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Observation and analysis of electrical structure change and diversity in thunderstorms on the Qinghai-Tibet Plateau

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ABSTRACT

A comprehensive observation on thunderstorms was conducted in the Qinghai area by using a very high frequency three-dimensional lightning mapping system and Doppler radar. The spatio-temporal evolution of the charge structure of the isolated thunderstorm was analyzed according to the developing process of thunderstorm, and the reasons for the change in charge structure diversity were studied. During the initial developing and mature stages of the thunderstorm, the charge structure was a steady negative dipole polarity, i.e., the negative charge region was above the positive charge region. Furthermore, the total number of flashes was lower during these two stages. During the thunderstorm's dissipation stage, the charge structure was varied and complicated, with a positive dipole, negative dipole, and a tripole charge structure changing and coexisting during this stage. This charge structure diversity was primarily caused by the collision and merging of two local thunderstorm cells, leading to a charge rearrangement and distribution and the formation of a new charge structure. The frequency of the negative cloud-to-ground and intracloud flashes increased sharply in the dissipation stage, reaching a maximum value. The increase in frequency of negative cloud-to-ground was mainly caused by the lower positive charge weakening during the dissipation stage. In addition, the relationship between charging regions and temperature layers was analyzed by combining sounding temperature data with the theory of a non-inductive charging mechanism.

1. Introduction

Many studies have shown that the charge structure of thunderstorms on the Qinghai-Tibet Plateau and other Chinese inland plateaus is peculiar. First, multiple-station ground electric field observations on Chinese inland plateaus since the 1980s have shown that a large lower positive charge region typically exists at the base of the thundercloud (Ye et al., 1980; Liu et al., 1987; Wang et al., 1990). Second, studies of the location of the charge moment neutralized by lightning discharges suggest a tripole charge structure often occurs, but with a larger than usual lower positive charge center (LPCC) at the base of some thunderclouds (Qie et al., 2005a, 2005b, 2009; Zhang et al., 2009). Zhao et al. (2010) used a corona probe sounding system to measure the electric field with GPS observations, verifying the above characteristics of Chinese inland plateau thunderclouds. While these and other studies determined some characteristics through observation, most of the observations were limited. However, the charge structure of a thunderstorm can change many times during the temporal development of a thunderstorm and in different ways depending on the type of thunderstorm. Therefore, more details and real time observation data are needed to understand the spatio-temporal evolution of the electric structure of an entire thunderstorm or of different types of thunderclouds.

With the widespread use of a very high frequency (VHF) lightning mapping system for comprehensive lightning observations in Qinghai Province, China beginning in 2009 (Zhang et al., 2010, 2015), it is possible to observe that the charge structure, lightning flash frequency, and type of lightning flash are very different in the various stages of thunderstorm development, especially in the later stage of a thunderstorm where a quite diverse charge structure occurs that has four charge layers (Li et al., 2013). Others (Wiens et al., 2005) have also reported similar results in other regions, with various reasons discussed (Tessendorf et al., 2005; Weiss et al., 2008). Weiss et al. (2008) used LMA (lightning mapping array) data and sounding data from a balloon-borne electric field meter to analyze a multicell storm charge structure. The results indicated that the charge structure was very complicated,

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with the most complex lightning structures corresponding to the parts of the storm with the largest reflectivity values and the deepest reflectivity cores, and the complexity of the storm was also enhanced by the merger of storm cells. Sullivan et al. (2014) also analyzed the charge structure of a multicell storm, and discussed the possible reasons for the development of an inverted charge structure. Moreover, the formation of charge structure is related to the environment. Arechiga et al. (2014) referred to the − 40 °C level, which corresponds to the top of the mixed phase region in the cloud, and has shown that the charge structure of a flash is mainly distributed through the 0 ~ − 40 °C temperature layer. Results from Bruning et al.'s (2014) study indicated that the depletion of supercooled water is a primary control of electrification. The atmospheric stratification of Qinghai-Tibet Plateau storms is very different from that of a plains storm. Thunderstorms on the plateau are usually unstable over whole layers, up to a height of 100 hPa, and possess low unstable energy. This special stratification reveals the particular structure of thunderstorms on the plateau (Zhang et al., 2005). The developing intensity of such thunderstorms is characterized by its lightning frequency. In addition, the evolution of charge structure has a very important correlation to lightning activity. The biggest advantage of three-dimensional (3D) lightning mapping systems is the temporal continuity maintained for each lightning flash observation and lightning discharge process through the high time resolution of the lightning mapping data. This makes it possible to more accurately track the charge structure evolution of an entire thunderstorm by accumulating observations of lightning radiation sources over time.

In this work, a 3D lightning radiation source mapping system (Zhang et al., 2010), Doppler radar data, and ground precipitation observation data in Qinghai Province, China, are used to analyze the precipitation process, charge structure evolution, and lightning discharge characteristics of a thunderstorm from 29 July 2011, in order to analyze the relationship between the storm's charge structure and lightning activity. Radar echo are also analyzed. The purpose of this paper is to determine the reasons for charge structure diversity found in thunderstorms in the Qinghai-Tibet Plateau.

2. Data and methodology

2.1. Instrumentation and data

Each summer from 2009 to 2015, this group conducted comprehensive observation experiments on lightning in Datong, Qinghai Province, China, which lies on the northeastern verge of the Qinghai-Tibet Plateau. The climate of this region can be classified as a plateau continental climate such as drying, less rain, cold and so on. Because there are a considerable number of mountains and valleys, there are considerable elevation changes in the region. Because of this topography, storms usually occur in summer, with some even accompanied by destructive hail. To observe these storms, an observation net consisting of seven stations distributed over an area of about 15 km in diameter was built (shown in Fig. 1 as black circles). Station elevations range from 2482.64 m to 2733.89 m. Mingde is the central station, located at E101.6201247°, N37.0132569° at a ground elevation of 2496.24 m, with the other six affiliated stations set up in a radial pattern (Zhang et al., 2015; Li et al., 2013; Wu et al., 2016). Each station is equipped with sensors for the 3D lightning VHF radiation source mapping system and the 3D broadband electric field mapping system.

The 3D lightning VHF radiation source mapping system was operated at a center frequency of 270 MHz with a 3 dB bandwidth of 6 MHz (Zhang et al., 2010). The received 3D broadband electric field signal was processed using a digital filter, with a resulting bandwidth of 1.5 kHz to 10 MHz, and with a time constant of 100 μs. The two systems synchronously received the radiation pulse signals produced by a lightning discharge, then measured the arrival times of the impulsive radiation event of the lightning discharge at each remote location using GPS technology. The peak value event resolution was 50 ns, and all impulses with a value larger than the background noise power were recorded. The two systems dealt with one peak value event in each successive 50 μs time window, with the radiation source position for each peak value event calculated used a nonlinear least squares method.

The location error of the 3D lightning radiation source mapping system has been calculated by Zhang et al. (2015) using information from a balloon-borne VHF transmitter flight path and geometric models. For radiation sources inside the network, the mapping system has an error of 12–48 m (root-mean-square, or rms) of horizontal uncertainty and 20–78 m (rms) of vertical uncertainty. For radiation sources outside the network, the range and altitude errors increase as a function of the range squared.

Besides the mapping system, a fast antenna (bandwidth of 160 Hz–5 MHz, time constant 1 ms, measuring range ± 2 kV/m) and a slow antenna (bandwidth of 0.03 Hz–2 MHz, time constant 6 s, measuring range ± 8 kV/m and ± 16 kV/m) were used to measure the electric field changes of each lightning discharge with a time resolution of 0.1 μs. These signals were synchronized by a triggering signal from the fast antenna. All seven stations were connected through a wireless broadband communication system. Data collection was controlled by a triggering signal sent either manually or automatically from the central station. The time was recorded using a 20 MHz high precision clock synchronized by GPS.

In addition to all of the station data, radar echo information from a C-band (5 cm) new generation Doppler weather radar (CINRAD/CC) 48.93 km away from the central station was available for the present study. The precipitation data and sounding data were provided by the Miaopu station of regional automatic station (the red circle in Fig. 1 Miaopu observation station) of the Datong Meteorological Bureau and the Xining sounding stations (35 km from the central station), respectively. This paper uses the distance and height base of the central Mingde station as the origin for coordinates. All of the elevations are above ground altitude (AGL).

2.2. Method of charge structure analysis

A 3D lightning VHF radiation source mapping system can continuously observe the 3D spatio-temporal evolutionary process of lightning discharge radiation sources in a thunderstorm. This data allows the direction of the preliminary breakdown process (up and down) to be determined for each lightning discharge. The charge structure is then inferred based on the bidirectional leader model that was proposed by Kasemir (1960) and described by Mazur and Ruhnke (1993). In this model, once a lightning discharge initiates in the strong electric field between regions of net positive and negative charge, it propagates in opposite directions from the discharge origin, producing a negative breakdown and a positive breakdown, respectively, at its two front sides. As described by Mazur and Ruhnke (1993), a positive charge region is generally penetrated by the negative breakdown, and a negative charge region is penetrated by the positive breakdown. Moreover, as described in Thomas et al. (2001), the negative breakdown is inherently noisier than the positive breakdown at the radio frequencies used by VHF measurement instruments, which means the number of radiation sources produced by the negative breakdown in the positive charge region are far more than the positive breakdown in the negative charge region and the negative breakdown is brighter. Thus, observations of a given flash will give a relatively greater number of radiation sources from the positive charge region, which makes it easier to determine the positive charge region. In addition, the negative charge regions are inferred when negative leaders retrace the path of the quieter positive leader. Mazur and Ruhnke (1993) described this retracing of the positive leader channel by negative breakdown seems to correspond to the recoil streamers. By studying the direction and the sequence of channel development and the density of mapped points