cloud-to-ground lightning flashes in the Chinese inland plateau has been performed in this paper, and the following results have been obtained. The positive CG ratio is around 16%, which is between that for typical American summer thunderstorms and Japanese winter thunderstorms. The first return stroke was usually preceded by long lasting electric field changes that is about 126.1 ms and 165.1 ms for negative and positive CG flashes, respectively. Preliminary breakdown processes could be clearly identified in positive CG flashes as well as in negative CG flashes while stepped leader process was only identified in negative CG flashes; For negative CG flashes the geometric and arithmetic mean inter-stroke intervals were 46.6 ms and 64.3 ms, respectively; About 54% negative CG flashes with multiple-strokes had at least one subsequent return stroke with a peak electric field larger than that of the first one. Furthermore, about 20% of the subsequent strokes had electric field amplitudes larger than those of the first return strokes. The geometric and arithmetic mean ratio of the subsequent stroke peak field to the corresponding first one were 0.46 and 0.70, respectively. The mean number of strokes per flash was 3.8 and 39.8% of the flashes were single-stroke flash. For positive CG flashes, the interstroke intervals were relatively longer with an arithmetic mean value of 91.7 ms, and only 13.0% of the flashes were multiple-stroke flashes.

Above results show that several features of the Chinese inland plateau lightning flashes are different from those generally reported for typical summer thunderstorms. The reason for such differences is still unknown and they deserve further investigations.

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