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Progresses in the Atmospheric Electricity Researches in China during 2006–2010

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ABSTRACT

Atmospheric electricity is composed of a wide range of electric phenomena in the troposphere, stratosphere, and even lower ionosphere. Research progress on atmospheric electricity in the past 5 years in China are briefly reviewed here. This research area has been greatly expanded through rocket-triggered lightning experiments and the increased use of high spatio-temporal resolution techniques for the detection and location of lightning. The main results described in this review are summarized in the following five aspects: (1) processes and parameters inferred from rocket-triggered lightning, (2) lightning physics and effects (observations and theoretical study), (3) lightning activities associated with different thunderstorms, (4) charge structure of thunderstorms (observations and simulation), and (5) the VHF/UHF lightning location techniques and discharge channel mapping.

Key words: lightning physics, thunderstorm electricity, lightning meteorology, lightning climatology, lightning effects

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1. Introduction

Atmospheric electricity is composed of a wide range of electric phenomena in the troposphere, stratosphere, and even lower ionosphere. In recent years, atmospheric electricity has received more and more attention not only because of several new discovered phenomena (e.g., sprites, elves, jets, and terrestrial gamma-ray flashes, TGFs, etc) but also because of its importance in research on severe convective storms, climate change, lightning forecasting and protection, and so on. Research in atmospheric electricity in China has mainly focused on lightning and thunderstorm electricity in the past 5 years. Qie et al. (2006), reviewed progress in atmospheric electricity during the period 1996–2004. The paper gave special attention to the research on lightning discharges and electrical structure of thunderstorm. The knowledge of lightning and thunderstorm electricity has been stimulated in the past 5 years profited by new lighting detection technologies with high spatio-temporal resolution. In the present paper, research progresses in the lightning and thunderstorm electricity in China mainly from 2006 to 2010 are reviewed.

2. Processes and parameters inferred from rocket-triggered lightning

Rocket-triggered lightning experiments using the rocket-trailing-wire technique were conducted separately in Binzhou, Shandong Province since 2005 (e.g., Qie et al., 2007) and Conghua, Guangdong Province since 2006 (Li et al., 2010). A new model rocket for artificial triggering lightning was developed and introduced successfully in the recent experiments in China (Qie et al., 2010). The body of the rocket was made of composite material, and parachute was assembled inside the rocket for safety. The newly developed rocket for triggering lightning provided a crucial tool not only for the study of lightning and its effects but also for the data accumulation of lightning current waveforms, which is essential to lightning protection design. Two

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*Corresponding author: QIE Xiushu, qiex@mail.iap.ac.cn triggering techniques, classical and altitude triggering, have been used in these experiments. The classical triggering technique involves launching a small rocket trailing a thin, grounded copper wire toward the charged cloud overhead. In the altitude triggering technique, the rocket usually spools out 70–100 m of insulating nylon followed by several hundred meters of copper wire. The surface electric field was used to be a reference for launching the rocket, because the electric field aloft is hard to be measured although it is more indicative (Qie et al., 1994). The surface electric field was usually 5–10 kV m^{-1} when lightning was triggered successfully. All of the triggered lightning flashes were negative in Binzhou and Conghua.

2.1 *Discharge current and close electromagnetic field of triggered lightning*

The discharge current and close electromagnetic fields of lightning are two important parameters for understanding lightning physics and designing lightning protection. The current and corresponding close electromagnetic field were studied based on the data from the Shandong Artificially Triggering Lightning Experiment (SHATLE), which began in 2005 (e.g., Zhang et al., 2006a; 2007b; Qie et al., 2007; Zhao et al., 2009; Yang et al., 2010). According to Yang et al. (2010), the peak currents for 27 direct measured negative return strokes varied from 5.8 kA to 45.7 kA with a geometric mean (GM) of 14.1 kA. The GM of 10%–90% rise time, 30%–90% rise time, and half-peak width in current waveforms were consistent with most of the results found in the literature. Based on the Diendorfer and Uman (DU) model (Diendorfer and Uman, 1990), Zhang et al. (2009a) calculated the return-stroke current waveforms and charge distribution along the lightning channel. The simulated current waveforms, divided into breakdown and corona current components, were in agreement with the optical measurements when the two different discharge time constants were properly chosen.

Return strokes produce the most readily identifiable electromagnetic signature and the most serious lightning-induced damage. Yang et al. (2008a) analyzed the characteristics of induced voltage in a horizontal conductor due to a nearby lightning discharge with 9-dart leader/return stroke sequences. The measured voltage induced by the return strokes varied from 4.6 kV to 18.6 kV. The simulated results showed that the induced voltage on both ends of the horizontal conductor would increase with increasing return stroke velocity and with the increasing height of the horizontal conductor.

Yang et al. (2008b) developed a magnetic field measuring system with two rectangular loops perpendicular to each other and detected the total horizontal magnetic field produced by lightning discharges. The magnetic fields at 60 m varied from 18 μT to 148 μT with a GM of 52 μT. The peak value of the 10%–90% rise time in magnetic field waveform was between 1 μs and 2 μs, with a minimum of 0.4 μs and a maximum of 8.4 μs (Yang et al., 2010). The vertical electric field changes of the leader/return stroke sequences of triggered lightning discharges at 60 m and 550 m appeared to be asymmetrically V-shaped (Qie et al., 2009a; Zhang et al., 2009b). The electric field changes of the dart leaders at 60 m and 550 m were 17.9 kV m^{-1} and 1.3 kV m^{-1}, respectively, yielding a horizontal distance dependence of $d^{-1.18}$.

Zhang et al. (2011a) employed two existing models, a "source charge" leader model and a return-stroke model of modified transmission line model with linear current decay with height (MTLL), both based on the assumption of uniform leader charge distribution along the channel, where the charges deposited by the dart leader are completely neutralized by the following return-stroke process to simulate the V-shape structure characteristics of the close dart leader-per-return stroke field change. The simulated results show that the return-stroke electric field was inversely related to the return-stroke speed at the early stage (within few tens of microseconds of the beginning of the return stroke). At the later stage (after $\sim$100 μs) the field was dominated by the deposited charge density component; the close electric field was independent of speed; and the ratio of the leader field to the corresponding return-stroke field tended to be -1. Therefore, at the early stage there was often some uncertainty regarding whether the charges deposited by the dart leader were completely neutralized by the following return-stroke process, based on the difference between the return stroke and the leader field on the ground. However, although several other return-stroke models exist, the results shown in the paper are strictly valid only for the MTLL model.

2.2 *Discharge processes and inferred parameters associated with leader channel*

The triggered lightning starts with an initiation of upward positive leader. Lu et al. (2009a) found that the two-dimensional (2D) propagation speed of the upward positive leader in its inception phase was $\sim 3.8\times10^4$–5.5×10^4 m s^{-1} in an altitude-triggered lightning. The stable downward negative leader propagated with a 2D speed of $\sim 1.9\times10^5$ m s^{-1}, an average step length of $\sim$3 m, and time step varying from 6 μs to 31 μs, with a mean value of 15 μs. Yang et al. (2009) analyzed the initial discharge stages of two triggered flashes based on the synchronous data of the current and close electromagnetic field. Zheng et al. (2006) and Yang et al. (2006) calculated some parameters for artificially triggered lightning leaders based on the slow electric field change data during SHATLE. The results indicated that the line density of charge along the leader channel was from 49.3 mC m^{-1} to 130.0 mC m^{-1}, the average dart leader speed was from 0.23×10^7 m s^{-1} to 1.48×10^7 m s^{-1}, and the charge neutralized by subsequent return stroke was from 0.16 C to 1.21 C.

M-components are perturbations or transient enhancements in the continuing current, the associated channel luminosity, and the electromagnetic field changes. The M-components were analyzed on the basis of discharge current and the corresponding electromagnetic fields at 60 m and 550 m from the triggered lightning channel (Zhang et al., 2011b). The M-component current at the bottom of the channel exhibited a V-shape with a leading edge of 78 μs and a trailing edge of 194 μs, whereas the electric field pulses at 60 m and 550 m showed trailing edges faster than leading edges. The peak of the M-component current lagged behind the electric field peak by tens of microseconds. When the distance increased to 550 m, the disparity of the time shift increased as well. However, the wave shape of the M-component current was similar to that of the magnetic field pulse. The M-component electric fields at 60 m and 550 m were 1.16 kV m^{-1} and 0.17 kV m^{-1}, respectively, and they exhibited a logarithmic distance dependence, which implies that the M-component charge density increased with height. Large M-components with peak current in the range of kiloamperes were found in a rocket-triggered negative flash in SHATLE 2009 (Jiang et al., 2011; Qie et al., 2011). Among the 31 distinct current pulses, there were five large M-components with unusually large peak current in a range of kiloamperes. The GM value of peak current for the five large M-components was 5.1 kA; half peak width was 76.3 μs; charge transferred was 550 mC; and rise time from 10% to 90% peak was 34.6 μs, while the corresponding values for the 18 typical M-components were 243 A, 400 μs, 110 mC and 319 μs, respectively. A two-wave model was used to examine the sensitivity of the predicted electric and magnetic fields to the speed and current reflection coefficient variations of the M-component (Zhang et al., 2011b). The simulated results showed that the effects were different for the electric and magnetic fields. The M-component speed essentially controlled the electric field but had little effect on the magnetic field. Larger reflection coefficient resulted in a larger magnetic field but a smaller electric field.

3. Lightning physics and effects: Observation and theoretical study

In the past 5 years, field experiments of natural lightning aimed at understanding lightning physics and effects were conducted continuously, mainly using lightning location techniques and high-speed video cameras. Along with theoretical study, some new phenomena have been revealed and explained.

3.1 *New observational evidences on positive CG lightning flashes*

Positive CG lightning effectively lowers positive charge from the cloud to ground and accounts for ∼10% of all CG lightning discharges. Due to their relative paucity, positive CG lightning is considerably less studied and less well understood than negative CG lightning. Kong et al. (2008) reported one positive CG flash with a pronounced stepped leader. The 2D propagation speed increased from 0.1×10^5 m s^{-1} to 3.8×10^5 m s^{-1} as the leader approached the ground. Based on the high-speed images, Kong et al. (2008) suggested that positive CG lightning discharges can be produced by branching of in-cloud discharge channels, probably when these channels occur near or below the cloud base. High-speed video images of such flash can be found in Fig. 3 of Kong et al. (2008). Using the data from Lightning Mapping Array (LMA), Zhang et al. (2006b) found that the discharge process of positive CG lightning propagated at a velocity of 10^5 m s^{-1} in clouds, and the channels after the return stroke propagated at a velocity two times faster than that before the stroke. During the final stage, the lightning channels developed at a velocity equal to that before the stroke and the radiation points appeared mainly at the end of the channel.

3.2 *Some new insights into the stepped leader and grounding contacts*

Using the high-speed video camera with a time resolution higher than 1000 frame per second in correlation with broadband electric field change signatures, some new insights into the stepped leader in negative CG flashes have been documented (Qie and Kong, 2007; Lu et al., 2008a, b; Kong et al., 2009; Zhang et al., 2009e). Qie and Kong (2007) and Kong et al. (2009) studied the progression features of the stepped leader with multiple grounded branches in detail. High-speed video images of such flash that induced four return strokes in turn can be found in Fig. 1 of Qie and Kong (2007). The corresponding time differences between two adjacent peaks in the waveform of electric field change were ∼4 ms, ∼9 ms, and ∼10 ms, respectively. The one-dimensional distances between two adjacent terminations, estimated from the images, were 184 m, 245 m, and 490 m, respectively. The average 2D speed of the four branches was estimated to be $\sim 1.1\times10^5$ m s^{-1}.

Lu 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 that the branches were almost identical in terms of geographical mean (GM) value of 10%–90% rise time and half peak width, which were ~0.4 μs and 1.1 μs, respectively. With the propagation of the leader toward the ground, the light intensity just prior to each pulse exhibited an apparent tendency to increase. From the statistical analysis on the waveform signatures of 59 lightning first-return strokes, Kong et al. (2009) found that ~15.3% were characterized by two or more peaks separated in time by 4–486 μs, which means that one lightning flash could strike at more than one point, suggesting that it is necessary to revaluate the present lightning density distribution, which assumes that one lightning flash strikes only one point. Lu et al. (2009b) performed a study of two associated upward lightning flashes that involved two adjoining, tall, grounded objects with a time difference of ~45.8 ms; they suggested that one upward lightning flash can trigger other upward lightning of opposite polarity from nearby tall, grounded objects.

3.3 *The non-linear fractal nature of lightning discharge: analysis and simulation*

The fractal feature is one of the most fundamental aspects of dielectric breakdown. Gou et al. (2007) suggested that lightning could be regarded as a large-scale cooperative phenomenon and that it evolved in a self-similar cascaded way. Based on the electric field change waveforms recorded using the slow antenna system, Gou et al. (2006) found, using a technique of wavelet-based local effective Hölder exponent, that the Hölder exponents sharply decreased to their minimum with the occurrence of return stroke. The standard deviation of Hölder exponent reached its maximum just before return stroke. Gou et al. (2009) also found that the fractal dimension of the electric field waveforms ranged from 1.2 to 1.5 with an average of 1.3. Zhao and Zhang (2009) found that the tortuosity of lightning channel should be taken into account in the calculation of lightning electromagnetic field when the tortuosity of the channel was considered. Gou et al. (2010) presented the analysis of fractal dynamics of the lightning initiation process with a coherent approach, and they found an apparently correlated long-range time and nonlinear cascade behavior within the initiation breakdown process of the lightning. This result suggests that the initiation of lightning may be associated with progressive build up of correlated strong electrical field regions by self-similar scaling up (inverse cascading) of discharges across scales from small to large. The result may be a promising contribution to our understanding of lightning initiation.

Tan et al. (2006a, b; 2007) developed a 2D fine-resolution lightning model, including non-inductive and inductive charge-separation mechanisms. The bi-level branched channel structures and horizontal extension were well demonstrated. Intracloud (IC) lightning discharges were simulated in 12.5 m (fine) and 250 m (coarse) resolution for 2D domain using an improved stochastic lightning model. Simulation results indicated that the bi-level branched channel structure, horizontal extending ranges, and maximum vertical electric field changes obtained from a fine-resolution lightning model were in better agreement with previously observed data than those from a coarser model. The IC flash channels from a fine lightning model had the fractal feature with fractal dimension of 1.43, and the propagation tendency was dependent on the potential distribution. In addition, fine-resolution lightning modeling showed that, after IC flash initiation at the boundary between positive and negative potential zones, potential wells attracted the leaders of opposite polarity into the central area and prevented their outward expansion. Leaders could propagate throughout regions of net charge of the opposite polarity, but they avoided the isolated charge areas of the same polarity. Tao et al. (2009) added a CG lightning scheme into the 2D fine-resolution model, and produced the fine branched channel structure of CG lightning with different types of cloud charge distributions, such as dipole, tri-pole, bi-dipole and multi-layer charge structures. The simulation presents similar features of CG lightning as those observed in realistic bipolar CG lightning.

3.4 *Spectra and electron density of lightning discharge channel*

The spectra of discharge channels are closely related to the plasma properties and the temperature of the channels (Yuan et al., 2006). More lines of oxygen ion spectrum (OII) with high excited energy were found in the spectra of IC lightning discharges in comparison with that of CG flashes (Wang et al., 2009b). According to the relative intensities of spectra lines and transition parameters, the temperatures for individual lightning strokes and at different heights of the discharge channels were calculated using the multiple-line method reported by Ouyang et al. (2006). The result showed that the temperature in return stroke channels varied from 29 000 K to 36 000 K. Zhang et al. (2007a) calculated the electron density according to the Hamiltonian line Stark broadening formula. The electron density varied from 4.68×10^{17} cm^{-3} to 5.03×10^{17} cm^{-3}. Simultaneously, with the Saha equation, the electron density was found to be in the range of 9.03×10^{17}–17.5×10^{17} cm^{-3}. Generally, the more intense the lightning discharge, the higher the channel temperature, the higher the electron density, and the higher the relative concentration of highly ionized particles, but the lower the concentration of neutral atoms.

3.5 *Lightning-induced red sprite above thunderstorms*

Transient luminous events (TLEs), including sprites, elves, jets, halos and gigantic jets, are discharges that occur above thunderstorms and last for a very short time. These short-lived optical emissions in the mesosphere can be emitted from the tops of the thunderclouds and reach up to the ionosphere, providing direct evidence of coupling from the lower atmosphere to the upper atmosphere. The Chinese Sprites Observation Campaign (CSOC) has been conducted since the summer of 2007 (Yang et al., 2008c). All of the observed sprites occurred in clusters, and their appearances were different. The estimated bottom elevation of one columniform sprite cluster was ∼ 47±12 km, and the top was 86±15 km. The vertical length of one carrot sprite was ∼42 km, with the bottom at 39±10 km and the top at 81±14 km. The duration of the sprites varied from a minimum of 40 ms to a maximum of 160 ms, with a mean value of 61 ms. All of the parental flashes that produced sprites were positive CG flashes located in large stratiform precipitation regions with radar reflectivity between 20 dBZ and 40 dBZ. The time delay between the sprites and parental +CG flashes varied from 3.4 ms to 11.8 ms.

3.6 *Characteristics of narrow bipolar events (**NBEs**)*

NBE is a distinct class of IC lightning discharge, which is associated with the strongest radio frequency emissions and produces typical narrow bipolar radiation field waveforms. The three-dimensional (3D) propagation of this new type of lightning discharge was observed for the first time in China by Zhang et al. (2010). The NBP originated at an altitude of ∼10.5 km in the upper positive-charge region. As a distinct difference from normal IC flash, its channels extended horizontally all around and produced many radiation sources. The source power of an NBP can approach 16.7 kW, which is much greater than that of normal lightning discharge, which ranges between 100 mW and 500 W. On the basis of the transmission-line model, Zhu et al. (2010) 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. The method involved integrating over the initial half-cycle of 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, even though the current amplitude suffered heavy attenuation along the propagating channel. Wu et al. (2011), on the basis of a large number of negative and positive NBEs, which they named compact intracloud discharges (CIDs), found that negative CIDs produced larger electric field changes on average and were more isolated from other discharge processes compared to positive CIDs. The locating based on ionospheric reflection pairs of CIDs confirmed that negative CIDs do occur at higher altitudes. The percentage of negative CIDs seems to increase with the convective strength.

4. Lightning activities associated with different thunderstorms

Lightning flashes can indicate vigorous convection, and the understanding of lightning activity in different thunderstorms is important for convective research and severe weather forecasting. Researches regarding lightning activity and its relationship with dynamic process and precipitation structure in different severe convective weather systems were conducted actively over the past 5 years.

4.1 *Lightning characteristics associated with severe convective weather systems*

Studies of lighting characteristics in different severe convective weather systems, such as hailstorms, mesoscale convective systems (MCSs), and squall lines, were reviewed. Hailstorms usually present dominant +CG flashes during the period of hail fall (Feng et al., 2006a, 2007, 2008; Liu et al., 2009). The +CG took more than 45% of the total CG flashes in one Shandong hailstorm case (Feng et al., 2008), which was much higher than the climatic mean value (12.5%) in the region. Hail was often reported in the region of dense +CG lightning. Sometimes hailstones appeared slightly at the right flank of the dense CG lightning region. The peak −CG flash rate usually occurred 0 to 20 minutes earlier than the hail, but the peak +CG flash rate usually appeared at the time of or after the advent of hail. Based on the total lightning information from SAFIR3000 3D lightning location system in Beijing, Zheng et al. (2009) found that the peak of the lightning frequency occurred ∼5 minutes prior to the hail falling. Only 6.2% of the total lightning was CG lightning, among which 20% was positive.

Feng et al. (2006b) and Liu et al. (2008) analyzed the evolution of CG flashes in typical MCSs. They found that almost all the CG flashes were negative at the first developing stage. The CG flash rate was high (>10 flashes min^{-1}) and −CG flash predominated during the mature stage of the storm. The CG flash rate declined rapidly with the increase of +CG lightning ratio at the dissipating stage. During the whole lifetime of an MCS, most −CG flashes occurred in the strong convective echo regions with radar reflectivity stronger than 40 dBZ, and its duration nearly corresponded to the period of strong convection. The charge structures in the convective region of supercell thunderstorms were inverted tripole (Zhang et al., 2006c). The positive CG lightning discharges occurred in the main part of the thunderstorms and originated from the positive-charge region located at the middle of the thunderstorms, while the negative CG lightning discharges occurred in the anvils of the thunderstorms.

Feng et al. (2009) studied a typical squall line system with damaging wind and hail that caused great economic loss. It was shown that +CG flashes accounted for 54.7% of the total CG flashes. +CG flashes tended to occur on the right flank, and −CG flashes on the left flank. Strong wind at the surface occurred in or near the regions with dense +CG flashes. Almost all +CG flashes occurred near the strong radar echo regions and in the front parts of the squall line. However, the −CG flashes almost exclusively occurred in the regions with weak and uniform radar echoes. Liu et al. (2011), based on the Beijing SAFIR 3000 lightning detection system and Doppler radar data, found that most of the lightning in a leading-line and trailing-stratiform (LLTS) MCS was IC lightning, while the mean ratio of +CG to −CG lightning was 1:4. The majority of CG lightning occurred in the convective region of the radar echo, particularly at the leading edge of the front. The distribution of the CG lightning indicated that the storm had a tilted dipole structure given the wind shear or the tripole charge structure. During the storm's development, most of the IC lightning occurred at an altitude of ∼9.5 km; the lightning rate reached its maximum at 10.5 km, the altitude of IC lightning in the mature stage of the storm. The spatial distribution of lightning was well correlated with the rainfall on the ground, although the peak rainfall appeared 75 min later than the peak lightning rate.

Pan et al. (2009) studied the spatial and temporal distribution related to seven super-typhoons that occurred in the northwest Pacific Ocean during 2005–2008, on the basis of the World Wide Lightning Location Network (WWLLN) lightning data. There were three distinct flash activity regions in mature typhoons, a weak maximum in the eye-wall regions (20–80 km from the center), a minimum between 80 km and 200 km from the center, and a strong maximum in the outer rain-bands (>200 km radius). The lightning in the outer rain bands was more than that in the inner rain bands, and <1% of flashes occurred within 100 km. Few lightning flashes occurred near the center after landfall. Each typhoon produced an eye-wall lightning outbreak during its intensification period and before the maximum intensity. Super Typhoon Sepat (0709) produced two eyewall lightning outbreaks during the period of its intensification, and the second outbreak occurred 2 h prior to its maximum intensity (Pan and Qie, 2010), indicating that lightning activity might have been used as a proxy for typhoon intensity change. By combining the TRMM-LIS lightning data and TMI data, Pan and Qie (2010) also found that lightning was most likely to occur in the deep convective systems with a polarized brightness temperature lower than 225 K. Lightning areas indicated by WWLLN were similar to those indicated by Lightning Imaging Sensor (LIS) on board the Tropical Rainfall Measuring Mission (TRMM) satellite.

4.2 *Relationship of lightning to precipitation and dynamical processes*

Combing the ground-based Doppler radar and the cloud image from the Geostationary Meteorological Satellites (GMS), Liu et al. (2009) found that most flashes for the hailstorms occurred in regions with temperatures lower than −40°C, while dense +CG flashes occurred in regions between −40°C and −50°C. −CG flashes occurred mostly in the relative weak radar echo region, and +CG flashes were distributed in the strong echo region, especially with a large gradient of echo intensity. The comparison between the wind field retrieved from Doppler radar and the location of CG flashes indicated that the flashes were located in the convergent region at lower to middle levels. Feng et al. (2006b) found that the relationship between +CG and −CG flash number and cloud top brightness temperature in a MCS could be fitted preferably by a three-power polynomial. Feng et al. (2009) found that the dense +CG flashes usually corresponded to updraft regions of the squall line system and did not occur in the core of the updraft, but just behind and close to the main updraft instead. The rear in flow jet, between 3 and 6 km, had an important role in the formation of the bow echo and very strong wind at the surface. Yuan and Qie (2010) found that most of lightning flashes occurred in the region of low brightness temperature for the squall line system, especially the region lower than 200 K, and a few flashes were also observed in the region of 240–260 K, which usually corresponded to the stratiform region of squall lines.

Based on the TRMM-based LIS and Precipitation Radar (PR) data, Feng et al. (2007) found that the probability of lightning occurrence was 20 times higher in the convective region than in the stratiform region. The convective rain took more than 85% of the total in two hailstorms. The linear relationship between flash rate and ice-water content was obtained, and its correlation coefficient was 0.69. The intensity of updrafts at 5 km MSL could be used as an indicator of lightning activities. Yuan and Qie (2010) found that convective rains only occupied half of area of stratiform rains, but the former contributed much more rainfall to the total than the latter. Most lightning flashes occurred near the strong convective region, and a few flashes occurred in the stratiform region of the squall line. At 6 km MSL, most of the lightning flashes occurred in the echo region between 35 dBZ and 50 dBZ, and few flashes in the echo region were smaller than 30 dBZ. There was a strong relationship between flash rate and ice precipitation content at 7–11 km MSL at a convective cell scale. Yuan and Qie (2008) found that when maximum radar reflectivity at 7 km MSL reached 36 dBZ, the probability of lightning occurrence was 50% in the premonsoon season, and it increased to 38 dBZ in the monsoon season. The flash rate of precipitation systems could be expressed as functions of maximum storm top height, maximum snow depth, and minimum polarization-corrected temperatures (PCTs), respectively. Among those, the most stable was the relationship between flash rate and maximum snow depth.

4.3 *Responses of lightning to environmental thermo-dynamical characteristics*

Xiong et al. (2006) analyzed the responses of lightning activity to the surface relative humidity in global and regional scale using the LIS/OTD (Optical Transient Detector) lightning data and NCEP meteorological data from 1995 to 2002. The higher relative humidity resulted in more lighting activities over dry regions and less lighting activities over wet regions. The watershed of relative humidity for lightning production was ~72%–74%. The relationships between lightning activities and a series of convective indices were investigated using 10-year LIS lightning data over nine monsoon-prone areas (Dai et al., 2009). Correlation analyses for each study area showed that higher lightning flash rates and lightning probabilities were associated with more unstable air and smaller vertical wind shear in a nearly saturated lower layer in most of the studied regions. But the correlation varied from region to region. Ambient moisture had a more important role in the convective development of thunderstorms in southern China than in other regions.

On the basis of the observations of the TRMM-based PR and Microwave Imager (TMI) data from 1998 to 2005, Yuan and Qie (2008) investigated the lightning activity and precipitation characteristics before and after the onset of the South China Sea (SCS) summer monsoon. The results showed that the lightning activity over the SCS began to enhance in April, peaked in May, and decreased after June. Compared to the premonsoon season, mean cell-level flash rate decreased 13% and mean flash optical radiance increased 15% during the monsoon season, respectively. The mean flash rate was higher during the premonsoon season. The vertical development of precipitation systems in the premonsoon season was stronger than that in the monsoon season, and frequent lightning activity was observed as a result.

5. Charge structure inside thunderstorms: Observation and simulation

Charge structure of thunderstorms determines, to some extent, the lightning discharge characteristics and types. The thunderstorm over the Tibetan Plateau showed many special features because of its unique dynamic and thermodynamic effects. The thunderstorm electricity over the Tibetan plateau and its surrounding areas were continuously studied over the past 5 years.

5.1 *Thunderstorm electricity over the Tibetan plateau and its surrounding areas*

The thunderstorm electricity at four different plateau regions were studied, including Naqu, located at the central Tibetan Plateau (31°29′N, 92°03′E, 4508 m MSL), Datong at 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) at Gansu Province in the Chinese Loess Plateau (Kong et al., 2006; Qie et al., 2009b; Zhang et al., 2009c, d; Cui et al., 2009).

According to the polarity of surface electric field, the thunderstorms in the four regions were divided into two categories (Qie et al., 2009b). (1) Special-type: The surface electric field underneath most of the thunderstorms had the same polarity as the clear sky, i.e., the surface electric field was controlled by the positive charge inside thunderstorms (defined as positive here, but defined as negative in the paper of Qie et al., 2009b). Qie et al. (2005a; b) suggested that this kind of thunderstorm was characterized by an unusual tripole charge structure with a larger-than-usual lower positive charge center (LPCC) at the base of thunderstorm, and nearly all of the flashes were IC flashes that occurred in the lower dipole. (2) Normal-type: The surface electric field was negative when the thunderstorms were overhead, being consistent with the normal thunderstorm observed in the other prominent lower altitude regions in summer. This kind of thunderstorm also had a tripole charge structure, but the LPCC was weaker than that of the former.

The characteristics of the surface electric field of thunderstorms in the four plateau regions were similar to each other, but the percentages of occurrence of the two types of thunderstorms were different. The percentage of special-type thunderstorms increased with altitude. The special-type thunderstorms comprised ~73%, ~60%, ~54%, and ~46% of the totals in Nagqu, Datong, Zhongchuan and Pingliang region, respectively (Qie et al., 2009b). The special-type thunderstorms in the Chinese inland plateau were divided into three types according to Zhang et al. (2009b): (1) IC-dominated type: no CG flashes occurred; (2) −CG-dominated type: >50% of CG flashes were negative; (3) +CG-dominated type: the dominated CG flashes were positive. The flash rate was quite low compared with other lower-altitude regions (Zhang et al., 2009a, b). The mean flash rate was usually 1–3 flashes min^{-1}, and the maximum flash rate was $\leqslant 4-10$ flashes min^{-1} in these regions. The thunderstorm was usually characterized by isolated cells, and the electrification was not strong. Furthermore, the 0°C layer was lower, which is favorable for the development of clouds, but the updraft was weak. Therefore, the electrification was weak and low flash rate was observed as a result.

5.2 *Charge structure inside the thunderstorm in Chinese inland plateau regions*

Using the data from the electric field changes from a seven-site network of slow antennas synchronized by Global Position System (GPS) with 1-μs time resolution in the Zhongchuan region, Cui et al. (2009) found that both the upper dipole and lower dipole were the source of IC flashes. They analyzed 10 IC flashes and found the heights of IC discharge moments of the lower five IC flashes were located between 3.3–5.6 km MSL and 6.8–7.7 km MSL for the upper five, respectively. Analyzing 16 negative and 2 positive CG flashes in the Datong region, Zhang et al. (2009c) found that negative charge region located at a height of 5.5–8.0 km MSL with mostly ~6.5 km MSL and positive charge at a height of ~8.5 km MSL, respectively, indicating that the charge structure of special-type storms could be represented basically by a tripole but with a larger-than-usual LPCC.

The first electric field profile inside a special-type thunderstorm in Pingliang region using a balloon-borne electric field sounding system, based on the principle of point discharge, suggested that there were four charge regions with three layers inside the storm and one at the lower boundary of the storm (Zhao et al., 2009). The LPCC region was between 4.5 km and 5.3 km MSL (3°C to −2°C). The main negative charge layer was between 5.4 km and 6.6 km (−3°C to −10°C). The upper positive charge layer lied between 6.7 km and 7.2 km (−11°C to −14°C), and the negative screening layer lay at the lower boundary. The observation results confirmed the previously inferred conclusions that the thunderstorms in the plateau regions have a tripole charge structure with a larger-than-usual LPCC.

The large LPCC may have an important role in lightning discharges. Wang et al. (2009a) found that the preliminary discharge of the discharge in the Zhongchuan region developed from the middle negative charge region to the LPCC based on the location of pulses from a seven-station network of fast antennas. Qie et al. (2005b) found that the weak LPCC was conducive to the occurrence of negative CG flash, while the larger LPCC was conducive to the polarity-inverted IC flashes or negative CG flashes with longer preliminary discharge. By using the LMA results in STEPS, Zhang et al. (2009f) also found that existence of LPCC resulted in longer duration of preliminary breakdown process in negative CG lightning flashes.

5.3 *Numerical simulation on charge structure inside thunderstorm*

On the basis of previous studies, numerical simulation aimed at understanding thundercloud electrification was conducted. Guo et al. (2007a, b), used a 3D thunderstorm model coupled with dynamical and electrical processes and found that inductive and non-inductive charging mechanisms have a crucial role in the evolution of electrical structure within thunderstorms, and that electrical development depends highly on ice-phase microphysical processes. The appearance time of maximal electric field was the same as that of maximal solid rainfall density and maximal ascending velocity, but later than maximal liquid rainfall density and maximal ascending velocity. Zhou and Guo (2009a, b) developed a 3D numerical model to simulate the electrification and discharge processes in a hail storm. The effects of the temperature and relative humidity profile on the charge structure in thundercloud were also analyzed by 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, then dipole charge structure usually formed.

6. The VHF/UHF lightning location techniques and discharge channel mapping

The electromagnetic radiation fields radiated from lightning discharges have been measured in a wide frequency band (Zhu et al., 2007; Wang et al., 2007; Cao et al., 2008). The initiation and progression of lightning discharge channel can be tracked in 3D by locating the lightning VHF/UHF radiation pulse in a high time resolution. In the past 5 years, advanced lightning VHF/UHF radiation locating techniques were developed successively based on the time of arrival (TOA) and interferometric techniques in China.

6.1 *TOA-based long baseline lightning locating techniques in 3D*

TOA lightning location 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. A 3D location system of lightning VHF radiation pulses (LLR) based on TOA and GPS technology was developed by Zhang et al. (2010). The LLR works at 270 MHz with a bandwidth of 6 MHz. It is composed of seven affiliated stations. The time and peak values are recorded every 25 μs. The digitization rate is 20 MHz. The 40-MHz high-precision clock is synchronized and calibrated by 1 pulse-per-second (PPS) output of a GPS receiver. The location error was estimated to be <50 m.

The 3D-channel evolutions of typical negative CG, positive CG and IC lightning flashes were discussed in detail based on LLR results together with the data from fast electric field changes. The locations of lighting discharge channels were in good agreement with those depicted by lightning mapping array (LMA) (Zhang et al., 2006a). Significant differences were found between the negative and positive CG lightning flashes in terms of the initiation and propagation of the radiation sources (Zhang et al., 2010). The preliminary breakdown of a negative CG lightning flash propagated at a speed of $\sim 5.2\times10^4$ m s^{-1}. The stepped leader of negative CG lightning flashes was triggered by negative initial breakdown. Thereafter, it propagated downward at a speed of 1.3×10^5 m s^{-1}. The initial process of the positive CG lightning flashes was also a propagation process of negative streamer. These streamers dominantly propagated horizontally in the positive charge region and accumulated positive charges at the lightning origin and, as a consequence, initiated downward positive streamers.

Multi-station observation of fast or slow antennas was used to locate lightning radiation source using TOA algorithm-based technology. Through 7-station measurements of broadband slow antenna and fast antenna systems, with baselines of about several kilometers, synchronized by GPS, Wang et al. (2009a) studied the initial breakdown processes of five IC discharges. All of the stations were synchronized by GPS with a time resolution of ±50 ns. The time constant and the bandwidth of the fast antenna system were 2 ms and 1 kHz–5 MHz, respectively, and they were 6 s and 10 Hz–3 MHz for the slow antenna system. The sample rate of both fast and slow electric field change sensors were 2.5 MHz with a detection limit of ~25 km. Radiation pulses in the initial stages of five IC lightning discharges were well located in 3D, and they developed from the main negative charge region to the LPCC using the TOA techniques. The radiation sources were found to be well associated with the radar echo of the storm, indicating that the technique could effectively locate the lightning radiation sources.

6.2 *Very short baseline lightning VHF/UHF radiation locating systems*

Very-short baseline VHF/UHF lightning locating systems can be realized in one station with individual antennas 10 m apart or even nearer. The time synchronization is not necessary in this kind of system, which is, in contrast, very critical in multi-station, long-baseline systems. The very short baseline system usually utilizes the VHF/UHF interferometric technique, which has very good performance for the noise-like bursts of electromagnetic radiation.

The interferometer measures the phase difference between the signals from different antennas. The VHF/UHF interferometer technique locates the azimuth and elevation of the radiation source using 4–5 antennas with two orthogonal baselines. To locate the sources in 3D, two or more synchronized interferometers are needed. Zhang et al. (2008) developed a narrowband interferometer system using a five-antenna array which consisted of short ($\lambda/2$)- and long (4λ)-baselines along two orthogonal directions. The interferometer was operated at a center frequency of 280 MHz with a 3 dB bandwidth of 6 MHz. The signal received by the center antenna of the array interfered, respectively, with the signals from all of the remaining antennas. These output signals were digitized with a sampling rate of 1 MHz and a resolution of 16 bits. The system error, which came 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, which existed inherently in interferometry, and to determine the direction of lightning radiation sources in two dimensions (azimuth and elevation) as a function of time with a time resolution of microseconds.

With the narrowband interferometer system, the whole progression process in time and space of a negative CG flash was reconstructed (Zhang et al., 2008). It was found that the preliminary breakdown event of the CG flash started from negative charge region and exhibited first a downward progression and then an upward propagation. Very intense and continuous radiations during stepped leaders became much stronger when the first return stroke began. In contrast, there were less and only discrete radiations during dart leaders. Stepped leader and dart leader may transform to each other depending on the state of the ionization of the path. The progression speed of initial stepped leaders was $\sim 10^5$ m s^{-1}, while that value was $\sim 4.1\times 10^6$ for dart leaders. M events produced hook-shaped field changes accompanied by active bursts of radiation at their beginnings. Following these active radiation processes, M events appeared to contact finally into conducting main discharge channels. The mean progression speed of M events was $\sim 7\times 10^7$ m s^{-1}, greater than that of the dart leaders and dart-step leaders. K events and attempted leaders were essentially the same as dart leaders, except that they could not reach the ground and initiate return strokes.

Qiu et al. (2009) proposed a phase filtering algorithm which combined circular correlation with translation-invariant denoising for a broadband interferometer. The system consisted of four broadband, circular, flat antennas aligning at four apexes of a square with a baseline of 15 m. The antennas had a flat amplitude-frequency response within 20–300 MHz, and they were connected to a digitizer through high-pass filters (>25 MHz). Frequency range within 30 to 300 MHz was used for lightning location. The broadband dE/dt pulses were digitized by a LeCroy 7100 at 1 GS per second sampling rate and 8-bit resolution. Three channels of the signals were used to locate radiation sources. The digitizer memory was divided into 4000 segments, with each recording 2 ms and a dead time <1 ms between segments. The application of the phase-filtering algorithm to a segment of observational data showed that it did a much better job in recovering the phase spectra than other techniques. Simulated data distorted by the addition of random noise were also used to illustrate the improvements of the method in resolving incident angle, which was compared with other wavelet-based threshold techniques and the conventional Fourier transform-based cross-correlation method. It was revealed that this algorithm could be utilized to retrieve well-defined paths which were not discerned by conventional method, and depict the branches more clearly and precisely.

7. Summary

Over the past 5 years the interest in atmospheric research has continuously grown in China, both in observations and in numerical simulation. The important goals of atmospheric research suggested for the near future are: (1) continuous development of the state of the art lightning detection technologies in high temporal and spatial resolution to reveal concisely lightning physics and mechanism, (2) the application study of lightning data in monitoring and forecasting of severe convective weather, (3) adequate parameterizations of lightning in mesoscale weather model and lightning forecasting, (4) TLEs observation and physical mechanism, (5) the response of lightning activity to climate change, (6) satellite or space station-borne missions for monitoring lightning activity in the global scale.

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