Characteristics of Lightning Discharges and Electric Structure of Thunderstorm*

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ABSTRACT

Progresses in the research on physical processes of lightning discharge and electric structure of thunderstorm in the last decade in China have been reviewed. By using the self-developed lightning detecting and locating techniques with high temporal and spatial resolution, the characteristics and parameters of lightning discharge in some representative areas in China have been obtained. Observations on lightning activity were conducted for the first time in the Qinghai-Tibetan Plateau in 2002-2005, and the special characteristics of the thunderstorm and lightning activity in the plateau were revealed. The lightning spectra in the band of visible light were recorded, and the spectral lines were identified in detail with introduction of modern theories of atomic structure. The techniques on artificially altitude triggered lightning and related measurements under a harsh electromagnetic environment have been well developed. Evidences of bi-directional leader propagation were observed by means of optics and VHF radiation during the triggered lightning discharges. Some lightning protection devices have been tested using the artificial lightning triggering techniques. In addition, the correlation between lightning activities and weather and climate was preliminarily studied.

Key words: lightning, physical process, optical spectra, thunderstorm, electric structure

1. Introduction

Lightning is a kind of disastrous weather phenomena characterized by instant high voltage, intense current, and severe electromagnetic radiation. The probability of ground facilities struck directly by lightning has been greatly reduced since the innovation of lightning rod by Franklin. However, the economic losses caused by lightning have been increased with wide application of micro-electronic and information technology. Lightning has been ranked as "one of the ten most severe natural disasters" by the United Nations, and "one of the social disasters in the electronic times" by Chinese Electro-technical Commission.

In the recent ten years, lightning researches in China have been focused on the scientific issues such as physical processes, mechanisms of lightning and the applications aimed at detection, and warning and protection of lightning. On the basis of the development of advanced lightning detection tools, the thunderstorm electricity and lightning characteristics in some representative regions in China have been studied. Important progresses have been achieved in the researches on lightning activities over the Qinghai-Tibetan Plateau, lightning spectra, artificial lightning triggering and its application, relationship of lightning to meteorology and climate change. Reviewed in the article will include four main areas of studies on physical process of lightning, electric charge structure of thunderstorm, artificial lightning triggering, and relationship of lightning to meteorology and climate change.

2. Physical process of lightning

2.1 *The primary processes of lightning and discharge parameters*

Cloud-to-ground (CG) lightning mainly includes processes of preliminary breakdown, stepped leader, first return stroke, inter-stroke process, dart (or dart stepped) leader, subsequent return stroke, and continuous current. The physical features and characteristic

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parameters of these discharge processes are very important in the understanding of lightning mechanism and design of lightning protection. In the last decade, natural lightning observation and artificial lightning triggering experiment were conducted continuously in the area of Gansu, Beijing, Shanghai, Jiangxi, Guangdong, Qinghai-Tibetan Plateau, and Shandong (Qie et al., 2000, 2002a, 2005a; Dong et al., 2002; Zhang et al., 2003a, b). Figure 1 shows the electric field (E-field) changes on the ground caused by a negative CG discharge in Zhongchuan, Gansu Province. The characteristics of E-field change caused by the return stroke and stepped leader in different time scales could be observed. Table 1 shows part of the characteristic parameters in the E-field waveform radiated from the return stroke. The rising time from 10% to 90% peak for negative return stroke was 4.7±1.9 μs, and the down time from peak to zero was 57.4±23.6 μs, and the half peak width was 66±19 μs. Qie et al. (2002b) found that 54% of the negative multiple-stroke ground flashes have at least one subsequent stroke with a peak E-field larger than that of the first return stroke, and about 20% of the subsequent strokes have peak E-field amplitudes larger than those of the first return strokes, although the first return stroke was usually considered to be the strongest.

Table 1. Part of characteristic parameters in the E-field waveform radiated by the first return stroke

Stroke type		10%-90% (Rising time) (μs)	Down time (μs)	Zero-crossing time (μs)	Half peak width (μs)
-CG	$R1$	4.7±1.9	57.4±23.6	10.2±4.6	66±19
	$R2$	3.4±1.5	42.1±19.1	8.8±3.7	47±17
+CG		11.5±2.4	24.2±22	63±20	15.5±4.8

Note: $R1$ represents the first return stroke, and $R2$ represents subsequent return stroke.

2.2 *Lightning spectra in the visible light band*

Among many methods of research in lightning physics, spectra are the only one that could reflect physical details within the discharge channels in a form of plasma because of ionization by large discharge current. The spectra of discharge channel are intimately related to the plasma properties and the temperature of the channel. Slit spectrograph was used to study the lightning spectra in the United States in the 1970s. The average temperature and electron density in the lightning channel are deduced from the observed spectra in the visible light band.

By using a slitless spectrograph, observations on the spectra of natural lightning were carried out in both Qinghai Plateau and coastal area of Guangdong, respectively. The spectra in the range of 400-700 nm for the first return stroke of negative CG lightning flashes were observed, and two lines with wavelength of 604.6 nm and 619.4 nm were recorded for the firs time in lightning spectra (Yuan et al., 2004). Based on the structure of spectra, the lines in lightning spectra are classified into two categories: essential lines and

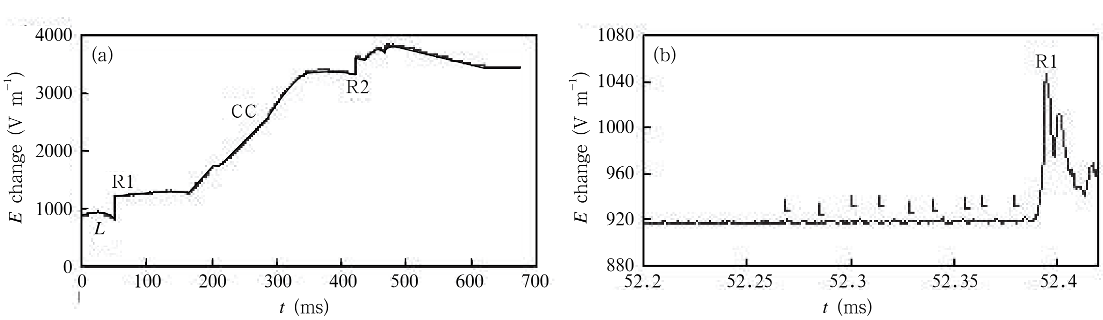

Fig.1. E-field changes on the ground caused by a negative CG discharge. (a) Whole waveform and (b) first return stroke and stepped leader. R1: first return stroke, R2: subsequent return stroke, L: stepped leader, and CC: continuous current.

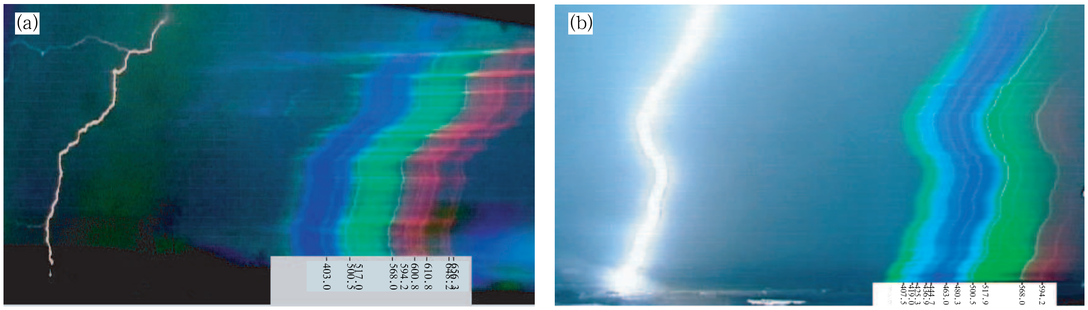

Fig.2. The optical spectra of the first return stroke (the unit of wave length is nm). (a) Xining, Qinghai, and (b) Foshan, Guangdong. The left image is by non-prismatic channel.

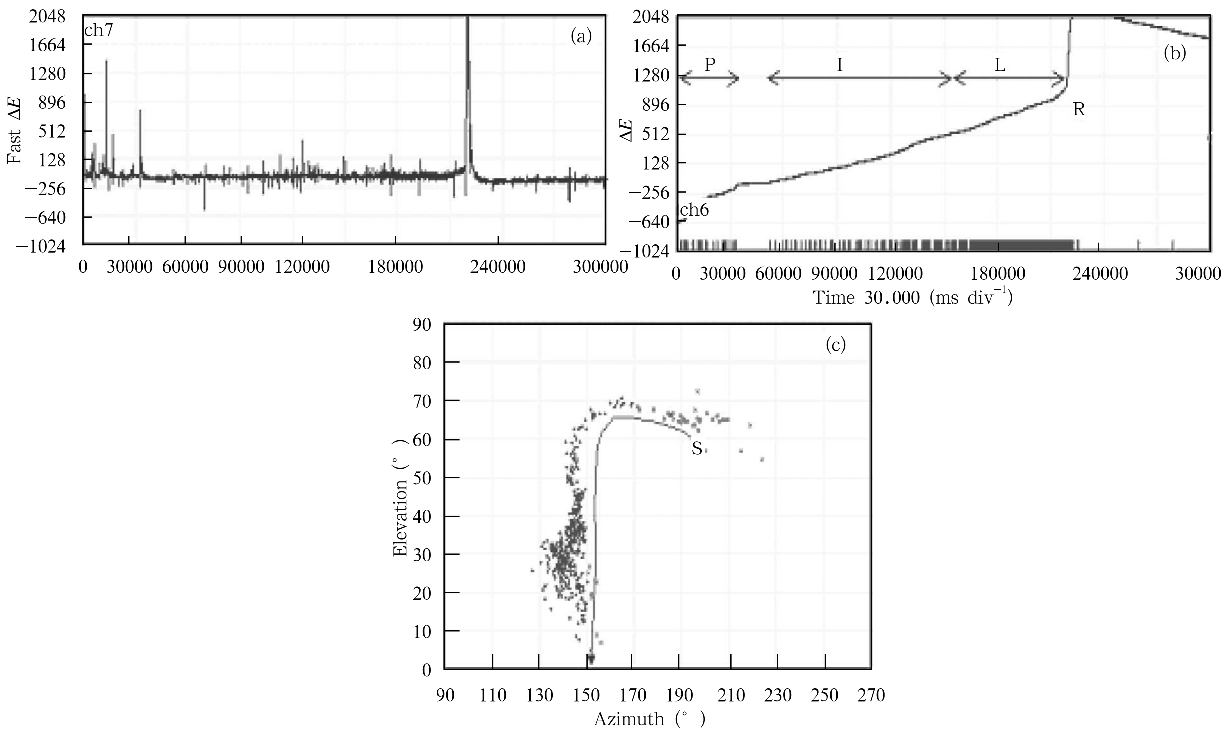

Fig.3. The E-field change waveforms and radiation source location. (a) The fast E-field, (b) the slow E-field, and (c)the radiation source location in azimuth-elevation format.

characteristic lines. The essential lines can be recorded in most of the lightning return strokes, and they reflected the common characters of discharge channel to some extent. The characteristic lines carry information reflecting the trait of each individual discharge process. The essential lines in both Qinghai and Guangdong include NII(399.5 nm), NII(463.0 nm), NII(480.3 nm), Hβ(486.1 nm), NII(500.5 nm), NII(568.0 nm), NII(594.2 nm), NII, NI(648.2 nm), Hα(656.3 nm), and so on. Figure 2 shows the optical spectra of first return stroke in Xining, Qinghai Province and in Foshan, Guangdong Province. The spectral energy is concentrated in the band of relatively shorter wavelength in Foshan, Guangdong, but longer in Xining, Qinghai, indicating that discharge energy and channel temperature are higher in Guangdong.

There are notable differences between the spectral features in Qinghai Plateau and Guangdong region (Yuan et al., 2002). Transitions between exited states of n=3 in NII ion were main composition of lightning spectra, corresponding to upper excited energy of around 23 eV. In the coastal area, lines with higher exited energy (30 eV) from NII to OII ions can be recorded. On the other hand, spectra in the plateau area are comparatively weak, and transitions from natural NI and OI atoms are intensified with the upper excited energy being around 13-14 eV.

2.3 *Locations of VHF/UHF radiation sources in thunderstorm and its correlation to the discharge process*

The VHF/UHF radiation from lightning is intimately related to the lightning initiation and development processes. Since the 1980s, the location techniques on lightning VHF/UHF radiation have been developed in the USA, France, and Japan by using the time of arrival (TOA) method, narrow and wide band interferometric methods. We have started developing similar location techniques since the late 1990s. The wideband and narrowband interferometers (Dong et al., 2002), TOA lightning mapping systems with both long and short baselines have been developed (Zhang et al., 2002a). Figure 3 is one example of the radiation location result and E-field changes of a negative CG lightning. The whole discharge process lasts about 300 ms and consists of only one return stroke. The long lasting preliminary breakdown process (PBP) occurrs just before the leader-return stroke process, and large positive pulses are superposed on its E-field, that is obviously different from other discharge stages. The intra-cloud radiation sources in initial stage of the discharge progress horizontally.

Zhang et al. (2002b) studied the IC flashes using the LMA data from STEPS in the USA. Figure 4 shows the radiation location result. The discharge initiats from the upper edge of middle negative charge region, and develops upward. When the discharge reaches the upper positive charge region, it develops simultaneously in both upper positive and middle negative charge region in horizontal. In the late stage of the discharge, it develops horizontally in the middle negative charge region. The discharge shows obvious bi-level structure with the upper corresponding to the positive charge region and the lower to the negative one. In the thunderstorm with tripole charge structure, the IC discharge occurs not only between the upper dipole, but also between the lower dipole which is called polarity-inverted IC discharge.

2.4 *The electrical and optical properties of stepped leader progression*

The electrical radiation properties of stepped leader in negative CG flashes are basically similar in South and North China. But the time interval and intensity of leader pulses are quite different. Yu and Qie (2001) simulated the charge density in the leader channel and suggested that just induced charge in the channel be not enough to explain the total charge in it. Gou and Zhang (2002) simulated the initiation of the stepped leader. Figure 5 shows one frame during the progression of stepped leader (Kong et al., 2003). Kong et al. (2003) found that the stepped leader usually progresses downward to the ground with multiple branches, and initiates several return strokes in sequence with a time difference of several microseconds. The four leader branches induce four return strokes with different ground contacting points as observed by high-speed digital camera. Corona ions would be produced from the natural points on the ground under the thunderstorm condition. Affected by the screen charge layer near the ground formed by the corona ions, the stepped leader usually progresses to the ground with multiple branches, and induces more than one termination on the ground, enhancing the difficulty and complexity of lightning protection.

3. Charge structure of thunderstorms

3.1 *Charge structure of thunderstorms over the plateau*

The Tibetan Plateau presents unique weather and climate characteristics because of its high elevation and great dimension. So far the investigation of lightning in the Tibetan Plateau has not been conducted with modern detection tools. Nevertheless, the plateau is usually covered by active cumulus convection in summer and there are many thunderstorms, hailstorms, showers, and convective clouds over there. In the summer from 2002 to 2005, comprehensive

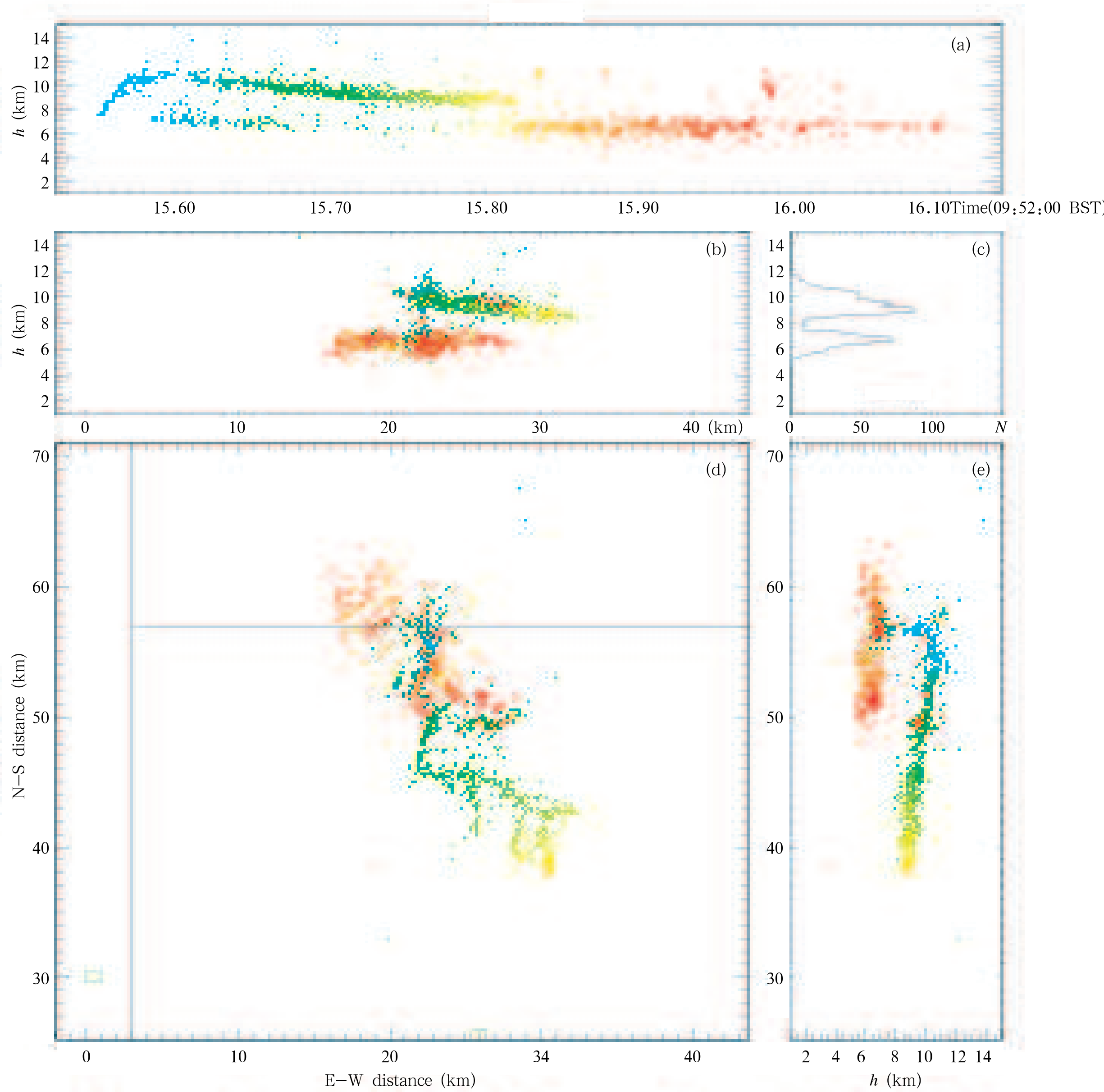

Fig.4. A typical normal Intra-cloud discharge. (a) Height-time plots, (b) north-south (N−S) vertical projections, (c) height distribution of number (N) of radiation events, (d) plan views, and (e) east-west (E−W) vertical projections of the lightning radiation sources.

observations on the lightning activities were conducted, for the first time, in the central Tibetan Plateau, with significant findings on the special characteristics of thunderstorm electricity and lightning discharge (Zhao et al., 2004; Zhang et al., 2004; Qie et al., 2005a, b). Thunderstorm was a frequent event in the plateau, while the flash rate was quite low with an average value of about 1 fl min^{-1}, which was over 10 times lower than the prominent low regions such as those in Shandong and Guangdong Province. Figure 6 shows the evolution of surface E-field of a typical thunderstorm. The up arrows mark the E change caused by negative CG flash. No positive CG flashes occurred during the whole lifetime of thunderstorm.

Fig.5. A return stroke with four grounding points observed by high-speed digital camera.

The surface E-field was positive in mature stage of thunderstorm and controlled by positive charge in the cloud. IC flash was dominated in the mature stage, and negative CG flash only occurred in the late stage of thunderstorm.

There usually existed tripole charge structure in the plateau thunderstorm. However, the lower positive charge center (LPCC) was much larger than usual. The LPCC participated actively in the IC flash and the initial stage of the negative CG flash. The IC flash occurred mostly in the lower dipole.

3.2 *The numerical simulation of charge structure*

A three-dimensional thunderstorm model coupled with dynamical and electrical process has been developed for theoretical studies on the spatial and temporal evolution of charge structure and its causes of formation (Yan et al., 1996; Zhang et al., 1999; Guo et al., 2003; Sun et al., 2004). Seven hydrometeors were included in the model, i.e., water vapor, cloud water, rain water, ice crystal, snow, graupel, and hail. It was found that the reversal temperature and relative humidity in the middle layer were the two key parameters in the formation of charge structure. In the same temperature profiles, the lower maximum disturbing central potential temperature $\Delta\theta$c corresponded to weak thunderstorm and quasi polarity-inverted charge structure, while higher $\Delta\theta$c to severe thunderstorm and dipole charge structure. With the $\Delta\theta$c in between, the storm was in tripole charge structure.

In the southern China, the convective available potential energy (CAPE) was high, and the main positive and negative charge center could rise to a high level, and dipole charge structure could form. In the northern China, however, the convection was conducive to tripole charge structure. The humidity also had an effect on the charge structure. Enhanced middle relative humidity would increase the instability of whole thunderstorm. Dipole charge structure corresponded to maximum humidity in middle layer, while quasi polarity-inverted charge structure to the minimum.

4. Artificial lightning triggering technique and its application

A common technique for artificial lightning triggering involves launching a small rocket trailing a thin, grounded copper wire toward the charged cloud overhead (Wang et al., 2000). This technique for triggered lightning is called classical triggering. Although the

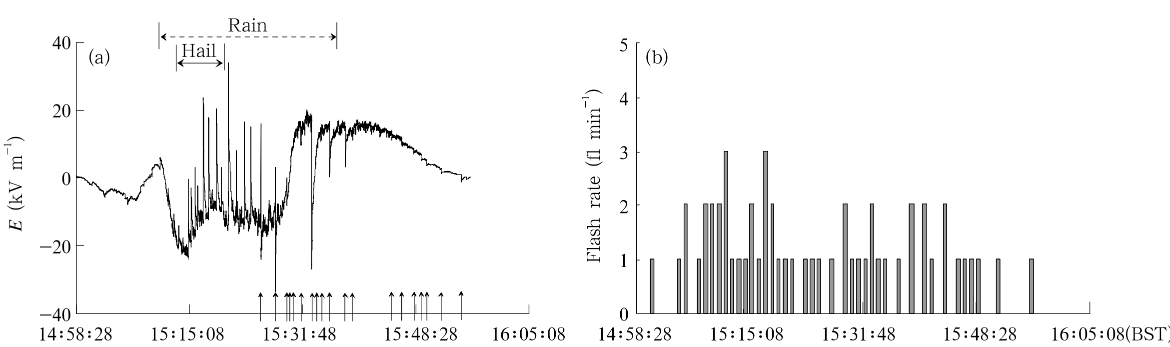

Fig.6. The evolution of average surface E-field with the up arrows representing the CG flash (a) and the flash rate (b) under a severe thunderstorm.

dart leaders and following return strokes are similar to those processes in downward negative natural flashes, the initial processes are distinctly different. In order to reproduce the initial phase of natural lightning (stepped leader followed by the first return stroke), an ungrounded wire is usually used. This technique is called altitude triggering and has a disadvantage of low probability of current measuring. The rocket usually spools out 50-100 m of insulating Nylon followed by 400-700 m of copper wire. After this last wire has been unreeled over a sufficient length, a bi-directional leader will be initiated from its extremities. As the negative downward leader from the lower end of the triggering wire approaches the triggering facility, an upward positive connecting leader is initiated from the grounded object. Once two leaders meet together, a return stroke will be initiated. More than 50 lightning flashes have been triggered with both classical and altitude triggering techniques in Gansu, Beijing, Jiangxi, Shanghai, Guangzhou, the Tibetan Plateau, and Shandong since 1989.

4.1 *The characteristics of artificially triggered lightning in the southern and northern China*

The characteristics of artificially triggered lightning are quite different between the southern and northern China (Liu et al., 1998; Wang et al., 2000; Zhang et al., 2003b). The triggered lightning usually included just continuous current stage with a maximum current of 1-2 kA and a neutralized charge of only several coulomb in the northern China, in contrast to that including both an initial continuous current with a time duration of about hundreds of milliseconds and several subsequent return strokes in the southern China. A typical triggered lightning lasted over 1.5 s with a discharge current being more than 10 kA in the southern China, much larger than that in the northern China. The overall efficiency of triggering was about 60% in China, similar to that in the Unite States. Figure 7 shows the discharge current of two artificially triggered lightning in Gansu corresponding to one classical and one altitude triggering, respectively. Figure 8 shows two pictures of classical- and altitude-triggered lightning in Nanchang (Liu and Xiao, 1998). The discharge channels were separated because of the horizontal wind, with each corresponding to a return stroke with large current.

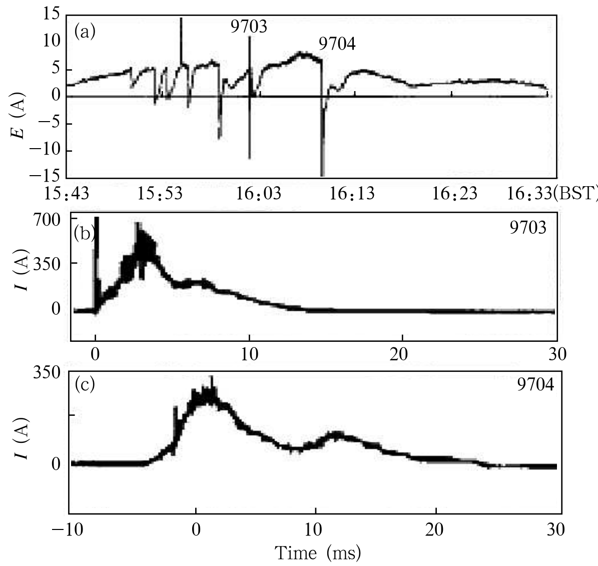

Fig.7. Record of E-field evolution during the lifetime of the thunderstorm (a), and the current of two triggered lightning flashes (b) and (c).

4.2 *Evidences of bidirectional leader in artificially triggered lightning by means of optics and VHF radiation*

Wang et al. (1998) documented optical images of bidirectional leader during an altitude triggered lightning in a distance of about 100 m (shown in Fig.9) by using a high speed digital camera (1000 f s^{-1}). The positive leader was initiated from the upper end of the wire and propagated upward, in comparison with the negative one in the opposite ways. Two leaders accelerated each other with the initiation of downward negative leader several microseconds later than the upward positive one. Dong et al. (2001) observed the weak VHF radiation of the positive leader in a near distance during an artificially triggered lightning by using wideband interferometer, providing evidences of bidirectional leader.

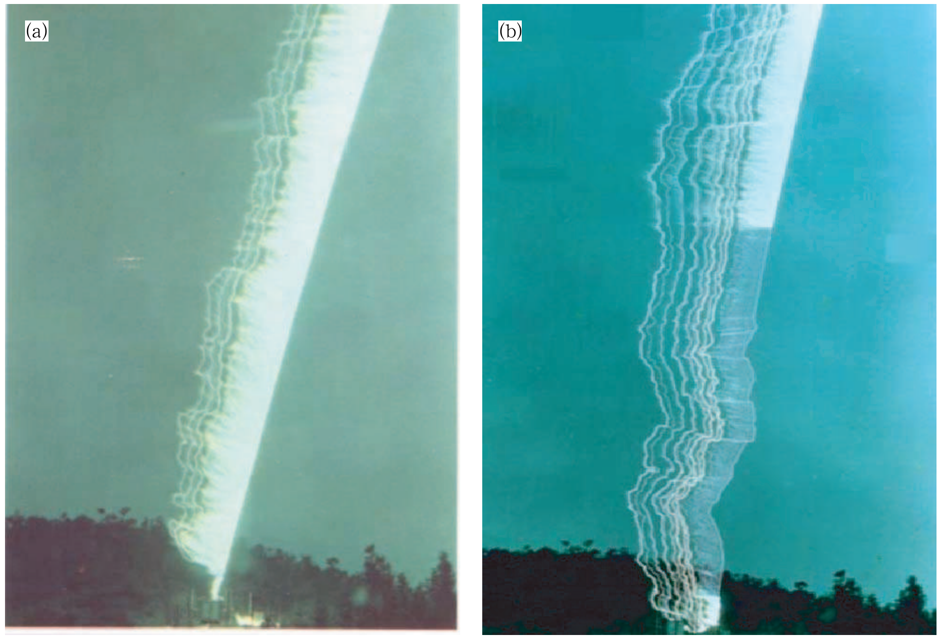

Fig.8. Two triggered lightning discharges in Nanchang photographed at a distance of about 80 m from discharge channel. (a) By using classical triggering technique, and (b) by using altitude triggering technique.

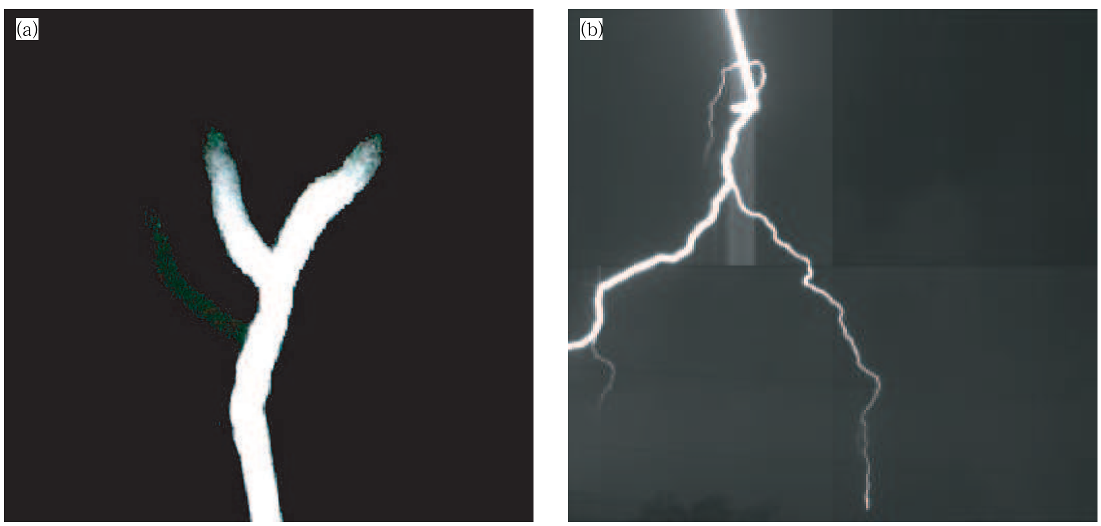

Fig.9. Development of upward positive leader (a) and downward negative leader (b) during altitude triggered lightning discharges.

4.3 *Attachment process and radiation characteristics of lightning in different distances*

By using the data of discharge current, E-field change, and high speed digital camera, Zhang et al. (2003b) analyzed the attachment processes in an altitude triggered lightning. Figure 10 shows the simultaneous record of E-field change at two distances for an artificially altitude-triggered lightning.

Dong et al. (2003) studied the frequency spectrum in the band of 25-100 MHz for natural and artificially triggered lightning, respectively, and found great differences between different discharge processes. CG flash had stronger radiation in the lower frequency

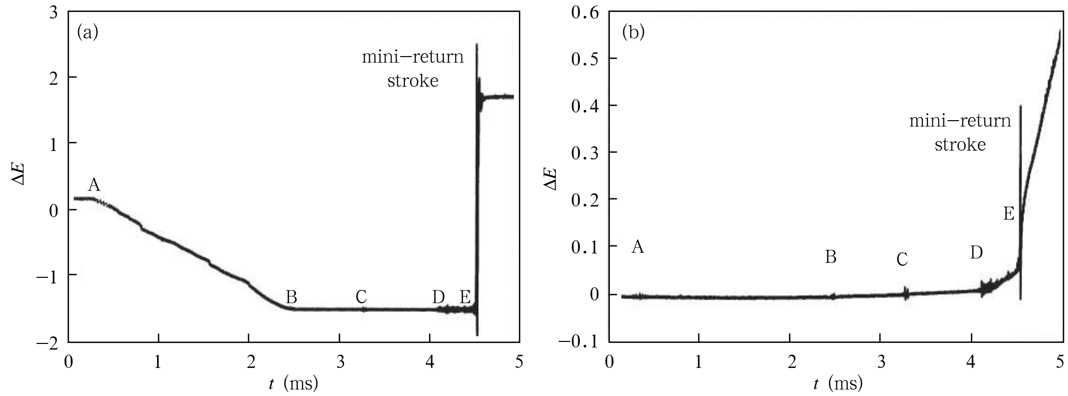

Fig.10. The simultaneous record of surface E-field change of altitude triggered lightning at two distances: (a) 60 m, and (b) 1300 m.

Fig.11. The photograph showing the reaction of SLE struck by an artificially triggered lightning. The SLE is installed on the top of a 10-m high iron tower.

band than IC flash. The processes of IC flash, PBP, and K-change showed strong radiation in the higher frequency band, indicating that these processes were characterized by negative breakdown with small spatial scales. The developing speed of breakdown process was estimated to be about 3×10^5 m s^{-1}. The radiation of stepped leader and dart stepped leader was in the high frequency band in the initial stage, but shifted to the lower band when approaching the ground, indicating that the discharge scales increased when it was getting to the ground. The radiation of positive leader during triggered lightning was mainly in the lower frequency band.

4.4 *The testing of lightning protection devices*

Artificially triggered lightning provided a kind of simulating source similar to the natural lightning with a known discharge location and time, making test the mechanism and effect of lightning protection devices possible. During the years from 1998 to 2000, the technique of artificial lightning triggering was introduced into testing conventional lightning rod and semiconductor lightning eliminator (SLE). Figure 11 shows the reaction of SLE which was struck by triggered lightning. The parallel connection among two or three pins usually occurred as expected. The discharge along the pin surface could also be observed. The downward leader of natural lightning was well simulated by the altitude-triggered lightning.

5. The correlation between lightning and meteorology and climate

5.1 *The lightning climatology in China and its surrounding areas*

The spatial distribution, seasonal variation, and diurnal variation of lightning activities in China were studied by using the data from weather station, lightning location system, and lightning sensors on satellites (Zhang et al., 2001; Qie et al., 2003a). Figure 12 shows the distribution of flash densities in China and surrounding areas. There were four belts of lightning activities that run parallel to the pacific seashore: offshore, middle, western, and western boundary regions. The density of flash rate decreased gradually from the southeastern coast to western region. The spatial distribution of lightning activities was consistent with

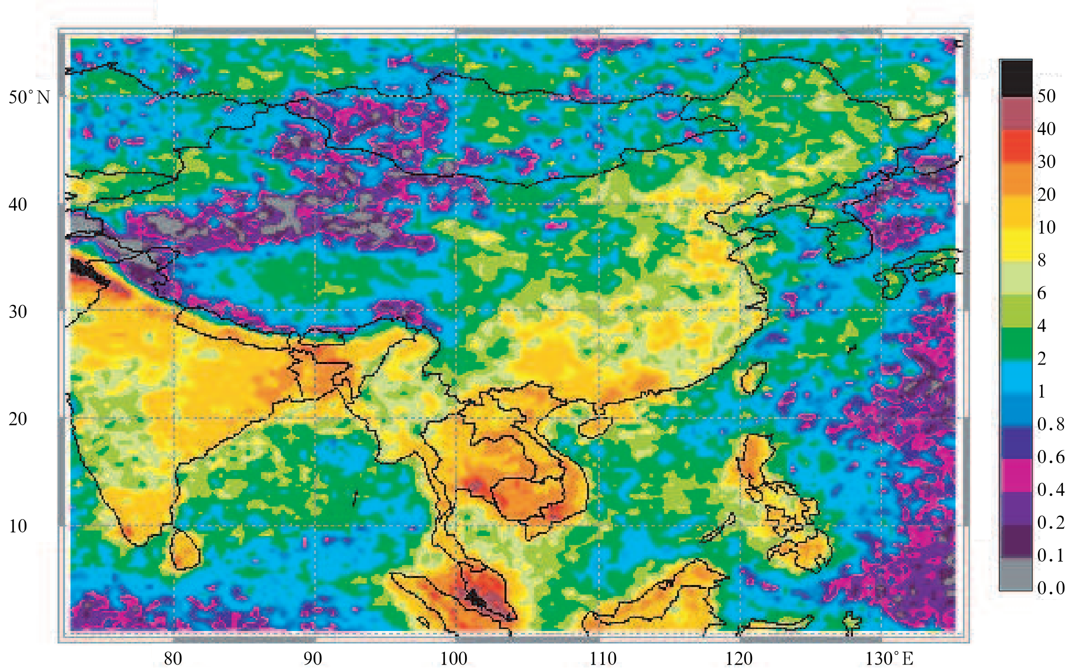

Fig.12. The distribution of flash rate (fl yr^{-1} km^{-2}) in China and surrounding areas.

that of precipitation.

Qie et al. (2003b) and Yuan and Qie (2005) studied the spatial and temporal distribution of lightning activities and their responses to the surface thermodynamic parameters in the Tibetan Plateau by using the LIS/OTD satellite data provided by Global Hydrology Resource Center. The lightning flashes in the plateau showed obvious diurnal and seasonal variations, and responded strongly to the torography and surface thermodynamic features. It also correlated non-linearly to the CAPE. The discharge intensity was weak in the plateau. And different flash intensities in different regions can be explained by existence of different CAPEs.

5.2 *The relationship between lightning and extreme weather and climate events*

The importance of lightning for climate studies has been increasingly recognized. Ma et al. (2004) analyzed the lightning activities in the southeastern China and Indo-China Peninsula during the 1997/98 El Niño event (ENSO) by using the LIS/OTD grid data in 2.5°×2.5° resolution, and found that a positive anomaly of lightning density occurred in the same time with Nino3 SSTA steep increasing in the spring of 1997 and remained in a higher level till the next spring. Xiong et al. (2005, 2006) analyzed the responses of lightning activities to surface relative humidity in global and regional scale by using the LIS/OTD lightning data and NCEP meteorological data (from 1995 to 2002). Figure 13 shows the distribution of correlation coefficient between the regional flash rate and relative humidity. It can be found that the higher relative humidity resulted in more lighting activities in dry regions but less in wet regions. The watershed of relative humidity for lightning production was about 72%-74%.

There are usually intensive electrification and active discharges in severe hailstorms because of strong updraft and complex microphysical processes with participation of ice particles. As an indicator of severe convection, characteristics of lightning activities in hailstorms and tornados have been studied. Feng et al. (2006) found that different thunderstorms presented different lightning features even under the same synoptic situation. Figure 14 shows the distribution of CG flashes superimposed on two PPI scans with a time interval of 10 minutes during a typical hailstorm.

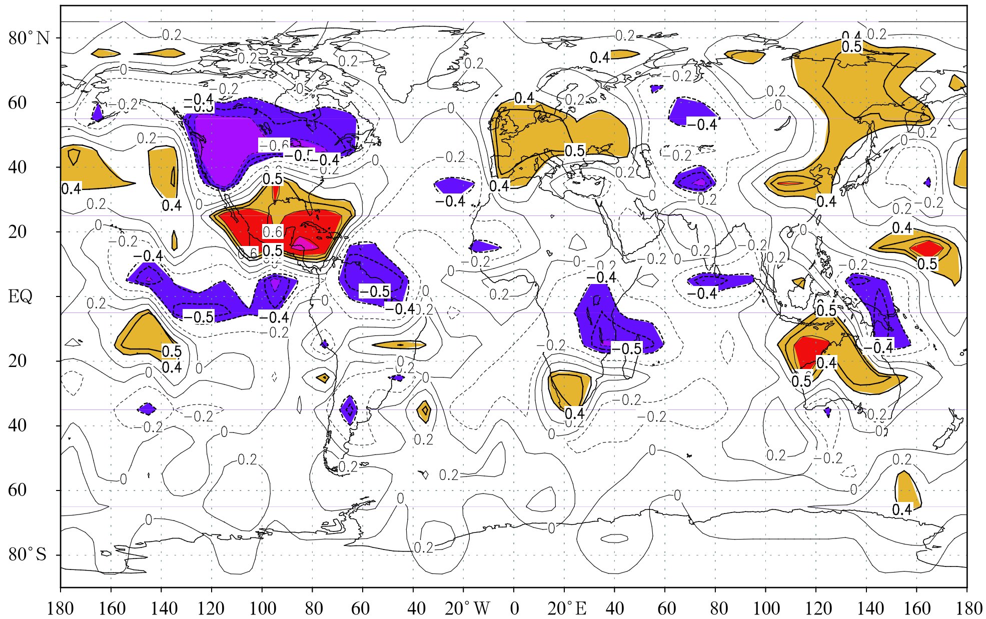

Fig.13. Distribution of correlation coefficients between the regional flash rate and the relative humidity. The dark and light shaded areas have passed the confidence limit of 99% and 95%, respectively.

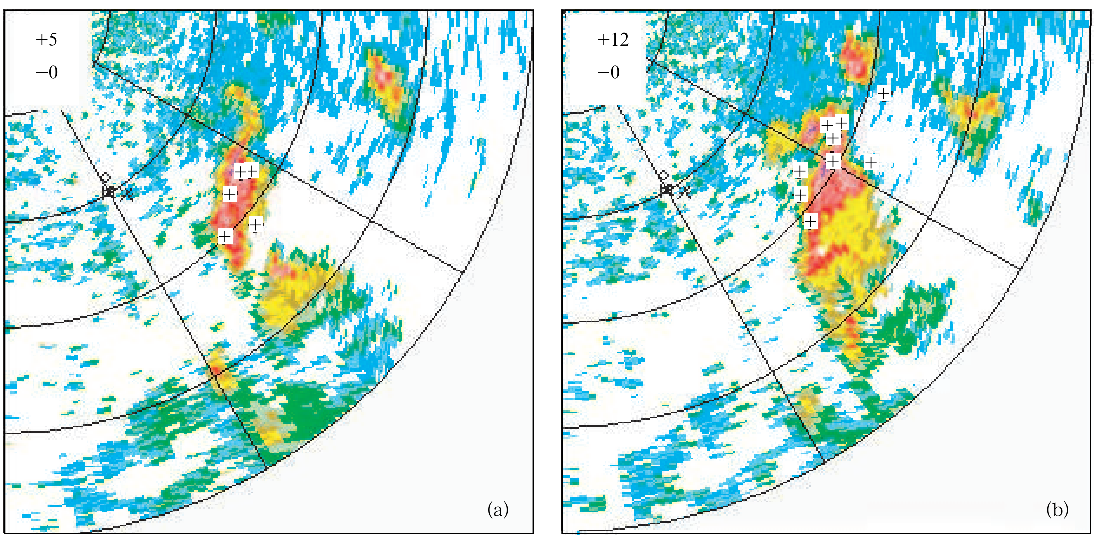

Fig.14. Distribution of CG flashes superimposed on two PPI scans with a time interval of 10 minutes during a typical hailstorm. ('+' and '-' stand for the positive and negative CG lightning within 10 minutes around the radar scan time, respectively.)

Negative CG flashes usually occurred in intense echo regions with reflectivity more than 50 dBz in contrast to 10-30 dBz for positive CG flashes which often occurred in weak and stable echo regions or cloud anvils, although they could be observed in strong convective region sometimes. Almost all hail falling events took place in the stage with active positive flashes with the peak positive flash rate a little ahead of hail events. The thunderstorm could lead to disastrous weather when positive CG lightning flashes occurred in cluster.

5.3 *The charge location of lightning discharge in thunderstorm*

Qie et al. (2000) analyzed the charge sources of individual strokes in multiple-stroke flashes to ground by using the electric field changes obtained at 5 sites on the ground beneath thunderstorm. The altitude of negative charge neutralized by the strokes was between 2.5 and 5.0 km above the ground with corresponding ambient temperature of -2.0–15.0°C, comparing with less than 2.0 km above ground with corresponding ambient temperature of about +5°C for neutralized positive charge. The comparison with radar echo showed that negative charge source corresponded to a region with radar echo greater than 20 dBz or on the edge of 40 dBz, while the positive region corresponded to a weak radar echo region of greater than 10 dBz.

Feng et al. (2006) analyzed the evolution of CG lightning in a typical mesoscale convective system (MCS) by using data from lightning detection system, Doppler radar, and satellite. They found that almost all the CG flashes were negative in the initial developing stage. The CG flash rate was high with a value of more than 10 fl min^{-1}, and the negative CG flash predominated in the mature stage of the storm. The CG flash rate declined rapidly with increase of positive CG lightning ratio in the dissipating stage. The CG flashes mainly occurred in the region with temperature less than -50°C and high temperature gradient in the front of MCS. There was no CG flashes in the cloud with a top temperature higher than -40°C. Negative CG flashes cluster in the region with intense echo (>45 dBz) and the corresponding duration coincided with the strong convection, implying that the negative CG flash could be used to indicate the strong convective region. Moreover, the dense positive CG flashes can also be observed in the strong echo region, in comparison with sparse ones in the weak and stable echo region or cloud anvil in the rear of MCSs. The data analysis also showed that the high positive CG flash rate could be in good correspondence with damaging weather. More attention should be paid to the advent of high positive CG flash rate in nowcasting of severe convective weather.

5.4 *The relationship between lightning activity and convective precipitation*

The correlation between CG lightning and precipitation suggested that the CG lightning be an important factor in estimation of precipitation in the arid and semi-arid region (Zhou et al., 2002). The regression equation between the average precipitation intensity R and the number of CG lightning flashes L in the main precipitation period may be expressed as R=1.692ln(L)−0.273. The correlation coefficient r is 0.86. The CG lightning flash rate can be used as an indicator for formation and development of the convective weather systems. Precipitation deduced from the CG lightning flashes was very useful, especially in regions with inadequate radar coverage.

6. Concluding remarks

New understandings on charge structure of thunderstorm and lightning physics have been achieved during the last decade through continuous observation in some representative regions in China. The first lightning experiment on the Tibetan Plateau clearly revealed the special charge structure and discharge phenomenon. Some exciting results have been documented in theoretical studies and observations on lightning spectra. Progresses have also been made in the area of artificial lightning triggering and its application. However, our understanding on lightning activities is still limited and not enough for lightning protection in the modernized society with wide application of micro-electronics and information technology. There are many questions about lightning activities and lightning mechanism unresolved because of the stochastic nature, risk of danger and instantness of lightning, especially the difference of lightning in different regions. Therefore, further studies are needed on lightning mechanism in time scale of sub-microsecond and lightning activities in different regions.

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