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# A Review of Atmospheric Electricity Research in China

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ABSTRACT

The importance of atmospheric electricity research has been increasingly recognized in recent decades. Research on atmospheric electricity has been actively conducted since the 1980s in China. Lightning physics and its effects, as important branches of atmospheric electricity, have received more attention because of their significance both in scientific research and lightning protection applications. This paper reviews atmospheric electricity research based primarily on ground-based field experiments at different regions in China in the last decade. The results described in this review include physics and effects of lightning, rocket-triggered lightning and its physical processes of discharge, thunderstorm electricity on the Tibetan Plateau and its surrounding areas, lightning activity associated with severe convective storms, the effect and response of lightning to climate change, numerical simulation of thunderstorm electrification and lightning discharge, lightning detection and location techniques, and transient luminous events above thunderstorms.

**Key words**: atmospheric electricity, lightning physics, rocket-triggered lightning, thunderstorm charge structure, lightning location techniques

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## 1. Introduction

The importance of atmospheric electricity research has been increasingly recognized in recent decades. Thunderstorms are a major player in the global atmospheric electrical circuit, the main components of which are the ionosphere, clear air, conducting earth, thunderstorms (especially the electric charge structure inside the storm) and lightning. In the last decade, new detection and location technologies for lightning with high temporal and spatial resolutions have greatly enhanced studies on atmospheric electricity in China, especially with respect to lightning physics and thunderstorm electricity.

Lightning is a type of disastrous weather characterized by high voltage, high peak current with large amplitude variation, and severe electromagnetic (EM) radiation. The probability of ground facilities struck directly by lightning has been greatly reduced since the innovation of the lightning rod by Benjamin Franklin. However, the economic losses caused by lightning have been increasing because of today's wide utilization of micro-electronics. Lightning research is important not only in terms of scientific research objectives, but also from the viewpoint of lightning protection practices.

Areas covered in this review include the physics and effects of lightning; rocket-triggered lightning and the physical processes of discharge; thunderstorm electricity over the Qinghai-Tibetan Plateau and its surrounding areas; lightning activities associated with severe convective storms; the effect and response of lightning to climate change; the numerical simulation of thunderstorm electrification and lightning discharge; and lightning detection and location techniques. Fi-

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nally, recent findings relating to sprites in the middle atmosphere above thunderstorms are briefly described.

## 2. The physics and effects of lightning

Knowledge regarding the physics of lightning and its effects at fine temporal resolution is very important not only in terms of scientific research objectives, but also from the viewpoint of lightning protection engineering, in particular when considering today's wide utilization of microelectronics nowadays. In the last decade, many field experiments of natural lightning have been conducted continuously in the areas of Gansu (e.g., Qie et al., 2000a, 2002b; Zhang et al., 2008), Guangdong (e.g., Qie et al., 2002a; Dong et al., 2002; Zhang et al., 2009e; 2014e), Qinghai (e.g., Qie et al., 2005a; Zhang et al., 2009c; Wang et al., 2013; Fan et al., 2014), the Tibetan Plateau (e.g., Zhang et al., 2004a; Zhao et al., 2004; Qie et al., 2005b), Shanghai (Zhu et al., 2003; 2014) and Shandong (Qie et al., 2007; Kong et al., 2008; Qie et al., 2014a). The main results from these experiments are outlined in the following sections.

### 2.1. *New insights into the progression of the stepped leader and dart leader*

The stepped and dart leaders are important processes in cloud-to-ground (CG) lightning flashes. Knowledge of leader progression is important for the interpretation of lightning initiation. Profiting from high-speed video with a temporal resolution of higher than 1000 frames per second in correlations with broadband electric ($E$) field change signatures, some new insights into the stepped leader in negative CG flashes have been documented (Kong et al., 2005; Qie and Kong, 2007; Lü et al., 2008a, Kong et al., 2009; Zhang et al., 2009e).

Qie and Kong (2007) studied in detail the progression features of the stepped leader with multiple grounded branches. From the time-expanded waveform of the $E$ field change during the return stroke stage, four sequential peaks could be clearly found. The corresponding time differences between two adjacent peaks were approximately 4, 9 and 10 μs, respectively. The four peaks corresponded to four return strokes induced by four different leader branches initiated from one channel trunk. The average 2D speed of the four branches was about $1.1 \times 10^5$ m s$^{-1}$. Lü et al. (2008a) analyzed the optical pulse characteristics of a downward stepped leader with six ungrounded branches. They found that the pulses originated from the main channel and the branches were almost identical in terms of geometric mean (GM) values of 10%–90% rise time and half-peak width, which were around 0.4 μs and 1.1 μs, respectively.

Qie et al. (2002a) found that the $E$ field change waveforms produced by the stepped leader in negative CG flashes could be divided into three types, in terms of the distant $E$ field characteristics between the final leader pulse and the return stroke pulse, and the amplitude of the last leader pulse correlated well to the following return stroke radiation field peak. Zhang et al. (2005) further analyzed the close $E$ field characteristics of stepped leader/return stroke process in negative CG flashes within 20 km. The leader-stroke waveform at distances of less than 3.4 km appeared as V-shaped pulses with negative leader $E$ field change, while it appeared as MP (monotonous positive)-shaped pulses with positive leader $E$ field change at distances greater than 5.1 km.

Jiang et al. (2014a) detected an upward negative CG lightning flash initiated from a high structure by a high-speed camera operated at 10 000 frames per second. They found, for the first time, that the bidirectional propagation of a dart leader developing through the preconditioned channel. The leader initially propagated downward through the upper channel with decreasing luminosity and speed and terminated at an altitude of about 2.2 km. Subsequently, it restarted the development with both upward and downward channel extensions. The 2-D partial speed of the leader's upward propagation with positive polarity ranged between $3.2 \times 10^6$ m s$^{-1}$ and $1.1 \times 10^7$ m s$^{-1}$, while the speeds of the downward propagation with negative polarity ranged between 1.0 and $3.2 \times 10^6$ m s$^{-1}$.

According to the current continuity equation and DU (Diendorfer and Uman) return-stroke model, Zhang et al. (2009b) studied the spatiotemporal characteristics of charge distribution along the lightning channel below 5 km. They found that the charge density deposited along the channel during the return-stroke process neutralized the leader charge and decreased upward along the channel. The transferred charge density decreased with time, the current in the channel ceased to flow, and the transferred charge became zero after a sufficiently long time.

### 2.2. *Electromagnetic field of the return stroke and its nonlinear fractal nature*

The return stroke is the optically brightest and most intense lightning process, and produces the most readily identifiable EM field signature and the most serious lightning-induced damage. On the basis of the electric field changes from wideband slow antenna, Zhang et al. (2003b) found that the zero crossing time of the first stroke radiation field was 63 μs and 66 μs for positive CG and negative CG flashes, respectively, and the corresponding overshoot depth was 20% and 31%, respectively. The initial peak of the return stroke radiation field was followed by several subsidiary peaks. The time interval between the successive peaks increased, whereas their amplitudes decreased in sequence. Zhang and Qie (2003) reconstructed the $E$ field waveforms of the return stroke in three different distance ranges (15–50, 50–100 and 100–150 km). A relationship between the return stroke radiation field change and return stroke current pulse was also rebuilt based on the traditional transmission line model. Qie et al. (2001) found that 54% of the negative multiple-stroke CG flashes had at least one subsequent stroke with a peak $E$ field change larger than that of the first strokes. Furthermore, about 20% of the subsequent strokes had a peak $E$ field amplitude larger than those of the first strokes. The GM of the peak field ratio of the subsequent to the first return stroke was 0.46.

On the basis of a statistical analysis of the waveform signatures of 59 first return strokes of negative CG flashes in Guangdong, Kong et al. (2009) found that 15.3% of the first strokes were characterized by two or more peaks separated in time by 4–486 μs, which meant one CG flash could strike at more than one ground point. Based on this research, it is necessary to re-evaluate the present lightning density distribution, which assumes that one flash of lightning strikes only one point—an assumption that has been widely employed when determining regional lightning protection levels.

Yang et al. (2008b) studied the characteristics of induced voltage in a horizontal conductor due to lightning. The simulated results showed that the induced voltage on both ends of the conductor would increase with increasing return stroke velocity and height of the conductor. The voltage would also increase with increasing of the matched grounding impedances on both ends of the conductor but the relationship was nonlinear.

The finite conductivity of the ground causes distortion of the EM field, whose amplitude decreases and rise time increases, when the lightning EM field propagates along the ground surface (Zhang et al., 2012a, 2012b, 2012c). For example, based on the 2D fractional Brownian motion (fBm) model describing the nature of the rough ground surface, Zhang et al. (2012a) analyzed the propagation effects of the rough ground surface on the vertical electric field generated by lightning return strokes, and found that the extra field attenuation increment caused by the roughness decreases with the decrease of the ground conductivity. When the ground conductivity is larger than 0.1 S $m^{-1}$ (wet earth), the frequencies higher than about 2 MHz are attenuated significantly by a rough ground surface with a mean square height of 10 m (Zhang et al., 2012d). Li et al. (2014) developed a 3D finite-difference time-domain (FDTD) method for simulating the lightning-radiated EM field over the 2D rough ground, and found that the effect of the 2D surface roughness on the horizontal field could not be ignored even at a distance of 100 m from the lightning channel, and the increase of the land roughness resulted in a lower magnitude of the horizontal field waveform.

Zhang et al. (2014a, 2014c) further analyzed the influence of the horizontally and mixed stratified conducting ground on the lightning-induced voltages on the overhead line by using the 2D FDTD method and the Agrawal coupling model, and found that the stratified conducting ground has much effect on the lightning-induced voltages on the overhead lines. Zhang et al. (2014b) also studied the effect of strike to tall objects on the far lightning-radiated electromagnetic field and presented the field-to-current conversion factors (FCCFs) for current peak inferred from observed magnetic field on the ground level. Assuming that a return stroke current contains two components, a breakdown current and a corona current, Zhang et al. (2009b) calculated each of the two components using the analytical expression with Heilder function, and found that the simulated current waveforms were in good agreement with the optical measurement if the discharge time constants were properly chosen, and the DU model was physically more reasonable and preferable in simulating the current along the lightning channel. Wang et al. (2012a) also found that the Heidler function component could reflect the physical characteristics of the subsidiary peaks in the current waveforms of return strokes. Zhao and Zhang (2009) found that, when the tortuosity of the channel was taken into account, the spherical or cylindrical symmetry vanished, and then the whole lightning channel could be regarded as a fractal antenna composed of a series of single line radiators in Cartesian space, suggesting that the tortuosity of lightning channel should be taken into account in the calculation of lightning EM field.

Lightning can be considered as a large-scale cooperative phenomenon, evolving in a self-similar cascaded way (Gou et al., 2007). On the basis of the *E* field change waveforms recorded by the slow antenna system, Gou et al. (2006) found that the Hölder exponent sharply decreased to its minimum with the occurrence of the return stroke, and the mean value was $-0.1$ by using a technique of wavelet-based local effective Hölder exponent. The time exponent variation was concave during the active stroke period. The standard deviation of the Hölder exponent reached its maximum just before the return stroke. Gou et al. (2009) also found that the return stroke process, in terms of its *E* field waveform, had apparent fractality and a strong degree of multifractality. They suggested that wavelet and scaling analysis might be a powerful tool in the interpretation of a lightning-produced *E* field and therefore in the understanding of lightning physics.

### 2.3. *Lightning characteristics as revealed by VHF radiation location techniques*

Lightning radiation in the very high frequency (VHF) band is associated with air breakdown processes. The VHF radiation characteristics from lightning discharge processes (Zhu et al., 2003; Chen et al., 2005; Wang et al., 2007; Cao et al., 2008) have been studied based on observation data. The location techniques of VHF radiation pulses are used to map or track the lightning discharge channel and infer the charge structure inside the thunderstorm (Zhang et al., 2008; Zhang et al., 2009f).

By using the data from a self-developed narrow band VHF interferometer system and the synchronous *E* field changes produced by lightning, Zhang et al. (2008) studied the processes of a negative CG flash containing 19 strokes. It was found that the preliminary breakdown events of the CG flash started from the negative charge region and exhibited firstly a downward and then an upward propagation. Very intense and continuous radiation was found during the stepped leader process, while less and only discrete radiation during the dart leader processes. *M*-component events produced hook-shaped field changes accompanied by an active burst of radiation at their beginning. Following these active radiation processes, *M* events appeared to finally contact main conducting discharge channels. *K* events and attempted leaders were essentially the same as dart leaders except that they could not reach the ground and initiate return strokes.

Three-dimensional images of lightning progression were obtained successfully for the first time in China based on a 3D lightning mapping system working at a frequency of 270 MHz with a 3 dB bandwidth of 6 MHz (Zhang et al., 2010). Significant differences between the negative CG and positive CG flashes in terms of the initiation and propagation of the radiation sources were found. The preliminary breakdown of the negative CG flash propagated at a speed of about $5.2\times10^4$ m s$^{-1}$. The stepped leader propagated downward at a speed of $1.3\times10^5$ m s$^{-1}$. The initial process of the positive CG flash was also associated with propagation processes of negative streamers.

### 2.4. *Spectra of the lightning discharge channel in the visible band*

Among many research methods in lightning physics, optical spectra analysis is the only one that can reflect the physical features within discharge channels, which are in the form of plasma because of the ionization by the large discharge current. The spectrum of a discharge channel is closely related to the plasma properties and temperature of the channel. Since 2001, observations of lightning spectra in the band of 400–700 nm have been carried out using a slitless spectrograph, and the average temperature and electron density in lightning channels have been deduced from the spectra in the visible band (e.g., Yuan et al., 2002, 2004a, 2006; Ouyang et al., 2006; Wang et al., 2009b).

Two spectrum lines of wavelengths 604.6 nm and 619.4 nm for the first return stroke of negative CG flashes were recorded for the first time in lightning spectra by Yuan et al. (2004b). Based on the spectra structure, the lines in the lightning spectra could be classified into two categories: essential lines and characteristic lines. The essential lines can be recorded in most lightning return strokes, which can, to some extent, reflect the common characteristics of the discharge channel. The characteristic lines carry the information reflecting the trait of each individual discharge process. The essential lines include NII (399.5 nm), NII (480.3 nm), Hβ (486.1 nm), NII (568.0 nm), NI (648.2 nm), and so on.

Notable differences have been found between the spectral features over Qinghai Plateau and the region of Guangdong (Yuan et al., 2002). The spectral energy is concentrated in the band of relatively short wavelength in Guangdong, while it is in the band of longer wavelength in Qinghai, indicating the discharge energy and channel temperature is higher in Guangdong. In Guangdong area, the transitions between exited states of $n=3$ in NII ions were the main compositions of lightning spectra, corresponding to upper excited energy of around 23 eV, and lines with higher exited energy (30 eV) from NII and OII ions could be recorded. On the other hand, the spectra over the plateau area were relatively weak, and the transitions from natural NI and OI atoms were strong, with the upper excited energies being around 13–14 eV.

Wang et al. (2009b) showed that the spectra of IC flashes demonstrate two different kinds of structural characteristics. One had a similar structure to that of a CG flash discharge, characterized by the lines of 500.5 and 568.0 nm being the strongest. The other was completely different, with the lines of 517.9 and 532.8 nm being the strongest; the upper excited energies of around 30 eV and the lines of 500.5 and 568.0 nm were very weak, in contrast. Meanwhile, more lines of OII with high excited energy were found in the spectra of IC lightning discharges in comparison with those of CG flashes in the same region.

According to the relative intensities of spectral lines and transition parameters, Ouyang et al. (2006) calculated the temperatures for individual lightning stroke at different heights of the discharge channel using a multiple-line method. The temperature in return stroke channels varied from 29 000 to 36 000 K. For a certain return stroke channel, temperature along the discharge channel showed a decreasing tendency with height. Zhang et al. (2007a) calculated the electron density according to the Hα line Stark broadening formula. The electron density varied from $4.68\times10^{17}$ to $5.03\times10^{17}$ cm$^{-3}$. Simultaneously, with the Saha equation, the electron density was found to range from $9.03\times10^{17}$ to $17.5\times10^{17}$ cm$^{-3}$. Generally, the more intense (i.e. large peak discharge current) the lightning discharge, the higher the channel temperature, the electron density and the relative concentration of highly ionized particles, but the lower the concentration of neutral atoms.

### 2.5. *New observational evidence on positive CG flashes*

A positive CG flash lowers positive charge to the earth, and usually neutralizes more charge than a negative flash. It is generally thought that less than 10% of CG flashes are positive on average, and positive CG flashes are less understood than negative ones because of the lack of observational data. Kong et al. (2008) reported a positive CG flash with a pronounced stepped leader. The fast $E$ field change of the positive leader immediately prior to the return stroke showed clearly pronounced pulses, indicative of a step-like development. The time intervals between the 26 leader pulses ranged from 3 to 31 ms, with a mean value of approximately 17 ms. The 2D propagation speed, estimated from the two adjacent frames, increased from $0.1\times10^5$ to $3.8\times10^5$ m s$^{-1}$ as the leader approached the ground. Kong et al. (2008) suggested that positive CG lightning can be produced by branching of the in-cloud discharge channels, probably when these channels occur near or below the cloud base.

Using data from the Lightning Mapping Array (LMA), Zhang et al. (2006a) analyzed the 3D spatial and temporal development of positive CG lightning discharges. The results indicated that a positive CG flash could be divided into three stages. The first stage was the discharge process in cloud with a long duration preceding the return stroke. This process propagated at a velocity of $10^5$ m s$^{-1}$, and produced intensive radiation with a magnitude equal to that of the negative leader. During this stage, the lightning channels developed horizontally in the positive charge region with fewer branches as the negative polarity breakdown. During the stage after the return stroke, the lightning channels propagated at a velocity of two times faster than that before the return stroke. This stage involved many positive fast impulses and corresponded to the continuing current process producing less and dispersed radiation points and more intensive radiation power. During the final stage, the lightning channels developed at a velocity equal to that before the return stroke and the radiation points appeared mainly at the end of channel. All of the radiation points of the positive CG flash appeared in the positive charge region of the cloud. Little or no radiation was detected during the positive leader just before the return stroke.

Qie et al. (2013) analyzed 185 positive CG flashes containing 196 return strokes in Da Hinggan Ling forest region (50.4°N, 124.1°E) of northeastern China documented with a multi-station network of fast and slow antennas. It was found that 71.9% of the positive CG flashes contained continuing current, but the average duration of continuing current was short with a GM value of 16.7 ms, because of the small size of the storm cell in this relatively high latitude region. According to the electric field waveforms indicative (or not indicative) of IC discharge, positive CG flashes can be classified into four types, i.e., ordinary positive CG flash (63.8%), hybrid positive CG-IC flash (21.1%), hybrid IC-positive CG flash (5.4%), and hybrid IC-positive CG-IC flash (9.7%). About 15.1% of the recorded positive CG flashes were byproduct of IC lightning discharge.

### 2.6. *Narrow bipolar events*

Narrow bipolar event (NBE) is a type of lightning discharge event. It is markedly different from regular CG and IC lightning in many respects. An NBE is associated with strong radio frequency emissions and narrow bipolar waveforms (Zhu et al., 2007, 2010a). The 3D propagation of NBEs was observed for the first time in China by Zhang et al. (2010). The NBE channels originated at an altitude of $\sim 10.5$ km in the upper positive-charge region and extended horizontally all around. The source power of an NBE can approach 16.7 kW, which is much greater than that of normal lightning discharge, which ranges between 100 mW and 500 W. The vertical scale of NBEs found by Liu et al. (2012) was in the range of 0.40–1.9 km, with an average speed of $0.44 \times 10^8$ to $1.0 \times 10^8$ m s$^{-1}$.

Negative NBEs produce larger electric field changes on average and are more isolated from other discharge processes compared to positive NBEs (Wu et al., 2011). Wu et al. (2012) found that the positive NBEs occur between the main negative charge layer and the upper positive charge layer, while negative NBEs occur between the upper positive charge layer and the negative screening charge layer at the cloud top. Lü et al. (2013) found that the NBE occurrence at 51 degrees N appeared to differ significantly from that in most lower latitude regions. Specifically, no NBEs with negative electric field pulses (positive charge moving up) were observed.

Wang et al. (2012) documented 236 NBEs in Shandong province. Of between, 32 occurred in isolation and 204 occurred in association with either IC or CG lightning discharges. Among the latter, 130 appeared to initiate lightning discharges, while 72 embedded in lightning discharges and the remaining 2 terminated the lightning discharges. No apparent difference among all types NBEs was found on the parameters of NBEs radiation waveforms. They found the NBEs occurred at a height ranging from 7 km to 16 km with a peak power ranging from 12 kW up to 781 kW in the 267–273 MHz passband.

Zhu et al. (2010b) introduced a direct technique to measure the time taken by the current front to propagate along the channel from distant radiation field pulses of the NBE on the basis of the transmission-line model, which involved integrating over the initial half-cycle of the narrow bipolar waveform of the NBE. The ratio of the integral result to the initial peak amplitude made a good approximation to the time taken by the current front to travel along the channel.

### 2.7. *Tall structures-related lightning and lightning attachment process*

Tall structures are usually used for lightning studies because of the high lightning incidence probability. Recently, high-speed video cameras have been used to observe the attachment process of lightning to tall structures with relatively high spatial and temporal resolution. Using high-speed images of two natural downward flashes struck on two tall structures in Guangzhou, Lu et al. (2012) analyzed 45 unconnected upward leaders (UULs) occurred in 19 downward negative flashes. Each observed UUL was initiated by a downward stepped leader before a new strike point was struck. The maximum distances for the downward leaders to attract the UULs with inception heights from 100 to 200 m, 200 to 300 m, and over 400 m were approximately 350 m, 450 m, and 600 m, respectively.

Lu et al. (2013) recorded a downward negative lightning flash that terminated at a 440 m high building. The attachment process in this flash exhibited an unexpected behavior in that the downward leader tip connected to the lateral surface of the similar to 400 m upward connecting leader (UCL) below its tip. It appears that the effect of the downward leader on the UCL was significant, while the effect of the UCL on the downward leader was negligible, except for the final 80 μs preceding the beginning of the first return stroke. The ratio of speeds of the downward leader and the UCL tends to decrease with time, ranging from 1.8 to 0.12.

Jiang et al. (2014b) studied the lightning flashes striking at a 325-m-tall meteorology tower in Beijing. Among eight upward lightning flashes documented during two thunderstorms, four were self-initiated events without lightning activity nearby prior to their initiation, two were triggered by the nearby positive CG with the initiation of the upward leaders from the tower lagged 0.4 ms and 5 ms behind, respectively, and the remaining two were triggered by nearby IC lightning activities. The average 2-D speed of the upward positive leader was $1.0 \times 10^5$ m s$^{-1}$ within several hundred meters above the tower tip.

## 3. Rocket-triggered lightning and the physical processes of discharge

A common technique for triggering lightning with this method involves launching a small rocket trailing a thin, grounded copper wire toward the charged cloud overhead, and is called classical triggering. In the altitude triggering technique, the rocket usually spools out 50–100 m of insulating Nylon followed by several hundred meters of copper wire. The electric field at the ground is usually used as a reference to launch a rocket for triggering lightning, although the electric field aloft is more indicative (Qie et al., 1994), but hard to measure. The surface electric field is usually 5–10 kV $m^{-1}$ when lightning is triggered successfully. Over 100 lightning flashes have been triggered with classical or altitude triggering techniques in several regions of China since then, including Gansu, Beijing, Jiangxi, Shanghai, Guangdong, the Tibetan Plateau and Shandong from 1989 to 2014. A new model rocket, made of composite material and assembled with a parachute, was newly developed and utilized successfully in recent experiments (Qie et al., 2010). Most of the results in the last decade are outlined below.

### 3.1. *Characterization of lightning currents and the close EM field*

The most serious lightning-induced damage is usually caused by close lightning discharges. Rocket-triggered lightning provides a unique opportunity for measuring the discharge current and close EM fields, which are essential for both understanding the physics of lightning and the design of lightning protection systems.

The Shandong Artificially Triggering Lightning Experiment (SHATLE) started from 2005 in Binzhou, Shandong Province (Qie et al., 2007; Zhang et al., 2006; 2007b). Zhang et al. (2009a) and Zhao et al. (2009a) studied the current waveform characteristics and corresponding close *E* field change during SHATLE. The whole discharge process of all triggered flashes lasted from 518 ms to 1900 ms. The GM value of the current peak was 12.1 kA (Qie et al., 2014a). Other current parameters are given in Table 1. The *E* field changes produced by the dart leader/return stroke sequences appeared as V-shape pulses at 60 m, and the distance ($r$) dependence of the dart leader *E* field change was $r^{-1.18}$ (Qie et al., 2009a; Zhang et al., 2009b).

The Guangdong Comprehensive Observation Experiment on Lightning Discharge (GCOELD) started from 2006 in Conghua, Guangdong. For the triggered lightning from 2006–2011 (Zhang et al., 2014e), the peak current of the return strokes ranged from 6.67 to 31.93 kA with a GM value of 15.9 kA. The maximum induced voltage generated by return strokes on the overhead power line (1200 m in length and 2 m above the ground) exceeded 10 kV. The maximum induced voltage on a vertical 10 m signal line was 3.10 kV. The triggered-lightning technique was also used to test the detection efficiency and location precision of Guangdong lightning location system (LLS) in Guangdong. It was explored that the LLS yielded detection efficiency and location error of 92% and 760 m, respectively, for triggered flashes. For RSs of the triggered lightning, the peak currents given by the LLS deviated from those measured at the base of the lightning channel by 16% on average.

Yang et al. (2008a) developed a magnetic field measuring system with two rectangular loops perpendicular to each other, with which the total horizontal magnetic field produced by lightning discharges was detected. The magnetic fields at 60 m, based on 32 return strokes, varied from 18 mT to 148 mT with a GM of 52 mT (Yang et al., 2010). By using Ampere's law of magnetic fields, the currents were inferred from the measured magnetic fields, which were in good agreement with the directly measured current at the base of the discharge channel. The system proved to be a useful tool for current retrieval and measurement of the close EM environment of lightning flashes (Yang et al., 2008a, 2010).

Zhang et al. (2003c) studied the statistical characteristics of the leaders in five altitude triggered negative lightning discharges in Guangdong in 1998. The *E* field change at close distance was characterized by negative discontinuous oscillating pulses superimposed on slow positive change during the stable propagation stage of the bidirectional leader. Meanwhile, the *E* field change at far distance began with bipolar pulses followed by unipolar pulses. Zhang et al. (2011a) employed two existing models, a "source charge" leader model and a return-stroke model of the modified transmission line model with linear current decay with height (MTLL), both based on the assumption of uniform leader charge distribution along the channel, to simulate the V-shape structural characteristics of the close dart leader/return stroke field change. They suggested that at the early stage there was often some uncertainty regarding whether the charge deposited by the dart leader was completely neutralized by the following return-stroke process.

### 3.2. *Discharge processes and new insights into the positive leader*

The high-speed camera has become an important tool in triggered lightning research. Using a high-speed camera system and two electric field antenna systems, Lü et al. (2008b) documented the initial processes of an altitude-triggered negative lightning event. The discharge began with the incep-

**Table 1.** Current waveform parameters based on SHATLE 2005–11.

| Experiment site | Sample size | Minimum | Maximum | Arithmetic mean | Standard deviation | Geometric mean | Standard deviation [lg (*x*)] |
|---|---|---|---|---|---|---|---|
| Peak (kA) | 36 | 4.4 | 41.6 | 14.3 | 9.2 | 12.1 | 0.23 |
| 10%–90% risetime (μs) | 36 | 0.2 | 8.4 | 2.0 | 2.1 | 1.9 | 0.47 |
| Half-peak width (μs) | 36 | 1 | 68 | 23.7 | 17.1 | 14.8 | 0.52 |
| Charge transfer within 1 ms (C) | 36 | 0.18 | 4.2 | 1.1 | 0.76 | 0.86 | 0.31 |

tion and propagation of an upward positive leader and then a bidirectional leader process. The 2D propagation speed of the upward positive leader in its inception phase was about $3.8 \times 10^4$ to $5.5 \times 10^4$ m s$^{-1}$ from about 393 to 452 m above the ground. The stable downward negative leader began at the tip of the unstable one, with a 2D propagation speed of about $1.9 \times 10^5$ m s$^{-1}$. Wang et al. (2012b) and Jiang et al. (2013a) found that the positive leader in the initial stage of the classical triggered lightning shows a similar stepped manner of propagation to that of the negative leader. The induced step length varies from 0.9 m to 3.7 m with a geometrical mean value of 1.7 m.

Yang et al. (2009) analyzed the initial discharge stages of two triggered flashes on the basis of the synchronous data of the current and close EM field. Lu et al. (2009) documented the initial processes of an altitude-triggered negative lightning event. The discharge began with the inception and propagation of an upward positive leader, then an almost simultaneous propagation of both the upward positive leader and downward negative leader followed, known as the bidirectional leader process. The 2D propagation speed of the upward positive leader in its inception phase was about $3.8 \times 10^4$ to $5.5 \times 10^4$ m s$^{-1}$. The stable downward negative leader propagated with a 2D speed of approximately $1.9 \times 10^5$ m s$^{-1}$. The average step length was about 3 m, and the time interval between steps varied from 6 μs to 31 μs with a mean value of 15 μs.

Dong et al. (2001) observed the weak VHF radiation of the positive leader at a close distance during a triggered flash using a broadband interferometer. The speed of the upward positive leader was on the order of $10^4$ to $10^5$ m s$^{-1}$. In classical triggered negative flashes, the speed of upward positive leaders ranged from $0.35 \times 10^5$ to $7.71 \times 10^5$ m s$^{-1}$.

### 3.3. *M-components with peak current in the range of kilo-amperes*

Large *M*-components with peak current in the range of kilo-amperes were found in a rocket-triggered negative flash in SHATLE 2009 (Jiang et al., 2011). Among the 31 distinct current pulses, there were five large *M*-components with unusually large peak current in the range of kilo-amperes. The GM value of peak current for the five large *M*-components was 5.1 kA, the half peak width was 76.3 μs, and the rise time from the 10% to 90% peak was 34.6 μs, while the corresponding values for the 18 typical *M*-components were 243 A, 400 μs and 319 μs, respectively. The waveform parameters of the return stroke and typical *M*-component were in good agreement with those found in previous triggered lightning (Yang et al., 2010; Zhao et al., 2011). The *M*-like events were superimposed on a slowly-varying continuing current, while the directly measured current prior to the stroke was not significant. One stroke/*M*-component (RM) event that exhibited both stroke and *M*-component features was also found in the same flash (Qie et al., 2011). The simultaneous *E* field and current waveform of RM implied a superposition of the dart leader and *M* incident wave in the channel. The proposed possible reason was that two branches with a common lower portion existed simultaneously in the upper part of the discharge channel. Zhang et al. (2011b) used the two-wave model, proposed by Rakov et al. (1995), to reveal that the speed of the *M*-component essentially controlled the electric field but had little effect on the magnetic field. A larger reflection coefficient resulted in a larger magnetic field but a smaller electric field. Jiang et al. (2013b) proposed a modified model based on Rakov's two-wave theory and confirmed that the evolution of *M*-component through the lightning channel involves a downward wave transferring negative charge from the upper to the lower channel and an upward wave draining the charge transported by the downward wave. The upward wave serves to deplete the negative charge by the downward wave at its interface and makes the charge density of the channel beneath the interface layer to be roughly zero.

## 4. Thunderstorm electricity on the Tibetan Plateau and its surrounding areas

The Tibetan Plateau is the largest and highest area in the world, with an average elevation exceeding 4000 m. Thunderstorms occur frequently in the summer season over the Tibetan Plateau because of its unique dynamic and thermodynamic effects. In the summers of 2003–05, comprehensive observations on thunderstorm electricity were conducted on the Tibetan Plateau and Chinese inland plateau regions (Qie et al., 2009b).

### 4.1. *Thunderstorm electricity in four different plateau regions of China*

Thunderstorm electricity has been examined experimentally in a number of studies across four different plateau regions, including Nagqu located in the central Tibetan Plateau (31°29′N, 92°03′E; 4508 m MSL), Datong on the Qinghai Plateau (37°04′N, 101°35′E; 2560 m MSL), and Zhongchuan (36°36′N, 103°39′E; 1970 m MSL) and Pingliang (35°57′N, 106°69′E; 1630 m MSL) in Gansu Province on the Chinese inland plateau.

Qie et al. (2003c, 2005b) found that thunderstorms, usually of small scale and short duration, occurred frequently in these plateau regions in the monsoon season. Hailstones with diameter less than 1 cm were usually observed with duration shorter than 10 min during thunderstorms. Sometimes, more than one thunderstorm process was observed during a single thunderstorm day. However, the lightning activity was weaker compared with that in other prominent lower regions. Using the Lightning Imaging Sensor/Optical Transient Detector (LIS/OTD) data from 1995 to 2002, Qie et al. (2004) and Zhang et al. (2004) found that the mean total flash density over the Tibetan Plateau was 3–5 flashes yr$^{-1}$ km$^{-2}$, that flash activity exhibited a seasonal variation and mainly occurred from June to August with a maximum lightning activity period from late June to mid-July, and that the diurnal variation peak appeared from 1400 to 1600 Local Standard Time (LST).

According to the polarity of the surface *E* field, Qie et al.

(2009b) divided thunderstorms in the four regions into two categories. (1) Special-type: The surface $E$ field underneath the thunderstorms had the same polarity as the clear sky, i.e., the surface electric field was controlled by positive charge inside the thunderstorms (defined as positive, as mentioned above). Zhang et al. (2004a) and Qie et al. (2005b) suggested that this kind of thunderstorm is characterized by an unusual tripole charge structure with a larger-than-usual lower positive charge center (LPCC) at the base of the thunderstorm, and usually the thunderstorm is characterized by IC flashes that occur mostly in the lower dipole. (2) Normal-type: The surface $E$ field was negative when the thunderstorms were overhead, consistent with the normal thunderstorms observed in the other prominent lower altitude regions during the summer season. This kind of thunderstorm also showed a tripole charge structure, but the LPCC was weaker than the former.

The characteristics of the surface $E$ field of thunderstorms in the four plateau regions were similar to each other, but the percentage occurrence of the two types of thunderstorm was different (Qie et al., 2009b; Zhang et al., 2009d). Table 2 shows statistical results for the two types of thunderstorm in the four regions. The percentage of special-type thunderstorms increased with the altitude of the region. The special-type thunderstorms represented around 73%, 60%, 54% and 46% of the total in Nagqu, Datong, Zhongchuan and Pingliang, respectively. The flash rate in the four plateau regions was quite low compared with that in other low altitude regions. Zhang et al. (2010) found that the flash rate of special-type thunderstorms was slightly larger than that of normal-type ones in the plateau regions.

In different stages of the thunderstorm, the surface $E$ field changes and lightning discharge types can be different. Qie et al. (2005a) found that, in the mature stage of a thunderstorm at Datong, most IC flashes occurred between the LPCC and the main negative charge center aloft, and CG flashes were rare in this stage. In the later stage, a weakened LPCC played a dominant role in the initiation of negative CG flash discharge (Qie et al., 2005b). According to the type of predominant flashes associated with the thunderstorm, Zhang et al. (2009d) found that special-type thunderstorms over the Chinese inland plateau can be divided into three types: (1) IC-dominated: no occurrence of CG flashes; (2) negative CG-dominated: $>50\%$ of CG flashes were negative; and (3) positive CG-dominated: the dominant CG flashes were positive. Among 22 cases of special-type thunderstorms in the Nagqu region, four thunderstorms produced no CG flashes. The percentage of CG flashes ranged from 1.88% to 76% for the other 18 thunderstorms, only in 6 cases the percentage of CG to total flash number was larger than 50%, and 15 cases were negative CG-dominated. Only three of the cases were mainly positive CG flashes and one of them occurred on 13 August 2003, which seemed to be the strongest thunderstorm in the central Tibetan Plateau during the 2-year observation period and produced 50 CG flashes with 49 being positive (Qie et al., 2009b).

### 4.2. *Charge structure of thunderstorms in the plateau regions*

Multi-station measurements on the $E$ field changes caused by lightning discharges is an effective way to estimate the charge centers inside thunderstorms. Point-charge and point-dipole models are usually used to analyze the neutralized charge centers for CG and IC flashes, respectively. For thunderstorms with a larger LPCC, it was found that IC flashes were usually polarity-inverted and occurred between the main negative charge center and the LPCC (Qie et al., 2000b). Zhang et al. (2004a) and Qie et al. (2005b) inferred the electric charge structure of thunderstorms and the characteristics of lightning discharges at the initial stage of thunderstorms using VHF location techniques and $E$ field changes in the Nagqu region. They found that most of the IC flashes were polarity-inverted and occurred between the negative charge region in the middle and the positive charge region at the bottom of the thunderstorm, suggesting the thunderstorms might have had a tripole charge structure. Recently, based on 3D localization of wideband electric field change pulses, Li et al. (2013) analyzed the charge structure of a thunderstorm in Qinghai Province, China. They found an inverted dipole charge structure at the development and mature stage of the thunderstorm, with four charge layers (positive–negative–positive–negative) at the dissipating stage, at heights of 5.0, 4.0, 3.0, and 1.8 km, respectively.

The existence of a middle negative charge and large LPCC over the Chinese inland plateau and Tibetan Plateau is widely recognized and accepted. However, evidence of upper positive charge in storms was not found until 2008. Using data from $E$ field changes from a seven-site network of slow antennas synchronized by a Global Position System (GPS) with a 1 μs time resolution in the region of Zhongchuan, Cui et al. (2009) found that the upper dipole was also a source of IC flashes. Among 10 IC flashes, five occurred between

**Table 2.** Statistical results of two types of thunderstorm in four regions.

| Region | Altitude (m) | Storm sample | Special-type | | | Normal-type | | |
|---|---|---|---|---|---|---|---|---|
| | | | Case | Percentage | flash rate ($\mathrm{min}^{-1}$) | Case | Percentage | flash rate ($\mathrm{min}^{-1}$) |
| Nagqu (31°29.0'N, 92°03.0'E) | 4500 | 30 | 22 | 73% | $1.2 \pm 0.26$ | 8 | 27% | $0.65 \pm 0.22$ |
| Datong (37°3.8'N, 101°34.9'E) | 2550 | 10 | 6 | 60% | $1.3 \pm 0.37$ | 4 | 40% | $0.82 \pm 0.15$ |
| Zhongchuan (36°36.2'N, 103°39.3'E) | 1970 | 11 | 6 | 54% | $2.2 \pm 1.31$ | 5 | 46% | $0.7 \pm 0.32$ |
| Pingliang (35°57.0'N, 106°69.0'E) | 1630 | 13 | 6 | 46% | / | 7 | 54% | / |

the upper dipole and the other five between the lower. The heights of IC discharge moments were located between 3.3 and 5.6 km MSL for the lower five IC flashes and between 6.8 and 7.7 km MSL for the upper five, respectively. Analyzing 16 negative CG and 2 positive CG flashes in Datong, Zhang et al. (2009c) respectively found that the negative charge region was located at a height of 5.5–8.0 km MSL (mostly around 6.5 km MSL) and the positive charge height was around 8.5 km MSL, indicating that the charge structure of special-type storms could be basically represented by a tripole structure but with a larger-than-usual LPCC. The height range of the main negative charge region is in good agreement with the result given by Qie et al. (2000a).

*In situ E* field measurement is a direct and effective method to determine more accurately the charge structure inside thunderstorms. A balloon-borne *E* field sounding system, based on the principle of point discharge, was designed by Zhao et al. (2009b). The first *E* field profile inside a special-type thunderstorm was obtained in the region of Pingliang. There were four charge regions with three layers inside the storm and one at the lower boundary of the storm. The LPCC region was between 4.5 and 5.3 km MSL (corresponding to a temperature region of 3°C to −2°C). The main negative charge layer was between 5.4 and 6.6 km (−3°C to −10°C). The upper positive charge layer was located between 6.7 and 7.2 km (−11°C to −14°C), and a negative screening charge layer was also detected at the lower boundary of the thunderstorm. These observational results confirmed that thunderstorms in the plateau regions are usually characterized by a tripole charge structure with a larger-than-usual LPCC.

A 3D thunderstorm model coupled with dynamical and electrical processes has been developed for theoretical studies on the spatial and temporal evolution of charge structure in the plateau regions (Guo et al., 2003, 2007). It was found that the lower maximum disturbing central potential temperature, the reversal temperature and relative humidity in the middle layer were key parameters for the formation of the charge structure. The simulation results by using real sounding data indicated that both types of thunderstorms appeared to begin with the lower dipole of a normal tripole structure, rather than with the upper dipole followed by the development of a weaker lower positive charge region.

### 4.3. *Initial discharge processes of lightning flashes*

The characteristics of the preliminary breakdown process involved in CG flashes are dissimilar in different geographical areas, which may be associated with the charge structure of thunderstorms. Due to the special charge structure inside the plateau's thunderstorms with a larger-than-usual LPCC, negative CG flashes usually proceed with a long preliminary breakdown process lasting several hundreds of milliseconds, similar to IC discharges (Qie et al., 2000a; Kong et al., 2006). Qie et al. (2000b) found that the K-type breakdown process could occur during the preliminary breakdown process, which they named as IC discharges. Using the time-of-arrival (TOA) method, they investigated the K-type breakdown processes during the long IC discharge process through five-station measurements of a wideband slow antenna system in the Zhongchuan region, and found that the K processes occurred in the lower part of the storm. It was found that both positive CG and negative CG flashes usually followed long lasting IC discharge processes with a duration of 170–300 ms, and K-type breakdown processes during initial IC discharge started from the negative charge region and propagated downward to the LPCC with an average speed of $1.5 \times 10^7$ m s$^{-1}$. Wang et al. (2009a) also found that the initial discharge of IC flashes developed from the middle negative charge region to the LPCC based on the location of pulses from a seven-station network of fast antennas.

Long IC discharges just before negative CG flashes were also found in Datong, with an average altitude of about 2650 m MSL. On the basis of slow antenna and high-speed digital camera observation data, Qie et al. (2005a) found that long-duration IC processes occurred just before the stepped leader/return stroke sequence. One such IC discharge process lasted approximately 160 ms and occurred in the lower part of the cloud with the lowest point at around 1.7 km above the ground. Zhang et al. (2003a) found that the preliminary discharge showed a bi-layer structure, by using a short-baseline lightning VHF pulse location system with the TOA technique. Using LMA data, Zhang et al. (2009f) also found that the preliminary breakdown process with longer duration time in negative CG discharges was an IC discharge process.

A large LPCC may play an important role in longer preliminary breakdown processes. However, from one case of typical thunderstorms on the central Tibetan Plateau (4508 m MSL), Qie et al. (2005b) found the existence of the LPCC did not cause positive CG flashes, and only negative CG flashes were observed in the late stage of the thunderstorm. The quite large LPCC prevented negative CG flashes from occurring because abundant lower positive charges could make IC discharges between the lower dipole possible. In the late stage of the storm, when the LPCC decreased greatly with the fall down of the most positive charge carriers (rain particles and graupel or hail) to the ground, negative CG flashes could be triggered frequently by the LPCC. This suggests that a weak LPCC is conducive to the occurrence of negative CG flashes, while a large LPCC is conducive to polarity-inverted IC flashes or negative CG flashes with longer preliminary discharge.

## 5. Lightning activities associated with severe convective weather

Severe convective weather, such as hailstorms, mesoscale convective systems (MCSs) and so on, generally produces not only heavy precipitation, damaging wind and hailstone, but also lightning discharges which sometimes cause serious damage. The lightning activity and its relationship with dynamic processes and precipitation structure in severe convective weather systems has been studied in the last decade based on data from CG lightning location networks, SAFIR3000 lightning data, Doppler radar, meteorological satellites, and Tropical Rainfall Measuring Mission (TRMM)-based sensors.

### 5.1. *Lightning characteristics in different thunderstorms*

Lightning is an indicator of vigorous convection. The lightning activities in different kinds of thunderstorms such as hailstorms, MCSs, and squall lines have been studied in China. Feng et al. (2006a, 2007, 2008) and Liu et al. (2009) found that hailstorms usually presented higher ratio of positive CG flashes during periods of hail fall in Shandong Province. The positive CG flashes represented more than about 45% of total CG flashes, which was much higher than the climatic mean value (12.5%) in the region. The falling of hail was often reported in the region of dense positive CG flashes. Sometimes, hailstones appeared slightly on the right flank of the dense CG flash region. There was a distinct CG flash rate increase in hailstorms during the period of fast development, while a rapid reduction in the CG flash rate occurred in the dissipating stage. The hail fall corresponded to an active positive flash period, and the increase of the positive CG flash rate was generally accompanied by a decrease of the negative CG flash rate. The peak negative CG flash rate usually occurred 0–20 min earlier than hailstone fall, but the peak positive CG flash rate usually appeared at the time of or after the advent of hail fall. When the polarities of CG flashes changed, it often indicated the advent of severe weather such as hail fall, damaging wind and heavy precipitation. Both the ratio of IC to CG flashes and IC flash density in hailstorms were much larger than those in common thunderstorms. Most positive CG flashes usually occurred in or near the strong echo regions in hailstorms, but the CG flash density or CG flash rate were usually lower than those in common thunderstorms due to higher cloud top and frequent IC flashes.

Zheng et al. (2009) analyzed the characteristics of the lightning activity and electrical structure of a hailstorm in Beijing by using total lightning information from the SAFIR3000 3D lightning location system. The results indicated that the peak of the lightning rate came about five minutes prior to hail fall. Only 6.2% of the total lightning was CG flashes, among which 20% were positive. In the stage of hail fall, the electrical structure of the hailstorm was inverted, with the main negative charge region located around the $-40°C$ level and the main positive charge region around the $-15°C$ level. In addition, a weak negative charge region briefly existed below the positive charge region. After the hail fall, the electrical structure underwent fast and persistent adjustments and became a normal tripole structure. The lightning activity and electrical structure were closely related to the dynamic and microphysical processes of the hailstorm. It was believed that severe storms with stronger updrafts were more conducive to an inverted tripolar electrical structure than normal thunderstorms, and the inverted distribution could then facilitate more +CC lightning in the severe storms.

Data from the Beijing SAFIR 3000 lightning detection system and Doppler radar have also provided some insights into the 3D lightning structure and evolution of a leading-line and trailing-stratiform (LLTS) MCS over Beijing (Liu et al., 2011; 2013b). Most of the lightning in the LLTS-MCS was IC lightning. Using CG location data, Feng et al. (2006b) and Liu et al. (2008) also found that almost all the CG flashes were negative in the first developing stage, and the CG flash rate was high (more than 10 $min^{-1}$) and negative CG flashes were predominant during the mature stage of the MCS. The CG flash rate declined rapidly with the increase of the positive CG flash ratio in the dissipating stage. The majority of CG lightning occurred in the convective region of the radar echo, particularly at the leading edge of the front. Little IC and positive CG lightning occurred in the stratiform region. During the storm's development, most of the IC lightning occurred at an altitude of around 9.5 km above the ground and the IC lightning rate reached its maximum at 10.5 km above the ground, in the mature stage of the storm. When the thunderstorm began to dissipate, the altitude of the IC lightning decreased gradually. The spatial distribution of lightning was well correlated to the rainfall on the ground, although the peak value of rainfall appeared 75 min after the peak lightning rate (Liu et al., 2011). Convective region of the LLTS could be characterized by a tripole charge structure with a negative charge region in middle or a multi-layer charge structure with three layers of positive charge and a two-layer negative charge region in between (Liu et al., 2013a, b).

Feng et al. (2009) studied a typical squall line system with damaging wind and hailstones causing great economic loss. It was shown that positive CG flashes accounted for 54.7% of total CG flashes. During the initial developing stage, the CG flash rate was less than 0.5 $min^{-1}$ and most of the CG flashes were positive. It increased significantly, up to 4.5 $min^{-1}$, along with the rapid development of the squall line, and the percentage of positive CG to total CG was more than 75% during this period. The CG flash rate began to decrease but the percentage of negative CG flashes to the total increased gradually and exceeded that of positive CG during the mature and dissipating stages. positive CG flashes tended to occur on the right flank and negative ones on the left flank. Strong wind at the surface occurred in or near the regions with dense positive CG flashes. Almost all positive CG flashes occurred near the strong radar echo regions and in the front parts of the squall line. However, the negative CG flashes almost exclusively occurred in the regions with weak and uniform radar echoes. The total flash rate in the storm was very high, up to 136 $min^{-1}$, and the ratio of IC to CG flashes was 35:1. The CG distribution features in the squall line were obviously different from those of ordinary MCSs.

Zhang et al. (2006b) found that the charge structures in the main part (convective region) of two supercell thunderstorms were the inverted tripole type. The positive CG flash discharges occurred in the main part of the thunderstorms and originated from the positive charge region located in the middle part of the thunderstorms, while the negative CG flash discharges occurred in the anvil of the thunderstorm. The charge structure was the inverted dipole type in the anvil region due to the slant of the charge structure in the main region toward the anvil region. The negative charge region located in the upper part of the anvil produced many negative CG flash discharges.

Pan et al. (2009) examined the spatial and temporal distribution of lightning in seven typhoons over the Northwest Pacific using data from World Wide Lightning Location Network (WWLLN). They found three distinct flash activity regions in mature typhoons, a weak maximum in the eyewall regions (20–80 km from the center), a minimum between 80 and 200 km from the center, and a strong maximum in the outer rainbands ($>$ 200 km radius). The lightning in the outer rainbands was greater in frequency than that in the inner rainbands, and less than 1% of flashes occurred within 100 km of the center. Few lightning flashes occurred near the center after landfall. Each typhoon produced eyewall lightning outbreaks during its intensification period and before the maximum intensity, indicating that lightning activity might be used as an indicator of typhoon intensity change. Zhang et al. (2012e), using the CG location data, also confirmed this kind of lightning distribution in Typhoon. Pan et al. (2014) studied lightning in 69 tropical cyclones over Northwest Pacific, and found that in more than half of the weak (Category 1–3) and strong (Category 4–5) typhoons, the peak value of lightning usually occurred before the maximum wind speed was attained.

### 5.2. *Relationship of lightning with dynamical processes*

Liu et al. (2009) found that most flashes of hailstorms occurred in the region with temperature lower than $-40°$C, while dense positive CG flashes occurred in the region between $-40°$C and $-50°$C. Negative CG flashes occurred mostly in the relatively weak radar echo region, and positive CG flashes were distributed in the strong echo region, especially with a large gradient of echo intensity. The CG flashes tended to occur in the cloud region with reflectivity between 25 and 35 dB$Z$.

For the case of an MCS, Feng et al. (2006b) found that negative CG flashes mainly occurred in the region with temperature lower than $-50°$C and a high temperature gradient in the front of the MCS, especially in cloud with temperature lower than $-60°$C, but there were few CG flashes in the region with temperature higher than $-30°$C. The relationship between positive CG and negative CG flash number and cloud top brightness temperature could be fitted preferably by a three-power polynomial distribution. According to the appearance of peak values, the hourly flash rate lagged behind minimum brightness temperature and the area of cold cloud shield with temperature $< -45°$C lagged behind the hourly flash rate. The cloud top continued to extend horizontally shortly after the CG flash rate reached its maximum. Downburst and damaging winds were possibly produced when that the bow echo was associated with the jump in the CG flash rate.

Feng et al. (2009) found that dense positive CG flashes usually corresponded to updraft regions of the squall line system, and did not occur in the core of the updraft, but instead just behind and close to the main updraft. Negative CG flashes usually clustered in the intense echo ($>$ 40 dB$Z$) region and their duration coincided with the strong convection, which suggested that negative CG flashes could be used to indicate the strong convective region. Yuan and Qie (2010) also found that, for a squall line system, most lightning flashes occurred in the region of low brightness temperature, especially the region of lower than 200 K, and a few flashes could also be observed in the region of 240–260 K, which usually corresponded to the stratiform region of the squall line.

### 5.3. *Relationship of lightning with the precipitation structure of the thunderstorm*

Feng et al. (2007) found that the probability of lightning occurrence was 20 times higher in the convective region than in the stratiform region on the basis of TRMM data. The convective rain contributed much more rainfall to the total than stratiform rain, and the convective rain represented more than 85% of the total in two hailstorms. The results suggested that the vertical distribution of cloud water content, cloud ice water content and precipitation-sized ice content are helpful to judge the developing stage and to nowcast the weather system's evolution. A linear relationship between flash rate and ice water content was obtained, and its correlation coefficient was about 0.69. Most lightning flashes corresponded to regions with updraft at 5 km MSL, and the intensity of updrafts at 5 km MSL could be used as an indicator of lightning activity.

Yuan and Qie (2010) investigated lightning activity and its relationship with precipitation structure for a strong squall line over South China using TRMM satellite data. The results showed that most lightning flashes occurred near the strong convective region, and a few flashes occurred in the stratiform region of the squall line. There was a strong relationship between flash rate and ice precipitation content at 7–11 km MSL at the convective cell scale, and the correlation coefficient was 0.92. Yuan and Qie (2008) studied the lightning activity and precipitation characteristics during the South China Sea summer monsoon season, and found that when maximum radar reflectivity at 7 km MSL reached 36 dBZ, the probability of lightning occurrence was 50% in the pre-monsoon season, and increased to 38 dB$Z$ in the monsoon season. The flash rate of precipitation systems could be expressed as a function of maximum storm top height, maximum snow depth and minimum polarization corrected temperatures (PCTs). Among those, the most stable was the relationship between flash rate and maximum snow depth.

### 5.4. *Assimilation of lightning data and application in MCS*

With the accumulation of high quality lightning location data, lightning data assimilation has become an important research topic. Recently, Qie et al. (2014b) established empirical relations between total lightning flash rate and the ice particle (graupel, ice, and snow) mixing ratio. The constructed nudging functions were applied in a MCS simulation with the Weather Research and Forecasting (WRF) model. They found that the representation of convection was significantly improved one hour after the total lightning data assimilation, even during the assimilation period. The precipitation center, amount, and coverage were all much closer to the observation in the sensitivity run with lightning data assimilation than in the control run without lightning data assimilation. This simple and computationally inexpensive assimilation technique showed promising results and could be useful when the event is characterized by moderate to intense lightning activity, especially in the region where radar data is unavailable, for example in mountainous regions and over the oceans.

## 6. Effect on, and response of, lightning to climate change

The importance of lightning in climate studies has been increasingly recognized. The following three aspects in this field are reviewed: (1) the lightning climatology in China and its surrounding areas; (2) lightning-induced $NO_x$, which is very important not only for studies of atmospheric chemistry and climate change in both the free troposphere and planetary boundary layer, but also for understanding of the global nitrogen cycle; (3) the response of lightning to climate change.

### 6.1. *Lightning climatology in China and its surrounding areas*

Climatic characteristics of global or regional lightning activities have received much attention, and represent an active research topic. In the last decade, the variation of lightning activity in China has been studied using satellite-based LIS/OTD lightning data (Qie et al., 2003a, 2003b; Yuan and Qie, 2004; Ma et al., 2005a). There were four belts of lightning activity that run parallel to the seashore, near the sea region, central region, western region, and western boundary region. The lightning density distribution over mainland China showed a distinctive large-scale variation trend with distance from the coast and latitude, which was consistent with the annual mean precipitation variation trend. The Tibetan Plateau, China's three-step staircase topography and latitude are three important factors affecting lightning distribution. The irregular distribution of lightning density was closely related to the irregular distribution of ground thermal and dynamical forcing.

The lightning activity on the Tibetan Plateau exhibited a seasonal variation in which it mainly occurred from June to August with a maximum flash activity period from late June to mid-July (Qie et al., 2003c). The diurnal variation of flash rate peaked during 1400–1600 LST, with the exceptions of the prominent high mountainous regions, which peaked earlier, and the prominent low basins, which peaked later. The lightning flashes over the Plateau responded strongly to the topography and surface thermodynamic features. Toumi and Qie (2004) found that the thermodynamic parameters and rainfall obtained from meteorological reanalysis data were broadly consistent with the observed seasonal cycle of lightning on the Tibetan Plateau. However, there was more lightning in spring than one might expect from a simple relationship with rainfall, temperature or cloud buoyancy. The cloud buoyancy and rainfall showed a better seasonal relationship when they were multiplied by the ratio of the sensible to latent heat flux (the Bowen ratio). This suggested that sensible heat flux plays an important role, at least on the Tibetan Plateau, in modifying the efficiency of generating lightning from cloud buoyancy.

### 6.2. *Lightning-induced NOx*

The chemical processes in the troposphere caused by lightning activity are very important, and also complicated. Lightning discharges produce nitrogen oxides ($LNO_x$). It is expected that with an increase of temperature, the total amount of $LNO_x$ will also increase. However, due to the difficulty in measuring the exact amount of $NO_x$ generated by a single flash, it is difficult to assign a certain concentration of $NO_x$ to a specific lightning discharge in a specific storm.

Zhou and Qie (2002), utilizing $NO_x$ analyzer, observed the $NO_x$ evolution under conditions of a thunderstorm. The results showed that the peak values of the average volume mixing ratio of $NO_x$ in the air corresponded to the lightning flashes during the process of thunderstorm, but there were time lags between the peak values of volume mixing ratio of $NO_x$ and lightning flashes. The order of the transportation time of $NO_x$ generated by lightning could be fitted with a quadratic relationship, and the coefficient was rather high, but no strict linear relationship between the transportation time and distance was found (Zhou et al., 2005). Zhang et al. (2014d) used a 3D-space cell-gridded approach to extract the lighting channel from VHF lightning locations, and a relationship between the NO production per unit arc length and atmospheric pressure is applied to the $NO_x$ production. The average $NO_x$ productions per CG and IC flash were estimated to be $1.89 \times 10^{25}$ and $0.42 \times 10^{25}$ molecules, respectively, in northeastern Qinghai-Tibet Plateau. The average annual total production of $LNO_x$ in East Asia was about 2.30 Tg (Zhou et al., 2004).

Guo et al. (2006) discussed the transportation of $LNO_x$ by advection and turbulence in thunderclouds using a 3D dynamic–electrification coupled model. The results indicated that strong discharges were mostly located in the region of the upper edge of the middle negative charge region corresponding to the ambient region of updraft and center of the horizontal speed field. $LNO_x$ was transported by advection and turbulence after flowing out from the discharge channel, and formed a density center in the weak wind field. Due to the variety of lightning and thunderstorms, the parameters of lightning discharge (energy, length, peak current, channel tortuosity, initial altitude of leader, number of return strokes, etc.) also have a wide range of distribution. Therefore, the measurements in individual field experiments may not be reliable for extrapolating globally. The global amount of $NO_x$

produced by lightning and thunderstorms is still highly uncertain.

### 6.3. *Response of lightning to climate change*

Lightning activity, as a kind of extreme climate event, has drawn more attention in terms of its response to climate change. The global or regional relationships between lightning activity and some meteorological parameters, such as sea surface temperature, terrestrial surface temperature and relative humidity, have been examined based on lightning data observed by satellite-borne LIS/OTD and National Centers for Environmental Prediction (NCEP) meteorological data.

The responses of lightning flash rates to El Niño events and the interannual variation of surface wet bulb temperature and air temperature were studied by Ma et al. (2005b, 2005c). During the 1997/98 El Niño event, a relatively significant positive anomaly of lightning activity occurred in Asia/Australia and the Indian Ocean, and the maximum anomaly percentage reached 30% and 50%, respectively. One of the most sensitive positive anomaly areas was from southeastern China to the Indochina Peninsula, where the position of the anomaly center for each season during the El Niño, as compared with normal years, had a westward shift; and, especially in winter or spring, there was a simultaneous northward shift. In addition, analysis of the interannual variation in the lightning density anomaly percentage, convective precipitation and high convective available potential energy (CAPE) days showed that each one among the three anomaly percentages was correlative with the other for the positive anomaly zone, and that the response of lightning activity to the El Niño event was the most sensitive. In 1997 the anomaly percentage of the positive anomaly areas in winter reached 498%.

Research on whether global and regional lightning activity functions as a sensitive indicator of climate change has shown that, on the interannual time scale, the global total flash rate has had a positive response to the variation in global surface air temperature, with a sensitivity of 17% $K^{-1} \pm 7\%$ $K^{-1}$ (Ma et al., 2005b). Also, the seasonal mean flash rate of continents all over the world, and that of continents in the Northern Hemisphere, had a sensitive positive response to the increase in global surface air temperature and wet bulb temperature, with a sensitivity of about 13% $K^{-1} \pm 5\%$ $K^{-1}$. Although the increase in global lightning activity might serve as an indicator of the increase in global air temperature, this may not be the case on the regional scale.

Pan et al. (2013) found that the diurnal variation of lightning above the sea show two peak values, occurring in the afternoon and morning respectively. Xiong et al. (2005, 2006) found that higher relative humidity resulted in more lighting activity in dry regions and less lighting activity in wet regions. The watershed of relative humidity for lightning production was about 72%–74%. Yuan and Qie (2008) found that the lightning activity over the South China Sea began to enhance in April, peaked in May, and decreased after June. Compared to the pre-monsoon season, the mean cell-level flash rate decreased by 13% and the mean flash optical radiance increased by 15% during the monsoon season, respectively. The mean flash rate was higher during the pre-monsoon season. The vertical development of precipitation systems in the pre-monsoon season was also stronger than that in the monsoon season, meaning frequent lightning activity was consequently observed.

The relationships between lightning activity and a series of convective indices have been investigated using 10-yr LIS lightning data over nine monsoon-prone areas in which high-impact weather events are frequently observed (Dai et al., 2009). Correlation analysis for each study area showed that a higher lightning flash rate and lightning probability were associated with more unstable air and smaller vertical wind shear in a nearly saturated lower layer in most of the studied regions. However, the correlation varied from region to region. The best correlation between lightning activity and the convective indices was found in eastern and southern China, whereas correlation was worst in some inland or basin regions in which topographic effects were more significant.

Although many studies have revealed some objective facts that there exist certain correlations between climate change and lightning activity, the mechanisms and physical processes involved in these correlations remains unclear at present. The diurnal solar heating, the latitudinal temperature gradient, the general circulation of the atmosphere, the location of regions of convergence and divergence, static and baroclinic instabilities etc., all influence the global distribution of thunderstorms. From short time scales (hourly, daily, monthly and annual) there seems to be obvious positive correlation between tropical lightning activity and surface temperature, upper tropospheric water vapor, cloud cover, and anvil ice content. Whether these relationships exist on longer time scales is still uncertain, although climate models do support positive correlation between lightning and global temperature. Thus, with regard to research on the relationship between lightning and climate, not only the functions of temperature but also other factors should be taken into consideration.

As we know, increases in greenhouse gases can lead to climate change, which may increase the intensity of strong thunderstorms and lightning activity. Meanwhile, thunderstorms will increase the amount of water vapor and ice crystals in the upper troposphere. Due to the production of $NO_x$, lightning activity increases the amount of $O_3$ and thus further increases the amount of greenhouse gases in the atmosphere. Therefore, an increase in lightning activity may make the climate even warmer through this positive feedback mechanism. Aerosol correlates with thunderstorms and lightning activity, as well as with climate change. While aerosol influences climate change, it also influences the electrification process to some extent by changing cloud microphysical characteristics. With the development of global lightning detection techniques, long-term observations of global lightning activity have been realized, from which important information concerning strong convection can be obtained. Such information, through its relationships with certain climate parameters, could provide a useful reference and further promote the application of lightning data in climate change research.

## 7. Numerical simulations of thunderstorm electrification and lightning discharge

VHF observations of lightning discharges and multi-parameter radar provide important knowledge for understanding the interaction between lightning discharge behavior and dynamic and microphysical fields in thunderclouds. However, the problem is that no technology in the foreseeable future is capable of simultaneously observing all of the dynamic, microphysical processes and *E* fields in evolving thunderstorms with high enough temporal and spatial resolution to delineate all their significant behaviors and interactions. Numerical modeling is able to provide insight into thunderstorm electrification and discharge processes and help discriminate the interactions between dynamic, microphysical processes and lightning discharges.

### 7.1. *Lightning discharge simulation with a 2D fine-resolution lightning model*

A 2D fine-resolution (12.5 m) lightning model, which was modified according to a stochastic lightning parameterization model (Mansell et al., 2002), was developed by Tan et al. (2006a, 2006b, 2007). The lightning discharge and electrification scheme, including non-inductive and inductive charge electrification mechanisms, has been integrated into a 2D and 3D cumulus model. The hydrometeors considered in the model included cloud droplets, rain, ice crystals, snow, graupel and hail. The microphysical process and electrification within a 250 m resolution were simulated in the thunderstorm domain. The cloud charge distributions at the fine resolution (12.5 m) were derived through an interpolation technique before the initiation of the lighting discharge. Figure 3 in the paper by Tan et al. (2006a) shows a simulated IC flash and the corresponding charge distribution background with a tripole charge structure before the flash initiation. The bi-level branched channel structures, horizontal extension and maximum changes of vertical *E* field simulated by the fine-resolution lightning model were in good agreement with previous observational results than those from a coarser model. After IC flash initiation (black diamond) at the boundary between positive and negative potential zones, potential wells attracted the leaders of opposite polarities into the central area and prevented their outward expansion. It was possible for leaders to extend all throughout the opposite charge region, but they avoided the isolated charge area of the same polarity.

Tao et al. (2009) added a CG flash scheme into the above mentioned 2D fine-resolution model, and produced the fine branched channel structure of a CG flash with different types of cloud charge distributions, such as dipole, tripole, bi-dipole and multi-layer charge structures to describe the relationships between CG flash channel propagation features and cloud charge distribution. The model results showed that the induced charges of opposite polarity were deposited in local volumes where the bidirectional leaders passed during a CG flash discharge. These charges were finally embedded in the pre-existing positive and negative dispersed cloud charge zones. This sub-process caused a more complicated charge distribution in thunderclouds, like a “multi-layer cake”. Although the embedding only affected the charge structure in a pair of positive and negative charge regions immediately next to the ground, the electrostatic energy of a thundercloud was significantly consumed when the discharge terminated and the *E* field strength weakened acutely. It was suggested that the observed bipolar CG flash is possibly due to the intense changes in electrical potential and polarity reversal of induced charges caused by the contact of the downward leader channel to the ground.

The subsequent neutralization of the residual charges in the channel volumes with surrounding dispersed cloud charges during the IC and CG flash was also discussed by Tan et al. (2007) and Tao et al. (2009). It was found that some residual charges were deposited in the local volumes of cut-off and non-conducting leader channels after the lightning discharge terminated and these charges were gradually neutralized with surrounding dispersed cloud charges. This process should relate to the turbulence exchange, advection transport, and gravitational sedimentation etc. in thunderclouds. The simulation also indicated that potential at initiation point is a key to decide whether downward leader reaches ground (Tan et al., 2014). The absolute values of initiation potential of CG flashes are greater than 30 MV, while the absolute values of initiation potential of IC lightning are basically less than 30 MV. Since potential field is determined by space charge distributions, polarities and types of lightning discharges are also dependent on relative locations and magnitudes of positive and negative charge zones near initiation points.

### 7.2. *Simulation of charge structure with a 3D thunderstorm model*

A 3D dynamics and electrification coupled model was developed to investigate the characteristics of microphysics, dynamics and electrification inside thunderstorms (Sun et al., 2002). The model included a full treatment of small ions with attachment to six classes of hydrometeors (cloud drops, rain, ice, snow, graupel and hail), five electrification processes, which included ionic diffusion, electric attraction, inductive charging, non-inductive charging and secondary ice crystal charging. The larger precipitation particles were also forced by the vertical component of electrical force in electrically intensive thunderstorms. For the horizontal and vertical advection terms, fourth-order and second-order finite differences were used, and the super-relaxation method was used to determine electric potential. The model had the capacity to reproduce many of the observed characteristics of thunderstorms in dynamical, microphysical, and electrical aspects.

A regional thunderstorm model, coupled with two primary non-inductive electrification mechanisms, the Takahashi (1978) and Saunders et al. (1991) schemes, was developed and used to simulate a thunderstorm that occurred in Beijing, based on Regional Atmospheric Modeling System (RAMS) by Li et al. (2012) and Liu et al. (2014). The results were in agreement with some observations and results of other models. However, the evolution processes and shapes of cloud charge distribution in the two schemes were different. The result of Takahashi (1978) scheme produced a tripolar charge distribution in the cloud before the first lightning discharge. The Saunders et al. (1991) scheme produced a transformation from an inverted dipole distribution to a tripolar charge distribution. The results from both schemes showed that the positive charge carrier at a low level of a thunderstorm is rain droplets, that aggregates and graupel are located at high levels, and that the charge center distribution of graupel is similar to the distribution of total charge in the thunderstorm cloud. Zhou and Guo (2009) also developed a 3D numerical model for simulating the electrification and discharge processes in a hail storm and performed simulation tests.

The effects of electrification on microphysical and dynamical processes were examined by performing two numerical experiments, with and without electrification processes (Sun et al., 2002). The model results showed that, when electrification processes were included, the mass transfer among hydrometeors in microphysical processes, especially collection and coalescence processes, changed considerably as a result of significant modification of the terminal velocities of large precipitation particles. The change of mass transfer in microphysical processes affected cloud buoyancy by changing the amount and distribution of hydrometeors, and latent heat release in the middle region of the thunderstorm increased, i.e. convection strengthened by including electrification processes. The amount and diameter of solid precipitation particles at the surface increased because a stronger updraft sustained large precipitation particles and prevented them from falling out of the cloud earlier.

The spatial and temporal evolution of charge structure and the interactions between electrification, convection and rainfall have been studied numerically by Guo et al. (2007). The results indicated that the inductive and non-inductive charging mechanism played crucial roles in the evolution of electrical structure within thunderstorms, and the electrical development depended highly on ice-phase microphysical processes. The appearance time of the maximal $E$ field was the same as that of the maximal solid rainfall density and that of the maximal ascending velocity starting to decrease, but later than the maximal liquid rainfall density.

The effects of the temperature and relative humidity profile on the charge structure in thunderclouds have also been analyzed by Guo et al. (2003) and Zheng et al. (2007). In southern China, the value of convective available potential energy (CAPE) was large, and the main positive and negative charge centers were raised to a high level, before a dipole charge structure formed. The humidity could also affect the charge structure. Enhanced middle relative humidity would increase the instability of the whole thunderstorm. A dipole charge structure corresponded to a maximum midlayer humidity, and a quasi polarity-inverted charge structure to a minimum one. With reference to the effects of initial disturbance, it was noted that in the same temperature profiles, the lower maximum disturbing central potential temperature ($\Delta\theta_c$) corresponded to a weak thunderstorm and quasi polarity-inverted charge structure, while higher $\Delta\theta_c$ corresponded to a severe thunderstorm and dipole charge structure. For intermediate $\Delta\theta_c$ values, the storm had a tripole charge structure.

The effects of electrical activity on hail fall at the surface and hail growth during thunderstorms were simulated by Zhang et al. (2004b). The results indicated that, compared to during the non-electrification process, hail with charge and a strong $E$ field made precipitation increase by 50%. Furthermore, the average diameter of the hail particles was 0.7 mm larger, and the time of hail fall lagged by three minutes. Electrical activity mainly influenced the collection and melting process of hail. Since electrification and discharge processes are very complex, comparisons of simulated results with observed data of the $E$ field distribution and lightning features during thunderstorms are necessary.

### 7.3. *The flash rate simulated by numerical models at the thunderstorm scale*

The flash rate at the scale of the thunderstorm has been studied via numerical simulation. Assuming that the collision between ice crystals and rimed graupel particles was a dominant mechanism for charge separation in thunderstorms, Xie et al. (2005) studied the effect of two ice glaciation mechanisms of crystal (Fletcher and Hallett-Mossop glaciation) and liquid water content on flash rate. The results showed that there was a large disparity in ice crystal number concentration distribution with increased pressure and temperature in the two glaciation mechanisms, which directly resulted in a difference of electrical activity in the thundercloud. With an increase in liquid water content, the time of the first lightning flash would be delayed, the location of the breakdown process would be lower, and the lightning flash rate would decrease.

## 8. Lightning detection and location techniques

Knowledge on lightning relies on the progress of lightning detection technologies. EM radio-frequency detection is the main technology for detecting and locating lighting discharge sources, because lightning emits significant EM radiation covering a very broad range of frequencies, from below 1 Hz to almost 300 MHz. In the microwave band (300 MHz to 300 GHz), and even in the visible light band (about $10^{14}$ to $10^{15}$ Hz), lightning is also detectable. Although the durations of various lightning processes are very short, the processes produce rich observable EM radiation. Lightning detection and location techniques in the frequency band at very low frequency (VLF) (3–30 kHz), low frequency (LF)

(30–300 kHz), high frequency (HF) (3–30 MHz), VHF (30–300 MHz) and ultra-high frequency (UHF) (300–3000 MHz) ranges have been developed worldwide. Each physical process in a lightning flash is associated with its characteristic electric and magnetic field, so different techniques are used to detect different discharge processes. There are three EM radio-frequency location techniques that are most commonly used: magnetic direction finding (MDF), TOA, and interferometry. 2D/3D lightning location systems based on long-baseline and short-baseline TOA VHF radiation pulse location techniques, and broadband and narrowband VHF interferometric, have been developed successively for the purpose of lightning research and warning systems in the last decade in China.

### 8.1. *TOA-based VHF radiation pulse location techniques*

TOA technology locates the radiation pulses emitted from lightning discharges, by measuring the time of arrival of the individual VHF pulses from lightning to different receivers. TOA-based location systems can be divided into two types: long-baseline and short-baseline.

A 3D lightning mapping system based on TOA and GPS technology was developed in China by Zhang et al. (2010). The principle of system was similar to the LMA (Rison et al., 1999), but worked at 270 MHz with a bandwidth of 6 MHz and was composed of seven affiliated stations. The time and peak values were recorded every 25 µs. The digitization rate was 20 MHz. The 40 MHz high precision clock was synchronized and calibrated by 1 pulse-per-second (PPS) output of a GPS receiver. 3D images of lightning progression were obtained successfully for the first time in China by using this system. The location error was estimated to be less than 50 m.

Fast and slow antennas, which respectively detect the fast and slow $E$ field changes produced by lightning discharge processes with microsecond or sub-microsecond time resolution, are very useful in research on the physics of lightning. Multi-station observations of fast or slow antennas can also be used to locate lightning radiation sources using TOA technology. Through multi-station measurements of broadband slow antenna systems synchronized by GPS, some special features of lightning discharges in the eastern Tibetan Plateau were investigated by Qie et al. (2000a). The bandwidth of the slow antenna was 0.2 to 2 MHz and the decay time constant was about 5 s. The $E$ field change signals were digitized at a sampling rate of 1 MHz with an amplitude resolution of 12 bits. Five observation stations covered an area of $10 \times 10$ km. The K-type breakdown processes during one IC discharge were found to develop from the main negative charge region to the LPCC by using the TOA techniques. Wang et al. (2009a) developed a similar TOA algorithm-based lightning location system using a fast antenna system with a bandwidth of 0.1 to 5 MHz and a time constant of 2 ms. The system contained seven stations with baselines of several kilometers. The high time-resolution GPS with a timing accuracy of 50 ns was used to synchronize the signals from each station. Radiation pulses in the initial stages of five IC lightning discharges were well located in 3D, and the radiation sources were found to be nicely associated with the radar echo of the storm, indicating the technique could effectively locate the lightning radiation sources.

Zhang et al. (2003a) developed a short-baseline TOA lighting radiation detection system with antenna separation of 10 m, central frequency of 280 MHz and bandwidth of 6 MHz. The signals were recorded with a sampling rate of 2 GHz and a record length of 500 MB. The segmented triggering mode was used to resolve the conflict of a very high sampling rate and relatively small capacity. Cao et al. (2012) modified the hardware with wide-band receivers (125–200 MHz) and data processing software of the system. To reduce noise and improve estimation accuracy of time delay, a general correlation time delay estimation algorithm based on direct correlation method and wavelet transform was adopted by Sun et al. (2013). Moreover, parabolic interpolation algorithm was used in the fractional delay estimation to improve the time resolution of the positioning system. The location results for a rocket-triggered lightning and an IC lightning indicated that the modified short-baseline time-difference of arrival (TDOA) technology could effectively map the lightning radiation sources in 2D. Short-baseline TOA VHF radiation pulse location systems can only locate the azimuth and elevation of the lightning discharge sources occurring nearby. Time synchronization is not a problem in this kind of system, which is, in contrast, very critical in multi-station long-baseline systems. Therefore, the cost of this system is relatively cheap and suitable for locating local lightning discharges in some key areas. However, it nevertheless has some shortcomings, such as only providing 2D location information, its relatively large elevation location error, and relatively short detection range. Essentially, the short-baseline time-difference of arrival technology is interferometer.

### 8.2. *VHF/UHF interferometer lightning location systems*

Lightning usually produces some noise-like bursts of EM radiation lasting for tens to hundreds of microseconds. It is very difficult to identify individual pulses from these bursts. The interferometer measures the phase difference between the signals from different sensors, and provides an efficient way for locating the noise-like pulses. The VHF/UHF interferometer technique locates the azimuth and elevation of the radiation source by using three to four antennas with two orthogonal baselines. To locate the sources in 3D, two or more synchronized interferometers are needed.

Dong et al. (2001, 2002) developed a broadband interferometer system by employing three identical broadband antennas, which were separated horizontally with distances of 10 m. These antennas were located at three apexes of a square and all connected to a Digital Storage Oscilloscope (DSO) via a 50-m-long coaxial cable, terminated with characteristic impedance of 50 Ω and through 25 MHz high pass filters. The sampling rate was 1 GHz, and the memory of each channel was divided into 2000 segments. Each segment recorded up to 1000 points. By using this system, the positive leader and negative breakdown processes in artificially triggered lightning and bidirectional breakdown processes in natural lightning were observed (Dong et al., 2002, 2003). Qiu et al. (2009) proposed a phase filtering algorithm which combined circular correlation with translation-invariant de-noising for the VHF broadband interferometry. The application of this algorithm can produce clearer 2D images of lightning discharges than the conventional algorithm did.

For broadband interferometer systems, a high speed digitizer and a large capacity recording system are needed to record broadband signals. Generally, the segmented triggering mode for each event is used to reduce the capacity requirement, so it is hard to record the lightning flash continuously. Furthermore, it is difficult to have two or more completely identical coaxial cables for a broadband interferometer. Therefore, the system error of broadband interferometers could be a little larger than that of narrowband interferometers.

Zhang et al. (2008) developed a narrowband interferometer system using a five-antenna array consisting of short and long baselines along two orthogonal directions. The interferometer was operated at a central frequency of 280 MHz with a 3 dB bandwidth of 6 MHz. The signal received by the central antenna of the array was separately interfered with the signals from all the remaining antennas. These output signals were digitized with a sampling rate of 1 MHz and a resolution of 16 bits. The system error that arose from frequency conversion was reduced through phase detection by directly using high frequency amplifiers. An interactive graphic analysis procedure was used to remove the fringe ambiguities that exist inherently in interferometry and to determine the direction of lightning radiation sources in 2D as a function of time with a resolution in the order of microseconds.

## 9. Transient luminous events above thunderstorms

Transient luminous events (TLEs) are very short-lived discharges that occur above thunderstorms, e.g. sprites, elves and jets. These fleeting optical emissions in the mesosphere can initiate from the tops of thunderclouds up to the ionosphere, providing direct evidence of coupling from the lower atmosphere to the upper atmosphere. The first ground-based video recordings of sprites were obtained in northern America in 1989 (Franz et al., 1990). Since then, several ground- and aircraft-borne observations have been used to explore these kinds of discharges. In addition to sprites, another two types of discharges, termed elves and jets (blue jets, gigantic jets), were recorded. The term "Elves" refers to "Emission of Light and VLF" perturbations from an EM pulse (EMP) source, which appear as a ring (at 90 km altitude) and can spread laterally at the speed of light over 300 km. Blue jets emanate from the top of thunderclouds up to an altitude of 40 km. Gigantic jets propagate upwards from thunderclouds to altitudes of about 90 km (Su et al., 2003). Observations of TLEs have been conducted recently in China.

### 9.1. *Observational studies on sprites associated with lightning*

The Chinese Sprites Observation Campaign (CSOC), aimed at understanding the characteristics of sprites over mainland China and the relationships between sprites and lightning flashes, has been conducted since the summer of 2007. The first observation site is located in Zhanhua County, Shandong Province (37°49′42″N, 118°05′06″E). The camera system used in the campaign is Watec902H camera, and the field of view (FOV) of the observation system is 31.1° (horizontal) by 21.2° (vertical).

A total of 17 sprites were first observed over two thunderstorms in 2007 (Yang et al., 2008c). All of the observed sprites occurred in a cluster, and their appearances were different, including "columniform sprites", "columniform sprites" with angel-like wings, "carrot sprites", "dancing sprites", etc. The estimated bottom elevation of one of the columniform sprites was about $47 \pm 12$ km and the top was $86 \pm 15$ km. The vertical length of one of the carrot sprites was about 42 km, with the bottom at $39 \pm 10$ km and the top at $81 \pm 14$ km. The duration of the sprites varied from 40 ms to 160 ms, with a mean value of 61 ms.

Yang et al. (2013a, 2013b) studied the characteristics of sprite-producing and non-sprite-producing summer thunderstorms. They found that the average positive CG lightning peak current in sprite-producing storms was larger than that in the non-sprite-producing one. The convection was also stronger in sprite-generated thunderstorms, but there was no obvious difference in the microphysical characteristics. The parental CGs of sprites were positive and located in regions with a cloud top temperature of $-40$°C to $-60$°C and radar reflectivity of 15–35 dBZ. Most of the sprites appeared in the period characterized by a sharp decrease in negative CGs and an increase in positive CGs.

### 9.2. *Observational studies on Gigantic jets*

Gigantic jet is a type of large-scaled transient discharge which occurs above thunderstorms. It connects the thunderstorms and ionosphere directly. Compared with sprites, gigantic jet is very difficult to be observed from the ground. Yang and Feng (2012) reported a gigantic jet event in eastern China, near the Huanghai Sea. The top altitude of this gigantic jet was estimated to be about 89 km. The gigantic jet-producing storm was a multi-cell thunderstorm and the gigantic jet event occurred in the storm developing stage, with the maximum radar echo top around 17 km. Different from results from other countries that positive CGs dominated during the time period of gigantic jet. It is by far the furthest from the equator gigantic jet recorded over summer thunderstorm.

Although some studies on TLEs have been conducted in the past few years in China, more cases are needed to provide statistically reliable characteristics of TLEs and associated lightning and thunderstorms. There are also significant questions raised that deserve study in the years to come. One question is the influence of TLEs, especially in terms of quantitative estimations of the chemical effect on the mesosphere. Another question is the *E* field established by a lightning discharge; no existing model considers the complete *E* fields produced by CG and IC discharges. Furthermore, the influence of TLEs on Earth's environment and space weather should also be studied.

## 10. Concluding remarks

New understanding on the physics of lightning and thunderstorm electricity has been achieved during the last decade through continuous observations in some representative weather system 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 aspects of *in situ* soundings of thunderstorms and lightning mapping technologies. Progresses has also been achieved in the area of rocket-triggered lightning and its application. However, our understanding of lightning activity and atmospheric electricity is still limited and not satisfactory for lightning protection in the context of modern society. Some key questions remain unanswered, such as the predominant electrification mechanism in different thunderstorms with very different manifestations of precipitation, the connection processes between CG discharges and ground objects, the physical mechanism of sprites and narrow bipolar events, and the long-term response of lightning and the global circuit to temperature change. High quality detection of lightning, in association with thunderstorm microphysics and dynamics, and long-term data accumulation will serve as crucial measures.

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