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Evolution of the impacts of the 2009-10 El Niño and the 2010-11 La Niña on flash rate in wet and dry environments in the Himalayan range

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Key Points:

- Impact of ENSO event on lightning differ in different meteorological regimes
- CAPE and flash rate are highly correlated during ENSO in dry/wet environments
- Progress of the monsoon affects the lightning activity in dry and wet environments

Abstract

Impacts of the 2009-2010 El Niño and the 2010-2011 La Niña events on the lightning activity in the climatologically dry and moist regions of the Himalayan range are studied from the 18-year (1995-2012) data obtained from the combination of Optical Transient Detector and Lighting Imaging Sensors on the TRMM satellite. Average flash rates in both regions are higher than the 18-year normal during both El Niño and La Niña events. Our results suggest that the impacts of El Niño and La Niña need to be examined season-wise separately in moist and dry regions. During El Niño, the flash rate increases from the month of February into the pre-monsoon season but has no significant effect in the monsoon and post-monsoon seasons in the moist region. On the contrary, flash rate does not change during the pre-monsoon but is higher than normal in the monsoon and lower than normal in post-monsoon season in the dry region. During La Niña, it does not change from its normal value in any season of the moist region and even in pre-monsoon season of dry region. However, it is higher than normal in the monsoon and post-monsoon seasons of the dry region. In the dry region, while flash rate is highly correlated with convective available potential energy (CAPE), surface temperature, and convective rain fall, it is highly correlated only with CAPE in the moist region during La Niña events. Moist convection and aerosols appear to be important parameters for production of lightning in moist and dry regions, respectively. Progress of the monsoon current dramatically affects the lightning activity in both moist and dry regions.

Index Terms: 3324 Lightning; 3304 Atmospheric electricity; 3374 Tropical meteorology; 0320 Cloud physics and chemistry

Keywords: Lightning; ENSO Impacts; Atmospheric electricity

1. Introduction

During the southwest Indian monsoon season (June to September) the moisture-laden low level winds from the Arabian Sea and the Bay of Bengal flow over land surfaces which have distinctly different terrain and land surface conditions. The moist airflow from the Arabian Sea traverses over the hot and arid Thar Desert and is warmed by the sensible heat flux in the northwestern subcontinent. On the other hand, moist air from the Bay of Bengal travels over the Bangladesh wetlands and Ganges Delta and further increases its moisture content in the northeast The moist airflows over the western and eastern Himalayan foothills encounter dramatically different convective systems[Romatschke et al.,2010; Medina et al.,2010]. The terrain in these regions plays a key role in releasing the convection over the small foothills and orograpphically enhances it to saturation. The deepest convective storms occur in these regions close to large topographic features [Zipser et al., 2006; Houze et al., 2007; Rasmussen and Houze, 2010; Rasmussen et al., 2014; Kamra and Nair, 2015]. Ramesh Kumar and Kamra [1912] reported that the maximum flash rate occurs in an arc shaped area along the foothills of the Himalayas and decreases on both north and south sides of it. Moreover, while 22.5% of change in lightning flash rate in the Himalayan foothills can be associated with variability in CAPE and ~7.5% of this variability can be associated with orographic lifting in the northeast region. Besides topography, several thermodynamic and anthropogenic factors such as convective available potential energy (CAPE), aerosol loading, vegetation cover influence the instability, moisture and lifting force with varying effects from region to region (Doswell, 2000; Orville et al., 2001; Kotroni and Lagnouvardos,2008; Penki and Kamra, 2013; Chakraborty et al., 2015). Kandelgaonkar et al. (2005) and Ranalkar and Chaudhari **(2009)** also stress the role of orography in determining the distribution of lightning in this region. In the dry northwestern region of the subcontinent extreme convective systems containing intense convective echoes whereas in the moist north eastern region extreme convective system containing broad straitform echoes have been observed [Houze et al., 2007, and Romatschke et al.,2010].Recently, Qie et al., (2014) also reported that deep convective storms and intense deep convective storms with their 40 dBZ echo-top at 18 km height or even exceeding that, are most frequent over the western most part of the southern Himalayan front.

In the tropics, differences in meteorological regimes are very influential in the distributions of the buoyancy and radar reflectivity of clouds in different seasons. However, since the lightning activity is also closely related with several other cloud characteristics such as updraft development, convective rainfall, radar echo-top heights, mixed-phase microphysics (Williams 1985, 1992; Williams et al. 1991, 2005; Rutledge et al., 1992; Zipser and Lutz 1994; Petersen and Rutledge 1998; Ushio et el. 2001; Cecil et al., 2005; Zipser et al., 2006), some of these observation show that flash rate is not uniquely related to radar top height indifferent meteorological regimes. Studies demonstrate that the peak flash rates in thunderstorms embedded in large scale monsoon airflow are an order of magnitude less than in more vigorous storms in the more unstable ‘monsoon break period’ regimes [Williams et al., 1992]. Penki and Kamra [2013] have recently studied the lightning activity in dry and moist environments in the Himalayan regions of the Indian subcontinent and found that flash rate is better correlated with convective parameters such as surface temperature, convective available potential energy (CAPE), and outgoing long wave radiation (OLR) in the dry region as compared to the moist region. Moreover, the aerosol optical depth (AOD) at 550 nm is highly correlated with flash rate in the dry region than in the moist region. Their results show that CAPE is ~120 times more efficient for increasing the flash rate in the dry region as compared to the moist region.

The linkage between lightning and environmental conditions can be beneficially investigated during ENSO event, when the tropical convection in general including the frequency and intensity of tropical storms and deep convection is influenced by the transport of heat, moisture, and momentum [Williams, 1992]. Study of such linkage is also prompted by several results such as (i) tropical land regions warm up in El Niño phase and cool down in La Niña phase [Williams, 1992; Hamid et al., 2001], (ii) lightning in the tropics increases nonlinearly with surface temperature and global lightning and it responds to surface air temperature on short time scale [Price, 1993; Nickolaenko et al., 1999; Williams, 1999; Christian et al., 2003; Williams et al., 2005; Ramesh Kumar and Kamra, 2012]. (iii) the number of lightning flashes over Indonesia increased during El Niño period in the 1997-98 ENSO [Hamid et al.,2001], and (iv) flash rate shows a contrast between El Niño and La Niña in the western pacific and East/Southeast Asia regions [Yoshida et al., 2007]. Lightning activity is more in tropical-extra tropical land regions and a southward/eastward shift occur in the global lightning activity, especially in southeast Asia during El Niño periods, and the greatest lightning contrast between El Niño and La Niña periods occurs at the latitudes of the descending air in the Hadley circulation [Satori et al.,2009]. Penki and Kamra's [2012] study shows that the lightning activity increase during the warm phase (El Niño) and decreases during cold phase (La Niña) of the 1997-1998 ENSO event when the usual inverse relation between the El Niño and the Indian summer monsoon rainfall was not observed.

Here we investigate how the development of the opposite phases of the ENSO event (El Niño and La Niña) affect the development of lightning activity in contrasting conditions of climatologically dry and moist environments in the two Himalayan regions. In particular, we examine how the lighting flash rate in these regions differ in the present case when the relation between ISMR and El Niño is observed from the 1997-1998 case of El Niño (Ramesh Kumar and Kamra, 2012) when this inverse relation is not observed. We also study how the progress of monsoon current influences the lightning activity in these two regions.

2. The 2009-2011 ENSO Event

We have selected the 2009-2010 El Niño and the 2010-2011 La Niña periods for the present study. Table 1 shows the monthly Nino 3.4 index values **from** June, 2009 to May, 2010 as reported by the National Oceanic and Atmospheric Administration (NOAA). El Niño started from July 2009 and the condition prevailed up to April 2010. Then, two months later, La Niña started in July 2010 and prevailed up to April 2011. As per the NOAA's criteria, 2009 is considered as moderate El Niño year and 2010 as strong La Niña year. During this ENSO event both its warm (El Niño) and cold (La Niña) phases occur in the same months of consecutive years. Moreover the negative correlation between El Niño and the Indian Summer Monsoon Rainfall (ISMR) and the positive correlation between La Niña and ISMR observed in several studies [Walker, 1918; Pant and Parthasarathy, 1981; Krishna Kumar et al., 1999], were also observed during this particular ENSO event. One of the objective of this study is to study the difference in lightning distribution in these two areas between this period and the 1997-98 period when the **inverse** El Niño-ISMR correlation was not observed.

The year 2009 was an extreme drought year, being the third most deficient year in precipitation during the 1901-2012 periods. The seasonal (June-September) rainfall deficiency for the country as a whole was 22% of the Long Period Average (LPA) (65% of its LPA over northwest India and 77% of its LPA over northeast India) as per the India Meteorological Department's (IMD) records. The 2010 monsoon season witnessed many anomalous rainfall and circulation features, even though it was declared by IMD as a normal monsoon season. As per the IMD's report, the seasonal rainfall over the country as a whole was 102% of its LPA. The 2010 summer monsoon produced the country’s worst flooding over the mountainous part of Pakistan and the northwest India [Houze et al., 2011; Webster et al., 2011; Lau and Kim, 2012; Rasmussen et al., 2015]. This flood has been attributed to the westward displacement of storms pertaining to great departure of synoptic scale circulation [Houze et al., 2011].

After 2002 (a deficient monsoon year), this was the only year when no depressions formed over the Indian Monsoon region during the entire season.

3. Data-set

The lightning data products used here are LIS/OTD data obtained from the website http://ghrc.nsstc.nasa.gov/. The monthly averaged flash rates expressed as flash rate density (fl km^{-2} day^{-1}) are derived from the LIS/OTD 2.5 Degree Low Resolution Monthly Time Series (LRMTS) data obtained during 1995-2012. The Optical Transient Detector (OTD) was launched in April 1995 and the Lightning Imaging Sensor (LIS) launched in December 1997 aboard the TRMM satellite. Both sensors measure total Intra-cloud (IC) and Cloud-to-ground (CG) lightning. The LIS detection efficiency ranges from about 69% near local noon to 88% over night [Boccippio et al., 2002]. To produce LRMTS, LIS and OTD flash rates and view times are smoothed precisely and are extracted for the middle day of each month [Cecil et al., 2014]. The lightning flash rates in an LRMTS have slightly over 3 months of temporal smoothing and 7.5°*7.5° spatial smoothing [Cecil et al., 2014].

Surface temperature, CAPE, and relative humidity are taken from ECMWF ERA Interim Monthly mean value data provided through http://data-portal.ecmwf.int/data/d/interim_daily/. Spatial resolution of the data is 0.75°. The TRMM convective rain rate data is used for Giovanni website (http://disc.sci.gsfc.nasa.gov/giovanni) Monthly rain rate in mm hr^{-1} is converted to mm day^{-1} by multiplying it with 24 for convenience. The spatial resolution of the data is 0.5°. Interpolated Outgoing long Wave Radiation (OLR) data sets are used from the NECP-NCAR website (http://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html). These monthly data-sets have spatial resolution 2.5°*2.5° latitude-longitude grid.

Aerosol optical depth at 550nnm have been obtained using Level-3 MODIS gridded atmosphere monthly global product 'MOD08_M3' (ESDT Long Name: MODIS/Terra Aerosol cloud Water Vapor Ozone Monthly L3 Global 1Deg CMG). Monthly average MOD08_M3 product files are available in Hierarchical Data Format (HDF-EOS) at spatial resolution of 1°x1° (MODIS, 2004). Here we used AOD data from March, 2000 to December, 2012, except for the months of May and June.

4. Methodology

We have analyzed the variability in the monthly Averaged Flash Rates (AFR) during the 2009-2010 El Niño and the 2010-2011 La Niña periods over the region using Grad's software. These monthly values of AFR have been compared with the mean AFR for the corresponding months of the period of 1995-2012 (hereinafter, called as normal period). The above analysis shows that lightning is mainly concentrated over two regions of northeast (NE) (19°N-28°N, 85°E-94°E, mean elevation of 306 m) and northwest (NW) (28°N-37°N, 70°E-79°E, mean elevation of 1934 m) [Ramesh Kumar and Kamra, 2013]. Next, we focus to study the evolution of the impacts of El Niño and La Niña on AFR in these two moist and dry regions of extreme convection over the eastern and western sides of the Himalayan range respectively. In order to understand these variations in AFR, we have analyzed the monthly variations in the surface temperature, OLR, CAPE, and AOD at 550 nm and their correlations with AFR in the NW and NE regions during El Niño and La Niña periods using Origin software. We have calculated the average of monthly climatology of each meteorological parameter for the 1995 to 2012 period for the NE and NW regions. The relative humidity data is vertically averaged from surface to 400 hPa level for each month. However, since MODIS data for AOD is available only from March, 2000, the average of monthly values of AOD is calculated only for the March, 2000 to December, 2012 period.

5. Results

5.1 Distributions of mean values of AFRs over the NE and NW regions.

Figure 1 shows the distribution of the mean **values of** AFRs for El Niño and La Niña periods from July 2009 to April 2010 and from July 2010 to April 2011, respectively in comparison with the normal period. AFR is highly concentrated over the NW and the NE regions and has somewhat higher values in central India, the Himalayan foothills, the Eastern India coastline, and the Southern peninsula. The oscillating Maddan Jullian mode may propagate over the northernmost region and produce the maximum thunderstorms and lighting activity (Kandalgaonkar et al. 2005). The alterations of wind field by the mountains in the NE and NW coupled with frictional convergence in the heat low and relatively high surface temperature produce the low pressure area over the central and northeast Pakistan. When compared to the normal period, the AFRs are higher in both the NE and the NW regions during both El Niño and La Niña periods. This is in contrast to the result of Ramesh Kumar and Kamra [2012], who report an increase in AFR during 1997-1998 El Niño and a decrease in AFR during the 2002-2003 La Niña in these regions, when the inverse relationship between El Niño and the ISMR was not observed. It amounts to that the non-occurrence of above-normal ISMR during 2002-2003 La Niña event or the factors causing it might have resulted in a decrease instead of increase in AFR. Alternately, the impact of the above- normal rainfall in the southwest monsoon season during 2010-2011 La Niña conditions might be responsible to enhance the AFR. We shall further discuss these changes in Section 6. Moreover, as compared to the normal period, the enhancement in AFRs is spread over larger areas in the NE region during El Niño period and in the NW region during La Niña period as compared to the normal period.

5.2 Monthly distributions of AFRs during El Niño, La Niña, and normal periods

Monthly distributions of AFRs in Figure 2 show that the enhancements in AFR in both the NE and NW regions decrease during El Niño, La Niña, and normal period with the progress of the monsoon from July to October, but increases from the late winter through pre-monsoon months of February to April. Very low or no lightning activity occurs in the winter months from November to January. In interpreting these monthly changes, one must remember the temporal smoothing of 3 months in lightning flash rate in the LRMTS.

AFR remains stronger in both El Niño and La Niña phases as compared to their normal values. The AFR enhancements during the July to October period and particularly during July and August are more during La Niña than in El Niño phase. From February onwards, the situation is reversed, i.e. AFR is more during El Niño than in La Niña phase.

The NE and NW centers of peak flash rate are connected with each other along a strip of uniform flash rate running through the Himalayan foothills. The north-to-south width of the strip in the Himalayan foothills widens in the monsoon season with respect to the normal period during both El Niño and La Niña periods; the width widening being more during El Niño than during La Niña period. Similar widening of the strip occurs in pre-monsoon season, but contrary to the monsoon season, it is more during La Niña than El Niño period. Wu et al. (2016) also report that the humidity transport passage from the northeastern to the northwestern end of the Himalayas extends to the central part of the southern Himalayan front during the monsoon establishment period when intense convective systems are distributed homogenously over this region.

In the next section we will present quantitative results of the variations in the monthly mean values of AFR during the 2009-10 El Niño, 2010-11 La Niña and the normal periods in section 5.4 we present the variations in the monthly mean values of some environmental factors and their correlations with the monthly mean values of AFR. In Section 6 we shall discuss the possibility of some effective correlations between the meteorological conditions and AFR associated with these changes during these periods.

5.3 Variations of monthly mean AFR during El Niño, La Niña, and normal periods

Figure 3 shows variations of the monthly mean values of AFRs during the 2009-2011 El Niño, La Niña, and normal period over the NW and NE regions. The mean AFR is minimum and almost nil during the winter months of December and January with no significant changes during El Niño and El Nino phases. However, the AFR value increases on both sides of this minimum. The increase in mean AFR in normal period of 4 months from the late winter month of January to pre-monsoon month of May is sharper in the NE than in NW and attains maximum values of 0.105 fl km^{-2} day^{-1} and0.083 fl km^{-2} day^{-1} , in the NE and NW regions respectively. On the other hand, the decrease in mean AFR in normal period in6 months from the monsoon month of June to December is sharper in the NW than in NE and attains maximum values of 0.10 fl km^{-2} day^{-1} and 0.08 fl km^{-2} day^{-1} in the NW and NE region, respectively. As a result, the mean AFR is more in the NE than in the NW region during the January-May period and is more in the NW than in the NE region during the June-December period. Similar trends in the mean AFR occur during El Niño and La Niña periods.

In the NE region AFR is more during El Niño than normal period during January-May, attaining its maximum value of 0.152 fl km^{-2} day^{-1} in May but has no significant increase during La Niña period. During La Niña, variations in mean AFR are not significantly different from those in the normal period.

In the NW region, AFR is more during La Niña period than the normal/El Niño period, throughout the period of June to December, attaining its maximum value of 0.132 fl km^{-2} day^{-1} in July. During El Niño period, AFR is above normal in the monsoon months of June and August, but below normal in the post-monsoon months of October and November (Figure 3).

5.4 Monthly variation of convective parameters and their correlation with AFR

In order to understand the relative effects of various meteorological parameters on the evolution of lightning activity in the dry and moist regions during the El Niño and La Niña phases, we have studied the monthly variations of some convective parameters and their correlations with the flash rate in these two regions. Figures 4 (a and b) show the monthly variations of Surface Temperature, Convective Available Potential Energy (CAPE), Outgoing Long-wave Radiation (OLR), and mean Aerosol Optical Depth (AOD) at 550 nm, relative humidity, and convective rainfall. Their correlation coefficients with AFR in the NW and the NE regions during El Niño, La Niña and normal periods are summarized in Table 3. Some salient difference are described below

1. Although surface temperature is minimum in January and maximum in July in both the NE and the NW regions, it varies over a range of only 10-11 °C in the NE, while it varies over a much larger range of 19-21°C in the NW region. On the contrary, during the same period, while relative humidity varies over a range of 50-55 % in the NE region, it varies over a comparatively much narrower range of only 16-35 % in the NW region. These parameters play important role

in determining CAPE which is almost nil or very low in winter months in both the NE and the NW regions. However, while the CAPE sharply increases from February to April in the NE region, it shows much smaller increase in the NW region during this period. The corresponding increase in AFR, especially during El Niño, is much sharper during this period in the NE than NW region. On the contrary, the difference in the CAPE values between monsoon months of July/August and winter months are approximately equal in both the NW and NE regions. The corresponding sharper change in AFR, especially, during La Niña, is even sharper during this period indicating higher efficiency of CAPE in increasing AFR in the NW than in the NE region. Study of Ramesh Kumar and Kamra (2012) also supports such conclusion. While the value of CAPE in the monsoon months of July/August decreases to roughly half of its values in the pre-monsoon months of April in the NE region, the July/August value of CAPE increases to roughly double its April values in the NW region. The flash rate in the two regions follow almost similar trend and the two have high correlation coefficients in both regions (Table 2).

2. In the NE region, OLR is lowest during the months of July-August in monsoon season but rapidly increases to high values in the post monsoon month of October and maintains those high values till April. On the contrary, in the NW region, OLR has generally high values in monsoon season, decreases to lowest values in February and increases again in March-April. Convective rainfall in both regions is maximum in July, decreases to very low values in winter and increases again in the pre-monsoon months. However, while the maximum value in July is 4.2-6.0 mm day^{-1} in the NE region, it is as high as 7.6-9.0 mm day^{-1} in the NW region.

3. Trends in the AOD variations are roughly opposite to each other in the NE and the NW regions. While AOD has roughly the increasing trend from monsoon to pre-monsoon season in the NE region, it roughly decreases in the same period in the NW region. The values of AOD in the NW region are particularly high in the month of July. The high AOD in NW is mainly due to frequent occurrence of dust storms over the Thar desert. Further, the densely populated and industrialized areas on western and eastern sides of the Indo-Gangatic belt are major source regions of different anthropogenic aerosols (Srivastava et al., 2012)

There are some marked differences in the NE and NW regions between El Niño and La Niña periods. Firstly, in the NE region, while the CAPE values increase from their low values in winter to the pre-monsoon month of April by 1842 J kg^{-1} during El Niño period, the corresponding increase is only 1127 J kg^{-1} during La Niña period. Secondly, in the NW region, while the AOD reaches its highest value of 0.73 in July during La Niña period, it reaches only _ 0.62 in the same month during El Niño period. Moreover, the winter values of AOD in the NW region are smaller during La Niña than El Niño period. Another notable feature in the NW region is while convective rain is as high as 9.0 mm day^{-1} during El Niño, it is only 7.6 mm day^{-1} during La Niña.

The correlation coefficients between flash rate and environmental factor analyzed here for 10 months from July to next April should exceed 0.63 so as to accord with the **confidence** level of 95%. Correlation coefficients of flash rate with above factors are summarized in Table 2 during both El Niño and La Niña periods in the NE and NW regions. Flash rate is highly correlated with CAPE in both the NE and NW regions during both El Niño and La Niña periods. In the NW region, flash rate has significant correlation with both relative humidity and convective rainfall during La Niña periods, but only with convective rain fall during El Niño phase. Flash rate is highly correlated with surface temperature in the NW region, but this correlation is not so strong in the NE region. Further, the correlation between flash rate and AOD is significant in both El Niño and La Niña phases in the NW region but only in El Niño phase in the NE region. OLR is poorly correlated with flash rates in both regions.

6. Discussion

The data presented here provides a good data-set to study the relative effects of El Niño and La Niña on the development and distribution of the flash rate in contrasting dry and wet climates of South

Asia, mainly for three reasons. Firstly, because the events of El Niño and La Niña occurred for the same duration and similar periods in two consecutive years (Table 1). Secondly, the normally observed inverse relationship between El Niño/La Niña events and the Indian Summer Monsoon Rainfall (ISMR) is followed in both years. This is in sharp contrast to the 1997-1998 ENSO when El Niño - ISMR relation broke down and in spite of being one of the strongest El Niño event of the century, ISMR turned out to be normal. Thirdly, the greatest lightning contrast between El Niño and La Niña periods occurs at the latitudes of descending air in the Hadley circulation where the regions of NE and NW are located (Sartori et al. 2009).In the 1997-98 case, Kumar and Kamra [2012] showed that the flash rate over the Indian region increased during El Niño phase and decreased during La Niña phase of the 1997-1998 ENSO. However, the present results clearly demonstrate that effects of the opposite phases of ENSO (El Niño and La Niña) need to be considered season-wise separately in the moist and dry environments.

Impact of different seasons on lightning activity is different in the dry and wet environments. Figure 2 and Table 3 clearly demonstrate that lightning activity is different not only in the NE and NW regions but also the trend of the change in lightning activity in a particular region differs from season to season. Table 3 summarizes the impacts of El Niño and La Niña events on lightning activity during different seasons in moist (NE) and dry (NW) regions. The results stress the importance of moist convection in these areas. In the moist environment of the NE where both surface temperature and R.H. increase from February to April, CAPE increases by 1842 J kg^{-1} during El Niño and by 1127 J kg^{-1} during La Niña. However, in the dry environment of the NW, where surface temperature increases by approximately the same amount as in NE but R. H. decreases during the same period, CAPE increase by only 201 J kg^{-1} during El Niño and by 228 J kg^{-1} during La Niña. Assuming that CAPE is a major, if not the only, source of the energy to produce lightning, we can roughly estimate its efficiency by calculating flash rate per CAPE (by dividing flash rate by CAPE) for comparison of CAPE's efficiencies in the NE and NW regions. The increase in flash rate per CAPE in the dry environment of NW is $41*10^{-5}$ fl km^{-2} day^{-1} per J kg^{-1} during El Niño and $33*10^{-5}$ fl km^{-2} day^{-1} per J kg^{-1} during La Niña, while in the moist environment of NE is $5.1*10^{-6}$ fl km^{-2} day^{-1} per J kg^{-1} during El Niño and $71*10^{-6}$ fl km^{-2} day^{-1} per J kg^{-1} during La Niña. Higher values of the ratio of flash rate per CAPE in the NW region clearly demonstrates the higher efficiency of CAPE in producing lightning flashes in dry environment of NW than in the moist environment of NE. The locally generated heat and prevailing meteorological conditions and orography in NW provide favorable conditions for the formation of thunderstorms and high lighting activity in spite comparatively low values of CAPE.

Another noticeable feature of Figure 4 is the high values of AOD in July in the NW during both El Niño and La Niña periods. Particularly higher values of AOD during La Niña than El Niño phase are significant in this region. Higher values of AOD can lead to higher values of flash rate in two ways. Firstly, they can cause the formation of clouds with higher cloud base heights. Secondly, they can cause the formation of smaller and more numerous cloud droplets which can be carried to the mixed phase heights in clouds where they can participate in cloud electrification processes. Thus higher values of AOD during La Niña phase than in El Niño phase may lead to more lightning in La Niña than in El Niño phase in the NW region which is in conformity with our result illustrated in Figure 3. Sharp decrease of AOD from July to September in both phases of ENSO can be associated with the scavenging of aerosol particles by raindrops in the monsoon season. Absence of monsoon rains in September in the NW may again result in an increase in AOD in the post-monsoon season. This trend of the AOD seasonal variation in the NW is roughly similar to the trend of the flash rate variations during the monsoon and post-monsoon seasons. Of course, aerosol is only one of the factor that affect convective storm and lightning flash. In the NE region, most important feature is the sharp and large increase in flash rate from February to April in the El Nino phase. During this period, however, AOD does not change drastically but CAPE sharply increases. Relative humidity and convective rain also show sharp and large changes during this period. It is worth noting that during La Nina phase in NE where there is no significant change in flash rate during this period as compared to normal period, relative humidity undergoes a decrease instead of a large increase as in the El Nina phase. Orographic features and land surface conditions of the mountainous NE and NW regions are grossly different and this could be another factor which can contribute to different seasonal trends in lightning activity in these regions.

Our results emphasize the role of meteorological regimes on the lightning production and Figure 3 effectively illustrates this. Climatic conditions of a region mainly determine the lightning activity in it and the impacts of El Niño and La Niña events differ in modifying the environmental conditions in different meteorological regimes. For example, despite the maximum value of 3.4 Nino index in December-January, the impacts of El Niño and La Niña events in both dry and moist regions are minimum because the lightning activity itself, basically determined by climatic conditions in both regions is minimum. Although flash rate increases on both sides of this minimum, the impacts of El Niño and La Niña on normal flash rates differ on both sides and are different in dry and moist regions.

Recent study of Yuan et al. (2016) also reported that response of lightning activity to ENSO events shows remarkable seasonal and regional difference over east/southeast Asia. They find that in their region, positive (negative) lightning anomalies are mainly located at both sides of 5º-20ºN (5º-15ºN) in El Nino (La Nina) spring and winter and located North of Equator in summer and autumn. In confirmation with our study their study also finds that the lightning increases in the regions with warm moist flow intersection and the relative humidity and CAPE play strong roles in the lightning anomalies in different regions during different ENSO phases.

Moist convection and aerosol concentration emerge as the two key parameters for the production of lightning in moist and dry environments, respectively. However, lightning activity is not independent and linear function of either of these parameters. For example, in spite of the very high values of AOD during the pre-monsoon season in the NW region, the lightning activity is not large probably because of the lack of sufficient moisture. On the other hand, lightning activity dramatically increases in this region with the arrival of monsoon current and incursion of moisture in July when the Bay of Bengal branch of the southwest monsoon reaches there. This is strongly supported by the finding of Wu et al., (2016) that the location of the most intense convective systems along the southern Himalayan front is closely related to the establishment of the transport passage from the eastern to northwestern side along the Himalayan foothills during the monsoon establishment period. Further, their backward trajectory analysis also shows that, in addition to local environment, the moisture transport from the Arabian Sea and Bay of Bengal are two important long-range transport pathways for the summer monsoon intense convective systems at the west end of the southern Himalayan Front. In moist environment of the NE region, while the CAPE and lightning activity rapidly increase in the pre-monsoon season, the increase in these factors is not so sharp in dry environment of the NW region. With the progress of monsoon season, lightning activity decreases in both the NE and NW regions with possible contribution of lower solar isolation, cooling of the ground with more rainfall, and due to scavenging of aerosols by rainfall.

Our analysis confirms the finding of Williams (1992) that tropical land regions warm up in the El Nino phase and cool down in La Nina phase. Moreover, the relative humidity in the NW region, is lower than in the NE region except in the winter season when no or very low lightning occurs in either of two regions. Under such conditions of high temperatures and low humidity, the winds blowing from the arid and semi-arid regions of the middle-East over desert regions of the NW, raise large number of dust particles into the atmosphere and hence enhance AOD values in the regions (Goudi and Middleton, 2006; Givehchi et al. 2013). On the other hand, as the moist airflow from the Bay of Bengal traverses over Bangladesh wetlands, Ganges delta and vegetated land surface in the NE, it further picks up moisture and the topography of the region provides favorable conditions for most convection to occur. Widely different values of humidity in the opposite phases of ENSO in the two regions will thus contribute differently in different seasons. Since CAPE is largely determined by wet bulb temperature in boundary layer, moderate difference in it may account for the large differences in lightning activity in the two regions (Williams et al., 1992).

Another factor that can influence the lightning activity in the NE and NW regions is the location of these regions below the downward leg of Hadley cell in tropics. Enhanced subsidence in the El Nino phase and reduced subsidence in the La Nina phase will change the convective activity and thus the vertical development of the clouds. Since lightning activity is very sensitive to the convective activity in clouds, it will be influenced differently in the opposite phases of ENSO.

Yet another factor to influence the lightning activity in the two regions is the opposite relationships of the El Nino and La Nina with ISMR. This factor might have substantially contributed during the 1997-98 ENSO when the El Nino-ISMR inverse relationship was broken and the contradictory results were found to what are reported in the present study (Ramesh Kumar and Kamra, 2012).

7. Conclusions

Our study demonstrates that impacts of El Niño and La Niña on flash rate should be studied season-wise separately in the moist and the dry environments. During the El Niño period, flash rate rapidly increases from the late winter into pre-monsoon season but has no significant effect in the monsoon and post monsoon seasons of moist environment. However, in the dry environment, flash rate does not change during the late winter and pre-monsoon but is higher than normal in monsoon and lower than normal in post monsoon season during El Niño. During the La Niña, the moist environment, flash rate does not change from its normal value in any season and even in the pre-monsoon season of dry environment. However, flash rate is higher than normal in the monsoon and post monsoon seasons of the dry environment.

Although climate of a region mainly determines the lightning activity in it, impacts of El Niño and La Niña events differ in different meteorological regimes. Moist convection and AOD appear to be key parameters for production of lightning in moist and dry environments, respectively. However, lightning activity is not an independent and linear function of either of these parameters. Other factors such as orography of the land, may significantly affect the lightning activity.

In dry environments flash rate is highly correlated with CAPE, surface temperature, and Convective rainfall, but it is highly correlated only with CAPE in the moist environment. Further, the correlation of flash rate with AOD is significant during both phases of ENSO in the dry environment but only during the El Niño phase in the moist environment.

Progress of monsoon dramatically affects the lightning activity. The lightning activity in the NW region dramatically increases with the arrival of the Bay of Bengal branch of the southwest monsoon and incursion of moisture in July. However, lightning activity decreases in both the NE and the NW regions as the monsoon progresses, possibly due to lower solar isolation, more rainfall cooling the ground, and the scavenging of aerosol particles by raindrops

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Legends

Figure1. Distributions of the mean value of the average flash rates during the El Niño (July 2009 - April 2010), La Niña (July 2010 - April 2011), and normal (1995-2012) periods over the NW and the NE regions.

Figure2. Monthly distributions of the average flash rates during the El Niño, La Niña, and normal periods over the NW and the NE regions.

Figure3. Variations of the monthly mean values of average flash rates during the El Niño, La Niña, and normal periods over the NW and the NE regions.

Figure 4(a)Variation of the monthly average values of (a) surface temperature, CAPE, OLR, and AOD and (b) relative humidity and convective rainfall during El Niño, La Niña and normal periods in the NW and the NE regions.