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Role of orography in inducing high lightning flash rate at the foothills of Himalaya

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Abstract

Surface electric measurements obtained beneath thunderstorms with almost similar characteristics at a station located close to the Himalayan foothills in northeastern India have been analyzed. All these thunderstorms had some similar features - occurred after midnight and lasted for a short duration of less than an hour, and an active stage of these thunderstorms lasted for 10 to 25 min. All these thunderstorms exhibited very high peak flash rates ranging from 40 to 80 flashes per minute during the active stage. A lightning jump of about 65 flashes per minute (fpm) was observed during two occurrences of these thunderstorms. Surprisingly, in spite of very high peak lightning flash rates and lightning jumps, no severe weather phenomena were observed at the ground during these thunderstorms. The formation of such small duration thunderstorms with very high lightning flash rates is attributed to the conversion of moisture in the valley during nighttime.

Keywords: Severe thunderstorms; Lightning jump; Himalayan foothills

Background

Many field experiments and laboratory studies have shown that the magnitude of updraft of a thundercloud is a major factor that is responsible for large-scale electrification of thunderclouds and hence the lightning flash rate and updraft velocity inside a thundercloud are closely related (Williams 1985; Williams et al. 2005). Vonnegut (1963) has proposed that the lightning flash rate is proportional to the fifth power of the thunderstorm's height which is generally known as 'fifth power relationship'. Williams (1985) has observed that the fifth power relationship holds fairly good over the continent. Price and Rind (1992) have shown that due to large difference in updraft speeds over land and ocean, this relationship does not hold true for ocean thunderstorms. However, more recently, Yoshida et al. (2009) have shown that the number of lightning flashes per second per convective cloud is approximately proportional to the fifth power of the cold-cloud depth (the height from the melting level to the storm height) and this relationship is not regional dependent. All these observations clearly indicate that the updraft velocity inside thunderclouds play important role in determining the lightning flash rate during thunderstorms.

The role of aerosols on microphysical and dynamical characteristics of cloud has been studied for a long time (Rosenfeld 1999, Rosenfeld and Woodley 2003, Khain et al. 2008, Rosenfeld et al. 2008). Many observations suggest that the aerosols influence the charge generation processes inside thunderclouds (Orville et al. 2001, Steiger et al. 2002, and Steiger and Orville 2003). Williams et al. (2002) have suggested that the observed contrast between lightning over continent and ocean may be due to differences in aerosol concentrations over land and ocean. They have suggested that the increase in aerosol concentration could reduce mean droplet size and thereby suppress warm rain coalescence and enhance the cloud water reaching the mixed phase region, which can increase the lightning flash rate. Moreover, it has been recognized that ice content inside thunderclouds plays an important role in lightning activity (Dye et al. 2000, Blyth et al. 2001, Lal and Pawar 2009). Therefore, an increase in ice nuclei also can enhance the lightning flash rate.

Another factor, which affects the lightning flash rate, is the orography of the region. Many studies have shown that the local orography can generate intense vertical velocity and affect a change in lightning flash rate by

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interacting with prevailing wind and/or large-scale processes (Zajac and Rutledge 2001; Bourscheidt et al. 2009; Pawar et al. 2010; Bourscheidt et al. 2009) in their study over South Brazil have shown that the terrain slope has more influence than altitude on thunderstorm occurrence and lightning activity. Pawar et al. (2010) have found a very high peak-lighting flash rate in spite of very low convective available potential energy (CAPE) over the northeast part of India. They attributed this high lightning flash rate to the short duration of an active phase of a thunderstorm.

Many parts of India experience thunderstorms during the pre-monsoon season (April to May) and such thunderstorms are generally severe in the northeastern part of India. Reasons for the formation of severe thunderstorms in this part are discussed in detail by Koteshwaram and Srinivasan (1958), Raman and Raghavan (1961), and Krishna Rao (1966). In this paper, we report observations made during three short-duration thunderstorms occurred in this region with very high peak flash rates (about 80 flashes per minute). Possible causes of such high lightning flash rates in these thunderstorms are discussed.

Methods

A vertical field mill, which can measure field up to ±12 kV/m, is used for measurement of atmospheric electric field observations. Details of the same are given in Kamra and Pawar (2007). Sensor plates of the field mill are kept flushed to the ground. Details of sensitivity and the procedure followed for observations are given in Pawar et al. (2010). We have followed the convention that the fair-weather electric field would result in negative polarity field change. The field mill has a range of around 25 km, and field changes occurring as far as 25 to 30 km can leave a signature in our field records.

Results

Observations of vertical electrical field were made during April 2007 at Guwahati (26.2° N, 91.95° E) in the northeast part of India. Figure 1 shows the position of the observation site on the India map along with the orography of this region. As shown in Figure 1, this site is situated in the valley of Brahmaputra river basin surrounded by tall mountains towards south and north. The peculiar local topography plays a crucial role in determining the weather and climate over this region (Goswami et al. 2010). As stated above, northeast India experiences heavy thunderstorms during pre-monsoon season, i.e., months of April and May. Some studies show that the frequency of occurrence of thunderstorms over the northeast part of India is more than 100 days/year and almost half of it occurs in two pre-monsoon months of April and May (Raman and Raghavan 1961; Tyagi 2007; Singh et al. 2011).

We have included, for discussion here, three thunderstorms with similar characteristics. Pawar et al. (2010) have reported the electrical characteristics of one such severe thunderstorm (which is included for analysis here). All these thunderstorms developed in late night hours and lasted for a short duration, and active phases of these thunderstorms lasted for less than 30 min. None of these thunderstorms produced severe weather - such as heavy winds, hails, heavy precipitation - at the ground. Upper air radiosonde observations made at 1730 hours around 30 km from the observational site on all these days showed that the CAPE was around 2,000 J kg^{-1} and level of free convection was at 800 m which are conducive for development of a thunderstorm. Although no radar observation is available, we could infer to some extent from observed electric field whether the storm remained stationary or not. Our observations indicate that the electric field induced by lightning remained similar up to the last observed lightning which

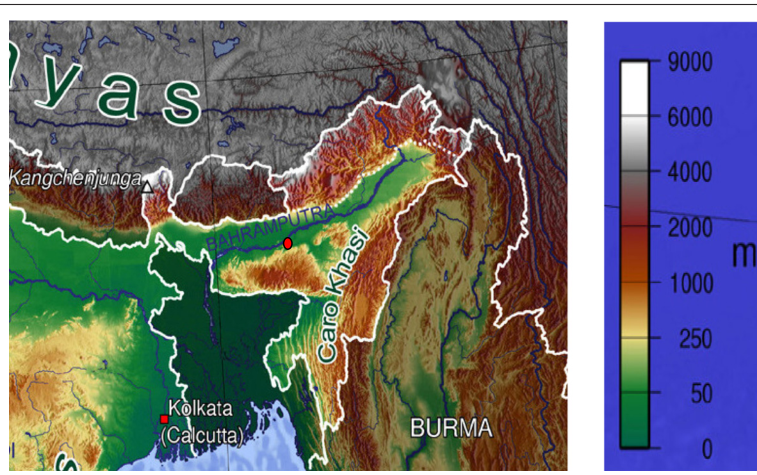

Figure 1 Observation site on the India map along with the orography of this region. Physical map of India showing the position of observation site (purple dot) along with the orography of this region.

suggests that these thunderstorms remained stationary overhead for most of their lifetime. By small thunderstorms, we mean storms of small duration.

Storms

A thunderstorm developed 2 to 3 km north of the observatory at about 2347 hours IST on 20 April 2007. Within a few minutes, it moved over the observatory and covered the sky overhead. This thunderstorm lasted about 1 h, and rainfall observed during this period was about 5 mm. Sky cleared up completely after the rain. As the storm occurred in late night, the active and dissipation stages of this storm (partly shown in Figure 2 and Figure 3) spilled to early hours of next day (21 April 2007). After about 1.5 h, at about 0217 hours on 21 April 2007, another thunderstorm developed near to observatory. This thunderstorm lasted about 2 h, and wind at surface remained calm or low during this thunderstorm. This thunderstorm exhibited normal end-of-storm-oscillation (EOSO) during dissipation stage. On 23 April 2007, thunderstorm developed after midnight at about 0110 hours. Drizzle started at the observatory at about 0130 hours and became little heavy at about 0150 hours. Meteorological data was also available from an Automatic Weather Station (AWS) located about 25 km at the Indian Meteorological Department (IMD), Guwahati. Data from this AWS showed that winds remained low between 2 to 5 m/s for the whole period of thunderstorms. Further, no appreciable amount of rain was recorded either at the observational site or at AWS site during these storms. Thunderstorms dissipated at about 0220 hours. IMD, Guwahati, situated about 25 km away did not record any of these storms. Further, there was no report in any local newspapers about occurrence of such severe thunderstorms and it is evident that these storms were confined to a small range.

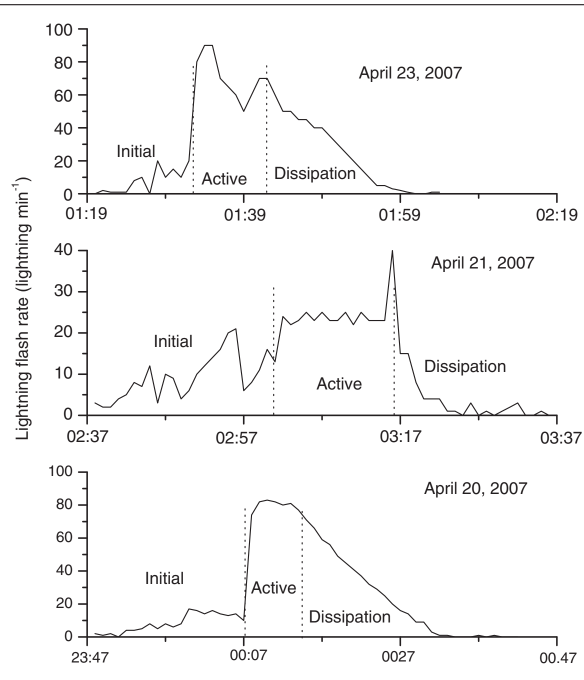

Figure 2 Lightning flash rate estimated from electric field record during different stages of thunderstorms. Variations of lightning flash rate derived from electric field during different stages of the storm on thunderstorm days.

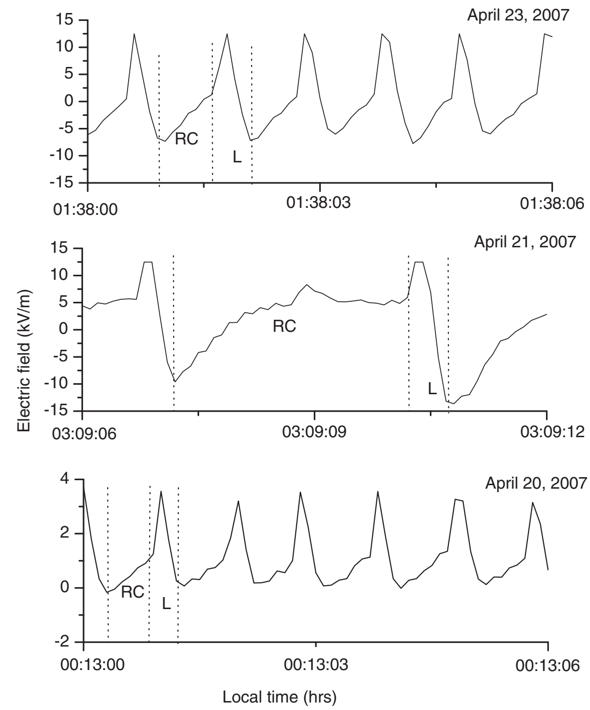

Figure 3 Electric field records in the active stage of the thunderstorms. Variations of electric field measured at the ground during the active phase of thunderstorms on 20 April 2007, 21 April 2007, and 23 April 2007.

Lightning flash rate

Figure 2 shows the lightning flash rate estimated from electric field record during three thunderstorms. As shown in Figure 2, these thunderstorms are divided into three stages - initial, active, and dissipating stage based on lightning activity. In the first thunderstorm, the initial stage lasted for about 20 min and lightning flash rate remained between 10 and 20 fpm. The active stage started at about 0012 hours and lasted only for 7 min up to 0019 hours. The lightning flash rate increased sharply to about 84 fpm within 1 to 2 min and remained between 75 and 85 during active stage. In the active stage, flash rate increased at the rate of about 65 fpm. As described by Williams et al. (1999), such a sudden jump in lightning flash rate is most of the time associated with increase in updraft and severe weather at the ground. In the dissipation stage, the flash rate decreased rather slowly and reached near to zero at about 0043 hours. Thunderstorm on 21 April 2007 also showed a high flash rate during the active phase. In the initial phase, flash rate was between 10 and 20 fpm, which increased to 20 to 25 fpm in the active phase. The active stage lasted for about 17 min in this thunderstorm. In this thunderstorm also, decrease in lightning flash rate during dissipation stage is slow. Thunderstorm developed on 23 April showed a low flash rate of about 10 to 15 fpm in the initial phase. This thunderstorm also showed a lightning jump in the active stage similar to that observed on the thunderstorm of 20 April 2007. The lightning jump in this case is about 60 fpm. The peak flash rate observed in this thunderstorm was 90 fpm. In this thunderstorm also, the active stage lasted for only 10 min. The flash rate started decreasing slowly in the dissipation stage.

Electric field changes induced by lightning and recovery curves

Electric field changes produced by lightning and recovery curves of surface electric field after lightning can give some information about charge distribution and charging processes inside thunderclouds. All these three thunderstorms show negative electric field changes indicating removal of negative charge from overhead and the recovery curves show building up of negative charge overhead. This behavior of electric field changes produced by lightning and recovery curves suggest the normal positive dipole (negative charge in the lower and positive charge in the upper portion of cloud) charge structure inside thunderclouds. The electric field changes and recovery curves observed on 20 April 2007 show some positive electric field changes also. Figure 3 shows the electric field records in the active stage of the thunderstorms. As the lightning frequency was very high during active stage of this thunderstorm, for clarity, electric field data for only 6 s is plotted here. Since the lightning frequency is very high, it is little difficult to distinguish recovery curves and electric field changes produced by lightning. Therefore, we have separated recovery curves and electric field changes produced by lightning by a dotted line for one lightning discharge in each thunderstorm. As shown in this figure, recovery curves in all the three thunderstorms indicate either building up of negative charge inside the cloud or clouds with normal polarity charge structure in the active stages of all the three thunderstorms. Surprisingly, the electric field changes produced by lightning discharges are quite similar in these thunderstorms during the active stage. Each lightning discharge has two electric field changes; negative field change immediately after the first field change which is always positive. The positive electric field is always smaller than the negative one in case of all the three thunderstorms. These electric field changes suggest that the lightning discharges destroy positive charge initially and then negative charge. Figure 4 shows the electric field records in the dissipation stage of thunderstorms. As shown in this figure, the time lags between two lightning discharges are more, compared to the active stage and hence the recovery curves are clearly seen. In this stage, each lightning discharge has two electric field changes - a small positive followed by big negative.

Discussion

Observations of these three thunderstorms over the northeastern part of India demonstrate that small thunderstorms can have very high lightning flash rates of about 40 to 90 fpm. A sharp increase in lightning flash rates, known as 'lightning jumps', of about 30 to 75 fpm is also observed in the beginning of the active stages of these thunderstorms. Earlier observations by Williams et al. (1991), McCaul et al. (2002), Wiens et al. (2005), and Schultz et al. (2009) show that very high flash rates (more than 60 fpm) and lightning jumps are always found to be associated with severe and big convective systems. However, our observations demonstrate that high lightning flash rates and lightning jumps can also be associated with small single cell non-severe thunderstorms. It should be noted here that the surface winds were low or calm during the whole thunderstorm period. Thunderstorms were overhead during their active stage. Though handicapped by absence of radar data, a pattern of electric field changes (Figures 3 and 4) and steady decrease of lightning flash rate during dissipation stage (Figure 2) suggests that thunderstorms have not moved away from the observational site during their lifetime. Electric field changes induced by lightning and recovery curves of electric field between two lightning flashes suggest that all the three thunderstorms were having a normal positive dipole-type charge structure. However, all the electric field changes induced by lightning starting with positive electric field change indicate that all the lightning discharges destroy some positive charge initially. This may be an indication of presence of widespread positive charge in the lower portion of cloud. As stated earlier, there are no radar observations and only this can give the exact distance of thunderstorms from the observational site. To overcome this, we have employed time-to-thunder technique to calculate horizontal distance of thunderstorms from the observatory. Despite the fact that this method may not be very accurate, this technique gives approximate distance and movement of thunderclouds. Further, storms that were either overhead or very close to observatory have only been considered for analysis.

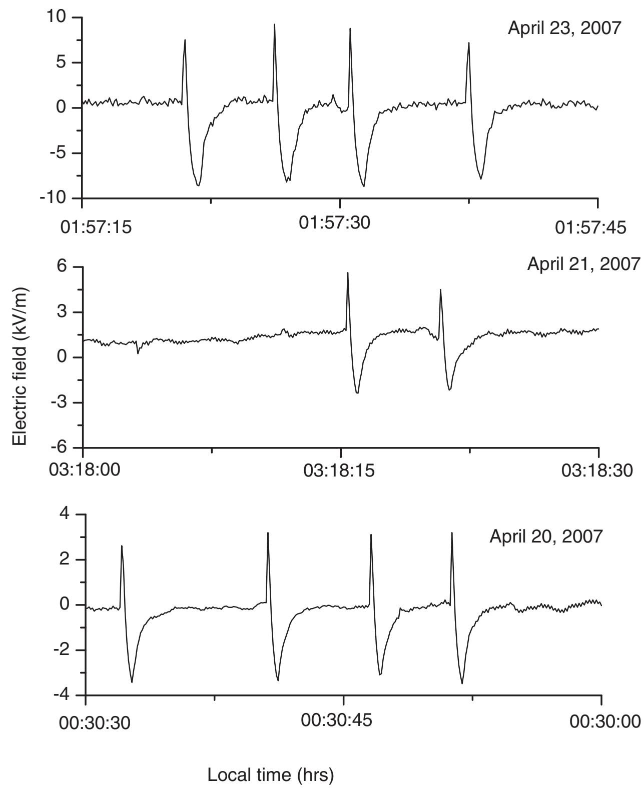

Figure 4 Same as Figure 3 but during the dissipating phase of thunderstorms.

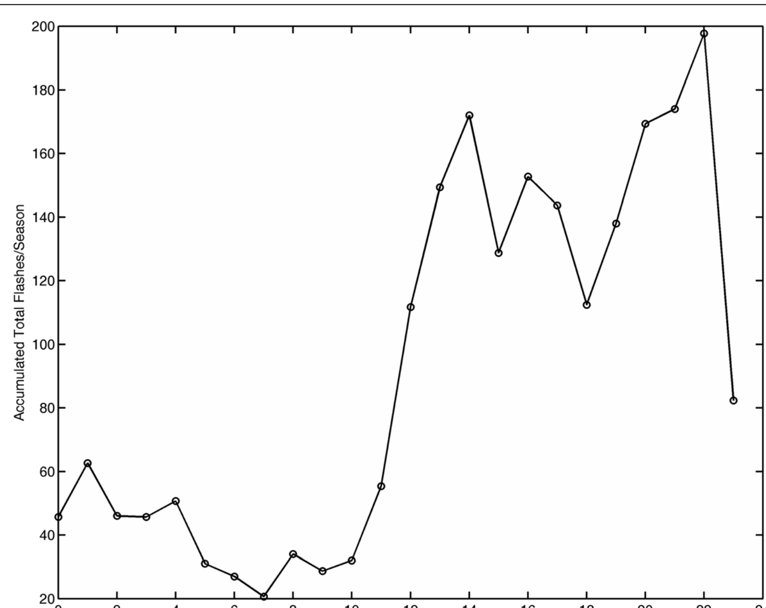

Figure 5 Diurnal variation of lightning over Guwahati averaged for pre-monsoon seasons of 2011 to 2013. Time scale (X-axis) is in UT.

With this, we can study the lightning activity or charging processes inside thunderclouds of stationary thunderstorms with fairly good approximation by having surface measurements of electric field at only one point (Pawar and Kamra 2004; Pawar and Kamra 2009).

Electrical characteristics of thunderstorms occurring over this region are sparsely studied. Recently, RameshKumar and Kamra (2012) have studied the spatiotemporal variations of lightning over the foothills of the Himalayas and their relationship with CAPE and surface temperature. They attributed the observed higher flash rate to diurnal cycle of mountain breeze. However, they have not examined the electrical nature of these lightning flashes. To the authors' knowledge, it is for the first time that observations demonstrate even small thunderstorms can exhibit very high peak lightning flash rates and lightning jumps. As shown in Figure 1, the observational site is situated in the Brahmaputra valley with 4- to 5-km-high mountains about towards the north and south. Barros et al. (2004) have shown that high mountains of Himalaya interact with prevailing winds in monsoon season and can produce deep convections over that region at late night hours. They have also suggested that the radiative cooling at high mountaintops can generate moisture conversions at the foothills and they may be responsible for deep midnight convections over that region. Our observations also suggest that moisture conversion at foothills due to radiative cooling at mountaintops during nighttime may be responsible for triggering of such deep convections over Guwahati during the pre-monsoon season.

To demonstrate our argument that severe thunderstorms normally occur at this place at late night hours, we have plotted diurnal variation of lightning activity during pre-monsoon months of 2011 to 2013 over 1° × 1° grid with Guwahati as center obtained from World Wide Lightning Location Network (WWLLN) in Figure 5. Lightning activity occurring over this grid at a particular hour on all thunderstorm days were first accumulated for that hour. These cumulative data were then averaged for one season which was again averaged for 3 years (2010 to 2012). WWLLN has about 80 low frequency sensors over the globe and its detection rate is about 10%. The network records locations of lightning strokes occurring over the globe (Lay et al. 2004). It is seen from Figure 5 that a general pattern of lightning activity over Guwahati remains less during day, increases rapidly after late afternoon, and remains high throughout the night. Diurnal variation shows two maxima - one at about 15 UT (2030 hours local time) and another at about 23 UT (0430 hours local time), and the second peak is stronger. Higher maximum observed after midnight over Guwahati strengthens our argument that the moisture conversions at the foothills due to radiative cooling in the night may be the main cause of lightning activity during nighttime over that region.

It is to be noted here that our hypothesis that conversion of moisture in the valley during nighttime leads to thunderstorms with high flash rates and lesser number of active phases needs to taken with caution as this is based on a limited number of observations. As stated above, observations of electrical field are not conducted regularly at this place and this observation was made during a campaign. The authors are aware that more such observations are required to strengthen our argument. Nevertheless, one needs to take into consideration that 3-year averaged data of lightning obtained from WWLLN lends support to our hypothesis.

Conclusions

Our observations of electric field made beneath thunderstorms at Guwahati, known for occurrence of severe thunderstorms during pre-monsoon season - locally known as '*Nor'wester*', show that high lightning flash rates and lightning jumps can happen in small thunderstorms without causing any severe weather phenomenon at ground. This study also brings out the fact that many severe thunderstorms occur over this region during late evening/night hours, which can be attributed to moisture conversions at the foothills due to radiative cooling.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

All the authors are involved in formulating and conducting the experiment. SDP prepared the initial draft. All authors participated in subsequent discussions, which improved the quality of manuscript. All authors read and approved the final manuscript.

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