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Optical and electrical characteristics of in-cloud discharge activity and downward leaders in positive cloud-to-ground lightning flashes

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ABSTRACT

The characteristics of five downward positive cloud-to-ground (CG) flashes were analyzed based on images from a high-speed video camera and electric field (E-field) changes from slow antenna and fast antenna systems. The flashes persisted for 740 ms to 1250 ms. The luminous durations of the leaders ranged from 4 ms to 24 ms. The average 2-D development speeds of the positive leaders ranged from 0.3×10^5 m/s to 2.0×10^5 m/s. The propagation speeds of the positive leaders increased as they approached the ground. Approximately 53.9% of the 89 observed positive CG flashes exhibited isolated monopolar pulses during the leader propagation and immediately prior to the return stroke. The average time interval between adjacent leader pulses was 15 μs according to the E-field changes. Most leaders of positive CG flashes (approximately 67.4%) began in the presence of prolonged and intense in-cloud discharge (IC) activity that ranged from 100 ms to 973 ms. A cloud discharge may be conducive to the formation of positive CG flashes. Generally, a higher occurrence of positive CG flashes corresponded to a higher occurrence of cloud flash, which suggests that positive CG flash can be initiated by a cloud discharge. Four positive CG flashes exhibited one return stroke, and only one flash had two strokes.

1. Introduction

Positive cloud-to-ground (CG) lightning flashes, which usually neutralize more charge than negative CG flashes, have attracted considerable attention because they are typically associated with severe thunderstorms (Rakov and Uman, 2003), can be correlated with middle atmosphere discharges, and may play a crucial role in the production of sprites (Lyons et al., 2008; Yang et al., 2008; Lu et al., 2013). Positive CG lightning may be the dominant type of CG lightning during the cold season, throughout the dissipating stage of a thunderstorm and in other conditions (Qie et al., 2002; Rakov and Uman, 2003; Romero et al., 2013). However, the characteristics of natural downward positive CG lightning in different regions remain unknown, such as large-scale pre-stroke activity (Saba et al., 2009; Nag and Rakov, 2012; Qie et al., 2013) and the traveling path of downward positive leaders.

The characteristics of downward-moving positive leaders from natural CG lightning flashes are not as well understood as those of negative leaders because positive leaders usually produce little or no radiation at HF to UHF (Shao et al., 1999). Based on optical images of both triggered and natural lightning flashes from streak photographs or high-speed video, upward positive leaders propagate in a stepwise fashion (Berger and Vogelsanger, 1966; Willett et al., 1999; Lalande et al., 1998, 2002; Yoshida et al., 2010; Biagi et al., 2011; Jiang et al., 2013). Moreover, distinct steps have not been observed in natural downward-moving positive leaders, and these leaders have been shown to exhibit intensity fluctuations (Berger and Vogelsanger,

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1966). However, increasing evidence has suggested that downward-moving positive leaders that precede positive first return strokes may propagate in a stepwise manner (Cooray and Lundquist, 1982; Hojo et al., 1985; Kong et al., 2008; Wang and Takagi, 2011). Hojo et al. (1985) reported that 1/3–1/4 of the waveforms of positive first return strokes observed in both summer and winter had discernible pulses preceding the return stroke field change. Kong et al. (2008) showed a nature positive leader traveling toward the ground with stepwise characteristics. Furthermore, Wang and Takagi (2011) presented an optical recording that temporally and spatially resolved the steps contained in a downward positive leader.

Additionally, optical investigations are needed to address various unknown phenomena, such as the low speed of positive leaders in natural lightning discharges at large scales, which has been proposed using a bidirectional model (Kawasaki and Mazur, 1992). According to previous direct measurements of the average vertical speed of a positive leader from streak photographs (Berger and Vogelsanger, 1966), the propagation speed of the leader ranged from 4×10^5 m/s to 2.4×10^6 m/s as it traveled to the ground, whereas for 19 downward negative leaders, the speeds ranged from 6×10^4 m/s to 1.1×10^6 m/s. Thus, the speed of positive leaders is thought to be faster than the speed of negative leaders, which introduces a discrepancy between the observed speed and proposed speed in bidirectional models (Shao et al., 1999). In laboratory experiments and rocket-triggered lightning flashes, lower velocity positive leaders have been obtained. In laboratory gap discharges, a speed of approximately 10^4 m/s for positive leaders has been reported (The Les Renardieres Group, 1977). The upward-moving positive leaders in rocket-triggered lightning were reported to reach a speed of 10^4 m/s during the initial stage (Fieux et al., 1975; Laroche et al., 1985; Yukio et al., 1985; Biagi et al., 2011; Jiang et al., 2013). More recent measurements have been obtained using a high-speed video camera system for optical observations of natural downward lightning flashes. Saba et al. (2008) showed that the speeds of positive leaders ranged from 0.3×10^5 m/s to 6.0×10^5 m/s with a mean of 2.7×10^5 m/s. Moreover, Kong et al. (2008) reported a single positive leader with speeds ranging from 0.1×10^5 m/s to 3.8×10^5 m/s when descending from the cloud to the ground. Recently, Wang and Takagi (2011) reported a faster (1.0×10^6 m/s to 2.5×10^6 m/s) positive downward leader using an Automatic Lightning Progressing Feature Observation System (ALPS). Campos et al. (2014) conducted a statistical analysis on both negative CG flashes and positive CG flashes and showed that the average speeds of the two CG flashes were within the range predicted by optical imagery (i.e., approximately 10^5 m/s).

This paper summarizes the characteristics of natural downward-propagating leaders that preceded positive strokes and the IC activities before the stroke based on optical images and E-field changes. The relationship between cloud flashes and positive CG flashes is discussed based on the E-field changes caused by lightning around the observation site.

2. Observation experiment data

A field experiment on thunderstorms and lightning (Qie et al., 2008) was conducted in the summer of 2006 in Shandong Province (37.5076°N; 118.0157°E). Optical images of lightning flashes were captured using a high-speed digital camera system with a 1 ms time resolution. The sensor of the high-speed digital camera is a 256 × 240 charge-coupled device array (CCD) array. The E-field changes caused by lightning flashes were measured using slow antenna and fast antenna systems. The time constants of the slow antenna and fast antenna system are 6 s and 2 ms, respectively, with frequency bandwidths of 2 MHz and 5 MHz, respectively. The detection distance of the antenna systems was approximately 25 km away from the station. All of the field measurements were digitized with a 2.5 MHz sampling rate and a 16-bit amplitude resolution, and the data were recorded on a PC. The data analyzed in the document were from one observation site.

Five thunderstorm systems were examined based on the data from the slow antenna and fast antenna systems. A total of 89 positive CG flashes were recorded during these thunderstorms. Among these flashes, five positive CG flashes were captured by the high-speed video camera system, the slow antenna and the fast antenna. Table 1 presents the parameters of these five flashes. The five flashes were located approximately 1.7 km, 5.1 km, 2.4 km, 1.7 km and 2.7 km from the observation site based on the acousto-optic difference. Four out of five flashes exhibited only one return stroke; only one flash had two strokes. The durations of the entire discharge process ranged from 740 ms to 1250 ms. The luminescence time of the continuing current (ΔToc) after the stroke persisted for 10 ms to 240 ms. Moreover, three positive strokes exhibited relatively long ΔToc values (i.e., from 160 ms to 240 ms), whereas the other three strokes had shorter times (i.e., 10 ms to 26 ms). All positive leaders began with prolonged and intense IC activity that ranged from 212 ms to 600 ms (ΔT_{IC}). Such prolonged activity prior to positive CG flashes was previously observed by Fuquay (1982) and Mazur et al. (1998) using electric field systems. Saba et al. (2008, 2009) also found that most positive leaders were preceded by intense IC activity. However, Nag and Rakov (2012), based on their electric field measurements, did not find evidence of preceding in-cloud activity.

Additionally, the five positive flashes were observed at night (local time). The positive leaders tended to exhibit a low intensity (Rakov and Uman, 2003). Thus, the black background should be conducive for optical observations of positive CG flashes. According to the radar echoes, the storm systems were at a dissipative stage when they were located above the observation station. Based on the E-field changes caused by the lightning flashes, the five flashes occurred during a high rate of positive CG flashes.

Table 1
Characteristic parameters of five positive CG flashes.

Flash	Occurrence time (Beijing time)	Duration (ms)	ΔToc (ms)	ΔT_{IC} (ms)	D (km)
214305	2006-6-13, 21:42:05	1250	10	177	1.7
231402	2006-6-16, 23:14:02	990	230	600	5.1
003718	2006-6-17, 00:37:18	806	26/164	212	2.4
012437	2006-6-30, 01:24:37	309	11	200	1.7
002237	2006-7-1, 00:22:37	740	240	437	2.7

Note: ΔToc is the luminescence duration of the continuing current; ΔT_{IC} is the duration of the IC activity before the first return stroke; and D is the distance between the lightning and the observation site.