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Possible role of aerosols in the charge structure of isolated thunderstorms

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ABSTRACT

The electric field and Maxwell current density measured below 32 small isolated thunderstorms over Pune (India) have been analyzed here. These data clearly show the presence of 10 out of 32 thunderstorms with inverted polarity charge structure. Values of Aerosol Optical Depth (AOD) on thunderstorm days taken from MODIS show that all the thunderstorms with inverted polarity occurred on days with significantly higher AOD compared to normal polarity thunderstorms. The peak flash rate did not show significant difference between normal polarity thunderstorms and inverted polarity thunderstorms. The dew point depression (DPD) during pre-monsoon thunderstorms shows good correlation with inverted polarity charge structure. Observations suggest that aerosol concentration plays an important role in the formation of inverted polarity charge structure in these thunderclouds. In presence of high aerosol concentration with adequate ice nuclei non-inductive charging mechanism can produce strong and wide spread positive charge region in the lower portion of cloud. However, observed good correlation of DPD with inverted polarity charge structure in the pre-monsoon period suggest that the effect of high cloud base height on inverted polarity charge structure as suggested by Williams et al. (2005) cannot be ruled out.

1. Introduction

Wilson (1920) first proposed a positive dipole charge structure in thunderclouds i.e. positive charge in the upper part and negative charge below it. Subsequently, many measurements confirmed that most of thunderclouds have three charge regions generated by charge generation processes i.e. a positive charge region in the upper portion of cloud, negative charge region in the middle level and small localized positive charge in the lower portion of cloud (Simpson and Scrase, 1937; Simpson and Robinson, 1941; MacCready and Proudfit, 1965; Marshall and Winn, 1982; Marshall and Stolzenburg, 1998; Bateman et al., 1999; Mo et al., 2002; Coleman et al., 2003; Williams, 1989). Williams (1989) summarized that thunderstorms have tripole charge structure with different emphasis given to the lower positive charge centers (LPCC). Different theories have been proposed to explain the formation of LPCC in thunderclouds such as drop breakup theory, charging associated with ice melting, or charge deposited by lightning. However, as explained by Williams (1989) the most satisfactory explanation for formation of LPCC is charge reversal microphysics. According to this hypothesis, positive charge is transferred to graupel at temperatures higher than reversal temperature.

It is also known for a long time that some thunderstorms can have different charge structure than generally observed in the typical thunderstorms (Vonnegut and Moore, 1958). During the Severe Thunderstorm Electrification and Precipitation Study (STEPS), Rust and MacGorman (2002), Rust et al. (2005), Lang et al. (2004) and Wiens et al. (2005) have reported some severe storms with consistent dominant upper level inverted dipole charge structure near the updraft (i.e. upper negative charge region and positive charge region below it). Lang et al. (2004) have reported that most of the thunderstorms during STEPS produced some sort of severe weather, and at least half of them were associated with more than 50% positive Cloud-to-Ground (CG) lightning. Further, they observed that in some of the severe thunderstorms, peak hourly fractions of positive CG lightning were greater than 90%. Based on electric field profiling and lightning mapping array data, Rust and MacGorman (2002), Hamlin et al. (2003) and Rust et al. (2005) suggested that severe thunderstorms which produced predominant positive CG during STEPS were associated with inverted polarity charge structures (i.e.) positive charge region in the midlevel and negative charge above it. MacGorman and Burgess (1994); Stolzenburg (1994); Carey and Rutledge (1998); Lang et al. (2000); Carey et al. (2003) have reported severe thunderstorms which produced positive Cloud-to-Ground (CG) flash rates comparable to negative CG flash rate. There are some reports of inverted polarity thunderstorms that are not associated with severe weather. During STEPS, Lang et al. (2004) have reported one non-severe thunderstorm with inverted polarity charge structure. Furthermore, Liu et al. (1989), Qie et al. (2005), Qie et al. (2009), Pawar and Kamra (2004, 2009) and Gopalakrishnan et al. (2011) have reported some non-severe thunderstorms, over the Tibetan Plateau and over the Indian region with wide

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spread and dominant positive charge in the lower portion of cloud. Qie et al. (2009) have studied the electrical characteristics of thunderstorms in four plateau regions with different elevations. They found that some thunderstorms forming over that region have strong and wide spread lower positive charge. They also observed that the thunderstorms with strong lower positive charge region were more frequent over highly elevated region and occurred when environment is drier than normal.

In the case of Pawar and Kamra (2004, 2009) and Gopalakrishnan et al. (2011) more than 80% of lightning activity arises from the lower negative dipole of these thunderclouds. These thunderstorms also can also be termed as "inverted polarity thunderstorms" because, for more than 50% of the lifetime of the thunderstorms, lower negative dipoles dominate the lightning activity of the storm. Studies by Marshall et al. (1995), Rust and MacGorman (2002) and Rust et al. (2005) suggest that some non-severe thunderstorm can have inverted polarity charge structure. It is worth to mention that some winter storms developing in large vertical wind shear can have tilted dipole charge structure with displaced upper positive charge region, which can produce positive CG strokes (Brook et al., 1982; Levin et al., 1996). However, such storms cannot be termed as inverted polarity storms. Bruning et al. (2014) have analyzed all the reports of inverted polarity thunderstorms and have shown that variability in non-inductive charge generation mechanism can continuously vary the electrification and charge structure in strong updrafts. They also emphasised that two- or three-dimensional storm flows or other electrification mechanisms are required to combine one or more of these electrification regimes into "inverted" or otherwise complicated local charge sequences.

The effect of aerosol on cloud microphysical, dynamical and electrical properties of cloud has been the subject of many research papers in recent years. Rosenfeld (1999) and Rosenfeld and Woodley (2003) have shown that the increase in aerosol can reduce the droplet size which can result in reduced precipitation in shallow clouds. However, many observations suggest that under some favorable conditions of strong instability and high humidity, the increase in aerosol concentration may enhance the convection which may result in increased precipitation (Andreae et al., 2004; Bell et al., 2008; Rosenfeld et al., 2008). Williams et al. (2002) suggested that the increased aerosol concentration can reduce mean droplet size, a suppression of warm rain coalescence and an enhancement of the cloud water reaching the mixed phase region, which can increase the lightning activity. Many observations which have shown that the increased precipitation and lightning activity over big cities support this idea (Orville et al., 2001; Steiger et al., 2002; Naccarato et al., 2003; Pinto et al., 2004). However, the observed increasing lightning activity over big cities can also be attributed to changed thermodynamic conditions due to heat island effect (Khain et al., 2008; Farias et al., 2009; Kar et al., 2009; Lal and Pawar, 2010). However, some studies show that higher aerosol concentration can have a negative effect on lightning activity in thunderstorms. Smith et al. (2003) compared the lightning characteristics of thunderstorms in the northwestern US after the fires of 2000 with those of storms in the Great Plains after the 1998 fires and found that the 2000 fires were not accompanied by significant lightning anomalies. Williams et al. (2002) who studied cloud electrification in the Amazon showed evidence for weaker than average clouds electrification for extreme polluted conditions in the early pre-monsoon period (October). Altaratz et al. (2010) studied the effect of smoke on electrical activity in the Amazon region and found that for low aerosol loading the increase in CCN concentration produces invigoration in electrical activity, while for higher values of aerosol loading the electrical activity decreases. Some studies have shown that aerosols not only effect a change in lightning flash rate but also the polarity of charge generation processes inside thunderclouds. Studies by Lyons et al. (1998), Murray et al. (2000), Fernandes et al. (2006) and Rosenfeld et al. (2007) have shown higher rates of positive cloud to ground flashes with high peak currents, in the presence of smoke from forest fires. These studies attributed the reversed polarity of graupel charging to the effect of reduced droplet size in the laboratory experiments.

Williams et al. (2005) proposed that the inverted polarity charge structure in thunderstorms is a result of superlative liquid water content in the mixed phase region. Williams et al. (2005) also show many evidences that higher cloud base heights are connected to inverted polarity thunderstorms. Studies by Liu et al. (1989) and Qie et al. (2005) also show that high cloud base height is associated with inverted polarity thunderstorms. A possible physical basis for the association of higher cloud base height with inverted polarity is based on cloud droplet size theory (Cummins and Williams, 2017). In laboratory experiments simulating the mixed phase conditions in thunderclouds, Avila and Pereyra (2000) have found a tendency for positive charging of the rimer with decreasing cloud droplet size. This charging polarity is opposite to the dominant negative charging (Takahashi, 1978) that is generally accepted as the primary mechanism for the prevalent storm polarity.

In this paper, we present the analysis of the electrical characteristics of 32 thunderstorms occurring over Pune (India) during 1996–2008. The charge distributions inside thunderclouds and the effect of different environmental conditions on charge structure of thunderstorms are discussed.

2. Instrumentation

A field mill described by Kamra and Pawar (2007) that has its sensor plate flush with the ground is used to measure atmospheric electric field. It can measure electric field in the range of ±25 kV m^{-1} with response time of 0.1 s. The field mill can sense the lightning-induced electrostatic field-changes of a thunderstorm 20–25 km away from the observatory.

The Maxwell current is measured with a direct current measuring method using a slow antenna. A flat aluminum plate of one square meter was kept flush with the ground andplaced on four porcelain insulators (Deaver and Krider, 1991). The decay time of 0.1 s is chosen for this antenna so as to by-pass the electric field-changes produced by intra-stroke processes (Deaver and Krider, 1991).

Data for Aerosol Optical Depth (AOD) is obtained from MODIS. MODIS is passive imaging radiometer onboard the Terra satellite and measures radiance counts in 36 high spectral resolution bands from 0.415 to 14.235 μm. The measured counts, geo-location and other derived geophysical, atmospheric and ocean products are archived at NASA Goddard Earth Sciences Data and Information Services Center (GES-DISC). GES-DISC Interactive Online Visualization and Analysis Infrastructure (GIOVANNI) is a web based interface (http://disc.sci.gsfc.nasa.gov/giovanni) through which most of the products are made available to users. MOD08_M3 is a level-3 global 1° × 1° gridded monthly product which is available from February 2000. The Aerosol Optical Depth (AOD) at 550 nm is used in this study.

We follow the convention that the fair-weather electric field and the associated Maxwell current carrying positive charge downward to the ground are of negative polarity. Further, positive (negative) field-change results in positive (negative) displacement current.

A dynamic condenser type microphone (AHUJA make) with impedance of 200 Ω and sensitivity 2.5 mV Pa^{-1} at 1 kHz with flat frequency response from 20 to 20,000 Hz is used to record thunder. As the microphone installed in the open field is prone to error because of high winds and other activities, the microphone and an amplifier were housed inside a 30 cm diameter deep pit covered with a sloping hat of 60 cm × 60 cm fixed above four rods of 45 cm height. The hat protects the microphone from rain falling directly on it. Details are given in Kamra and Pawar (2007). All meteorological observations were made at India Meteorological Department's (IMD) observatory located ~4 km from our observational site at synoptic hours.