J. Earth Syst. Sci. (2019) 128:180
https://doi.org/10.1007/s12040-019-1203-9

Distribution of lightning in relation to topography and vegetation cover over the dry and moist regions in the Himalayas

Sunil Oulkar[1,2], Devendraa Siingh[1,*], Upal Saha[3,4] and Adarsh Kumar Kamra[1]

[1]*Indian Institute of Tropical Meteorology, Dr Homi Bhabha Road, Pashan, Pune 411 008, India.*
[2]*Present address: National Centre for Polar and Ocean Research, Vasco-da-Gama, Goa 403 804, India.*
[3]*Department of Physics, Banaras Hindu University, Varanasi 221 005, India.*
[4]*Present address: National Centre for Medium Range Weather Forecasting, Noida 201 309, India.*
**Corresponding author. e-mail: devendraasiingh@tropmet.res.in devendraasiingh@gmail.com*

MS received 24 April 2018; revised 12 March 2019; accepted 29 March 2019; published online 25 June 2019

The impacts of elevation, terrain slope and vegetation cover on lightning activity are investigated for contrasting environments in the north-east (NE) (21–29°N; 86–94°E) and the north-west (NW) (28–36°N; 70–78°E) regions of the Himalayan range. Lightning activity is more at a higher terrain slope/elevation in the dry NW region where vegetation cover is less, whereas it is more at a lower terrain slope/elevation in the moist NE region where vegetation cover is more. In the wet NE, 86% (84%) of the annual lightning flash rate density (LFRD) occurs at an elevation <500 m (terrain slope <2%) and then sharply falls off at a higher elevation (terrain slope). However, only 49% (47%) of LFRD occurs at an elevation of <500 m (terrain slope <2%) and then rather gradually falls off at a higher elevation (terrain slope) in the dry NW. The ratio of the percentages of LFRD and elevation points is much higher in the NW than in the NE above an elevation of ∼1000 m. The impacts of terrain slope and elevation in enhancing the lightning activity are stronger in the dry NW than in the moist NE. The correlation coefficient of the LFRD with the normalised difference vegetation index is higher in the NW than in the NE on both the regional and annual scales. Results are discussed as a caution in using any single climate variable as a proxy for projecting a change in the lightning–climate relationships in the scenario of global warming.

Keywords. Lightning flash rate density; elevation; terrain slope; normalised difference vegetation index.

1. Introduction

The distribution of lightning activity over different geographical regions is of interest due to the substantial damages it causes to agriculture, electric power networks, property and life (Mills *et al.* 2010; Zhang *et al.* 2011; Holle 2016). The dominant seat of lightning is thunderstorms which are the deepest convective clouds in the Earth's atmosphere (e.g., Zipser *et al.* 2006). Thunderstorms are generally initiated by cloud buoyancy that drives vertical motion in electrified convection, resulting from a disparity in localised surface temperature (Williams 1992, 2005; Siingh *et al.* 2011; Kumar *et al.* 2018). The induction of buoyant forces and moisture into the atmospheric boundary layer is directly influenced by the atmospheric forcings such as frictional drag, solar heating and moisture inflow which initiate the thermal convection at the surface (Stull 1988;

Sikka and Narasimha 1995). Hence, the location of occurrence of the most extreme convection associated with lightning activity is closely related to the land-surface conditions and the topography of the region and differs for the dry and moist environments.

Over the Indian subcontinent, the occurrence of lightning is maximum along the Himalayan foothills, especially on the north-east (NE) and north-west (NW) sides of the Himalayan range (Kandalgaonkar *et al.* 2005; Ranalkar and Chaudhuri 2009; Ramesh Kumar and Kamra 2012; Penki and Kamra 2013; Siingh *et al.* 2013, 2014; Saha *et al.* 2017). It is believed that the pattern of the mountain ranges in the NW arc of the Indian subcontinent and the alteration of the wind field due to frictional convergence in the low heat and relatively high surface temperatures give rise to low pressure over central and northern Pakistan. On the other hand, the supply of moisture from the Bay of Bengal along with localised convection is favourable for the genesis of thunderstorms along the NE arc of the Himalayas (Sikka and Narasimha 1995; Houze *et al.* 2007; Romatschke *et al.* 2010). The local orography can generate intense vertical velocity and affect a change in the flash rate by interacting with prevailing wind and/or large-scale processes (Bourscheidt *et al.* 2009; Houze 2012; Barros *et al.* 2004; Albrecht *et al.* 2016). Cummins (2014) also reported that the formation of convective clouds over high terrain is driven by mountain–valley circulations and thus generally begins in the late morning or early afternoon. Penki and Kamra (2013) estimate that 22% changes in the lightning flash rate density (LFRD) in the Himalayan foothills can be associated with the variability in convective available potential energy (CAPE) and the increase in CAPE due to orographic lifting in the NE region of the Himalayan foothills may contribute to ~7.5% increase in lightning activity.

Enhanced lightning activity is also related with the elevation and slope of the terrain. Galanaki *et al.* (2015) showed that terrain slope enhances the cloud-to-ground (CG) lightning activity during winter and autumn in the eastern Mediterranean region. Ziv *et al.* (2009) demonstrated that the combination of the slope angle and coastline favours convection and the associated lightning activity in an area of Israel. Surface topography also affects the orographic jets which occur under favourable conditions such as sufficient slope, steepness and mountain altitude (Egger and Hoinka 1992). Dissing and Verbyla (2003) obtained a positive relationship between lightning and elevation in the interior of Alaska up to a maximum elevation of 1100–1200 m. Schulz and Diendorfer (1999) also reported that lightning flash density increases up to altitudes ranging from 500 to 2000 m in Austria. Extensive studies in the Tibetan Plateau of 4000 m (mean altitude) have provided an insight into the development of thunderstorms and lightning activity in high-lying areas (Qie *et al.* 2003, 2014). Orville and Silver (1997) suggested possible topographical effects on lightning activity over the contiguous United States, especially in the regions of the Appalachians and Rocky Mountains Arizona. Wagner *et al.* (2006) reported a good relation between lightning and altitude with respect to the wind direction and thunderstorm frequency over the United States. Goswami *et al.* (2010) revealed that the steep topographic gradient rather than altitude is responsible for producing deep convection. Santos *et al.* (2013) analysed the climatology of lightning activity over the Iberian Peninsula for the period from 2003 to 2009 and the effect of various forcing factors including terrain elevation in the lightning occurrence. They indicated that the lightning activity occurs predominantly over land where it is associated with orographic lifting during the warmest months while it occurs over the Mediterranean Sea where it is linked with near-surface thermal contrasts during the coldest months.

Vegetation is another factor which is known to interact with the overlying atmosphere by influencing surface energy and hydrological budgets (Kaufmann *et al.* 2003; Siqueira *et al.* 2009). The normalised difference vegetation index (NDVI) represents vegetation cover and health of vegetation and plays a significant role in the global climate studies including convective growth and lightning activity (Sellers *et al.* 1986; Shilong *et al.* 2004; Mabuchi *et al.* 2005; Kumar *et al.* 2016; Saha *et al.* 2017 and references therein). Kilinc and Beringer (2007) reported a noticeable difference in the distribution of the CG lightning flash density on various types of vegetation in the northern territory of Australia. Galanaki *et al.* (2015) found that the forested areas present an increased potential for producing lightning activity. Kotroni and Lagouvardos (2008) reported that the forested and wooded areas increase the lightning yield in contrast with shrubland areas. Recently, Kumar *et al.* (2016) studied the variation of lightning flash distribution, rain and NDVI and their dependency on meteorological parameters along the Indo-Gangetic Plain from 21° to 35°N.

The main objective of this investigation is to study the impacts of elevation, terrain slope and vegetation cover on the lightning activity in the contrasting weather and climatic environments of the NW (dry environment) and NE (humid environment) regions of the Himalayas. Also, the relative importance of these factors on the convective systems electrification has been investigated in the dry and humid environmental conditions. The contrasts in geographical, meteorological and climatological differences between the two regions are described in detail in the next section.

2. Area of study

The two areas for this study are highlighted in figure 1. The NW region (28–36°N; 70–78°E) and the NE region (21–29°N; 86–94°E) are located on the opposite ends of the Himalayan range and experience extreme opposite climates. The wet NE region is surrounded by the Eastern Himalayas, the NE hills (Lushai and Patkai Hills), the Barak Valley plains and the Brahmaputra–Ganges delta and is followed by the moist vegetated land surface, crops at low elevations. This region has a humid sub-tropical climate with a hot, humid summer and is influenced by both the south-west and NE monsoons. In the dry NW region, barren desert land and the Indus plains rise sharply to the Himalayan range.

The buoyancy of the moist low-level flow from the Arabian Sea increases when it passes over the Thar Desert. However, the convective instability is not released upstream of the foothills because this flow is capped by the dry and warm flow from the Afghanistan and the Tibetan Plateau. Finally, deep convection is triggered when this unstable flow is lifted by orographic lifting in the NW region (Medina *et al.* 2010). The convective systems in the NW region contain intense convective echoes. On the other hand, the moist airflow from the Bay of Bengal during the monsoon season enhances its moisture content during its passage over Bangladesh and the Brahmaputra–Ganges delta and develops mesoscale convective systems during its gentle and upward motion as it encounters the Himalayan mountains in the NE (Ramage 1971; Sikka 1977; Goswami 1987). These systems contain a broad stratiform echo. Thus, in both the NE and NW regions, the moist extreme convection is closely related to the unique topography of each region (Medina *et al.* 2010). Some of the deepest convective storms which exhibit extreme lightning activity as well as several lightning hotspots are observed in these regions (Zipser *et al.* 2006; Albrecht *et al.* 2016).

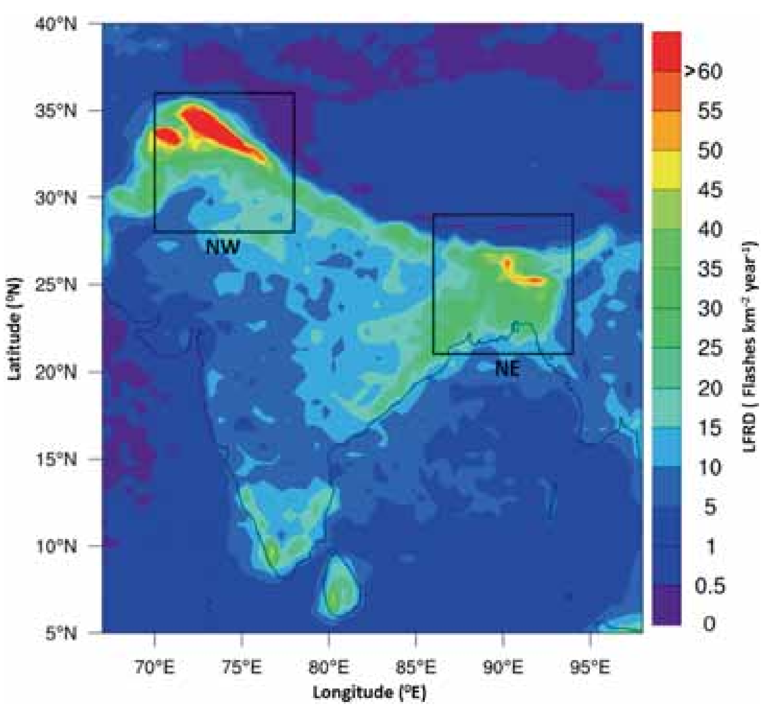

Figure 1. Spatial distribution of the time-averaged LFRD for the period 1998–2013 over South Asia.

3. Datasets used and methodology

The lightning flash rate data *are* obtained from the space-borne optical sensor, lightning imaging sensor (LIS), mounted on the Tropical Rainfall Measuring Mission (TRMM) satellite for the 1998–2013 period. Data files are available from the Global Hydrology Resource Center (GHRC) (website: http://ghrc.msfc.nasa.gov). The high resolution full climatology (HRFC) data of LIS gives a 0.5° × 0.5° grid resolution composite of total [intra-cloud (IC) and CG] lightning bulk production (Cecil *et al.* 2014, 2015). The LIS measures total (IC+CG) lightning with a detection efficiency of ∼69% near local noontime to ∼88% during the night with little sampling bias (Boccippio *et al.* 2000, 2002; Christian *et al.* 2003; Cecil *et al.* 2014). The LIS observes a point on the Earth for 90 s, sufficient time to estimate the flashing rate. Furthermore, an average of 15 yr of data provides a reasonably good mean value for the lightning climatology of the region. The LIS data from both, the 0.5° HRFC mean annual flash rate and the 0.5° high resolution monthly climatology mean monthly and seasonal flash rate climatology have been used in our present analysis.

The NDVI was obtained using a moderate resolution imaging spectroradiometer (MODIS). Vegetation indices product presents gridded statistical summaries of standard monthly L3 Global ∼0.05° CMG MODIS Terra Vegetation Indices monthly product, MOD13C2 v5 (Huete *et al.* 2002). MODIS NDVI provides consistent spatial and temporal comparisons of vegetation canopy greenness, a composite property of leaf area, chlorophyll and canopy structure. The NDVI is defined as (NIR−VIS)/(NIR+VIS), where NIR is near infrared and VIS is visible and the values vary from −1 to +1. Positive values of NDVI indicate dense vegetation canopy and negative values of this index indicate cloud and snow fields. Standing water results in very low positive or, even, slightly negative values of NDVI. NDVI generally generates small positive NDVI values (0.1–0.2) for soils, very low values (0.1 and below) for barren areas of rock, sand and snow, moderate values (0.2–0.3) for shrub and grassland and high value (0.6–0.8) for tropical rainforests.

The elevation data derived from Shuttle Radar Topography Mission (SRTM), datasets result from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA), as well as the participation of the German and Italian space agencies. SRTM gives 1 arcs global elevation data and 1 arcs equivalent of an approximately 30-m resolution (http://dds.cr.usgs.gov/srtm/). SRTM successfully collected radar data over 80% of the Earth's land surface between 60°N and 56°S latitude with data points posted every 1 arcs. The slope data were calculated from the elevation database with the method described by Monmonier (1982). The elevation was computed with a 100 m interval in the lowest level from 0 to 500 and 500 m interval from every 500 to 5000 m for the analysed land point with 0.5° resolution. The number of the land points for each bin was chosen and converted into a percentage of land point for the NE and NW regions. The analysed land point where lightning occurs is taken into account in percentage frequency of the lightning activity over both the regions. From the elevation database, the terrain slope (m deg^{-1}) is computed. The slope at grid points is calculated using the formula of Monmonier (1982) as

$$\text{slope} = \sqrt{\left(\frac{\text{right} - \text{left}}{2 * \text{res}}\right)^2 + \left(\frac{\text{top} - \text{bottom}}{2 * \text{res}}\right)^2}, \tag{1}$$

where res is the resolution, and left, right, top and bottom are the elevation (in m) at these positions adjacent to a grid point, representing the east–west and north–south slope vectors. The resultant of both vectors gives the final slope (m deg^{-1}) at the grid points.

The elevation of the right and left grid points is used for finding the east–west slope, and the elevation of top and bottom grid points is used to find the north–south slope. The resultant of both vectors gives the slope at the grid points. The slope can be expressed by the tan (slope)∗100, which is the result in percentage (Monmonier 1982).

4. Results

4.1 *Variability of lightning activity and vegetation cover with topography*

Figure 1 shows the spatial distribution of the time-averaged LFRD for the time period 1998–2013 over south Asia. It also identifies the two regions, the NW and the NE which exhibit the maximum values of LFRD in the region. Figure 2 shows the spatial distributions of LFRD and NDVI averaged over the period 1998–2013 superimposed

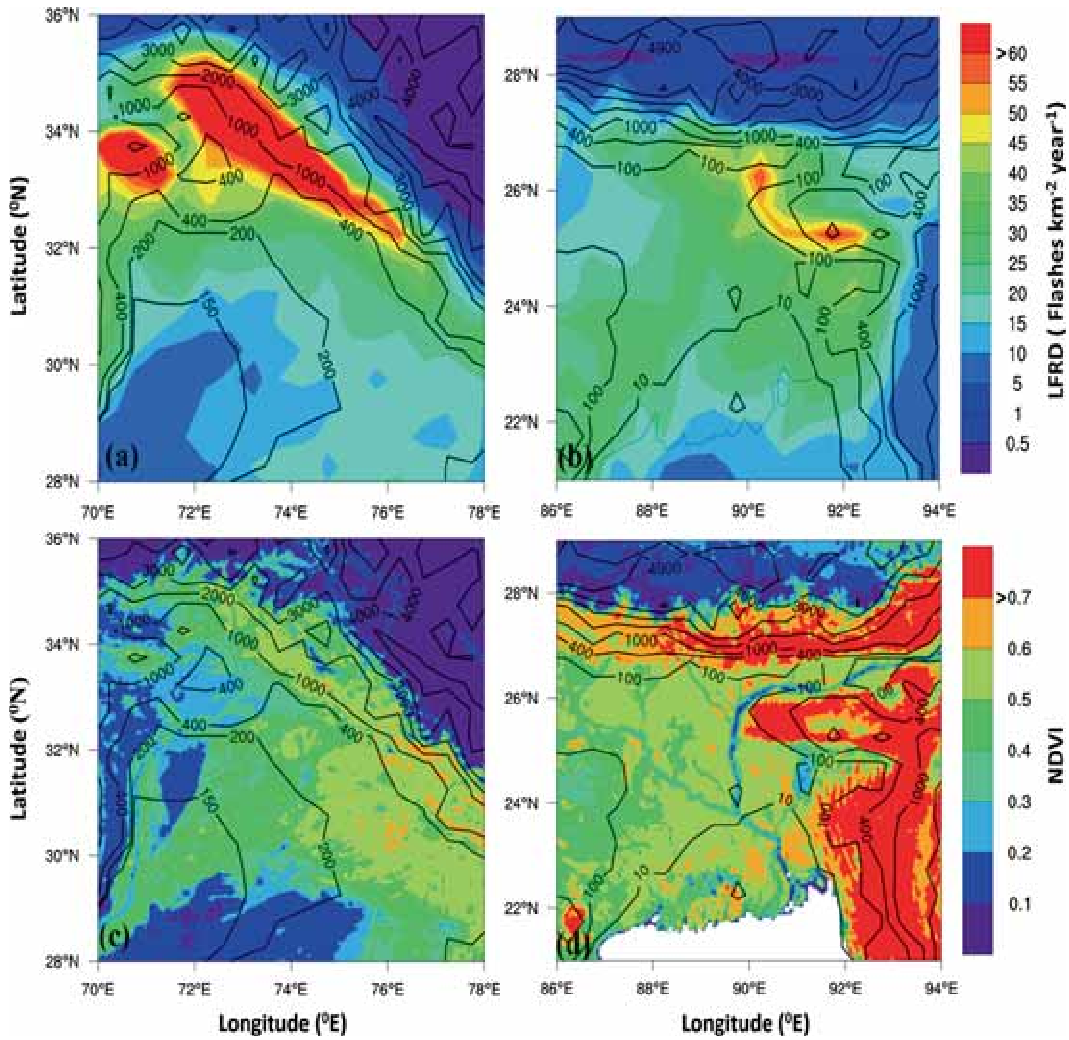

Figure 2. Spatial distribution of the time-averaged LFRD (panels **a** and **b**) and NDVI (panels **c** and **d**) for the period 1998–2013 with contours of elevation superimposed over the NW and the NE regions of the Himalayan range.

with contours of elevation over the NW and NE regions. Although the maximum elevation in both the NW and NE regions is approximately equal and ranges between 4800 and 5000 m, the lightning distributions in the two regions are dramatically different. The maximum lightning activity (>50 flashes km^{-2} yr^{-1}) occurs at elevations of about 400–2500 m in the NW, but only at about 100–400 m in the NE. Most of the NE region of India has 50–80% of its area under forests (Dikshit and Dikshit 2014). Vegetation cover over the NW and the NE is drastically different due to dry conditions in the NW and moist conditions with high rain in the NE. As a result, vegetation cover is more and has a mean NDVI of 0.53 and a maximum of 0.7 in the NE as compared to a mean of 0.32 and a maximum of 0.4–0.5 in the NW. Moreover, the maximum vegetation cover occurs mostly at altitudes of 100–2500 m and reduces to much lower values at higher elevations in the moist NE. On the other hand, vegetation cover is very small (NDVI $\approx$ 0.1) at low altitudes but slowly increases with altitude up to $\sim$2500 m. However, it still remains smaller than 0.6 in the dry NW region which may be due to the terrain cultivation. Comparing figure 2(a and b) with figure 2(c and d) suggests that in the moist NE region, lightning occurs most frequently at low altitudes where vegetation cover is more, while in the dry NW region, the lightning activity and vegetation cover increase with elevation up to $\sim$2500 m.

Figure 3 shows the spatial distributions of the time-averaged LFRD over the period 1998–2013 superimposed with the contours of the terrain slope over the NW and NE regions. Figure 3(a and b) shows that LFRD is maximum in the regions with a terrain slope of <5–15 in the NW but in the regions of a low terrain slope of only $\sim$1 in the NE.

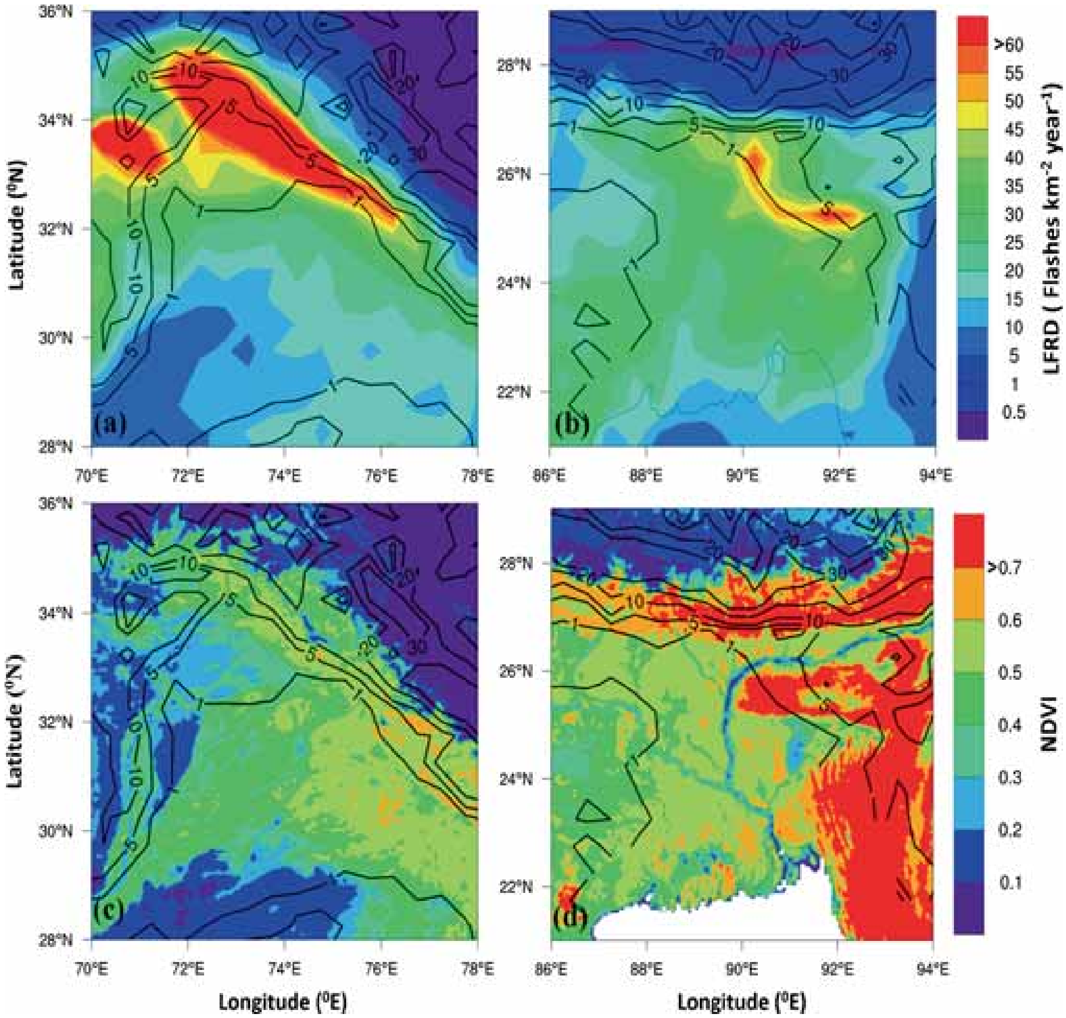

Figure 3. Spatial distribution of the time-averaged LFRD (panels **a** and **b**) and NDVI (panels **c** and **d**) for the period 1998–2013 with contour lines of terrain slope superimposed over the NW and NE regions of the Himalayan range.

However, LFRD decreases from their maximum values in both the NW and NE regions on both the lower and higher terrain slopes and reduces to very low values in the plains. From figure 3(c and d), vegetation is more in the NE region with lesser terrain slope whereas a higher slope associated with terrain cultivation is needed for vegetation to grow in the NW region. Hence, from figure 3, it may be concluded that the dry NW region is much more susceptible to lightning activity where slope (elevation) is higher even when there is no vegetation cover, whereas lightning occurrence in the moist NE is linked with lower terrain slope (elevation) and higher vegetation.

4.2 *Relationship of lightning distribution with elevation and the slope of the land surface*

Information on the lightning activity in different geographical regions can help in better understanding the land surface interactions with the atmosphere. This can be effectively investigated by comparing the percentage numbers of the land points and the annual LFRD in the same bins of elevation over the NE and NW regions. Land points are defined as the number of grids having a particular range of elevation/slope. Here the grid size is taken as 0.5×0.5. In the NW region, lightning activity is low below 100 m elevation and most of it occurs between 100 and 2500 m elevation zones (figure 4). While 54% of the analysed land points have an elevation of <500 m and the corresponding percentage of LFRD is 49%. On the other hand, for 16% of the analysed land points of elevation between 500 and 2500 m, the corresponding percentage of the flash rate is 42%. In contrast, over the NE region, the highest number of LFRD occurs at lower elevations and sharply decreases to very low values at higher elevations. Figure 4 shows that for 47% of the land points having an

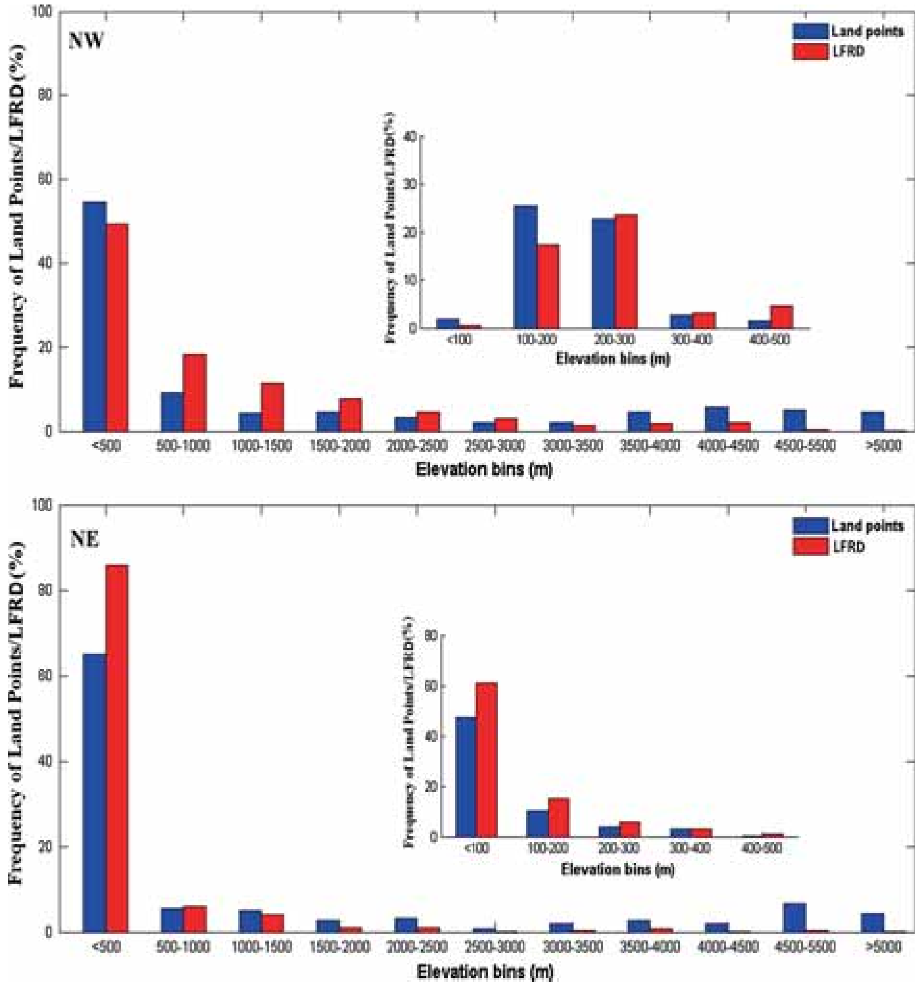

Figure 4. Percentage numbers of land points and annual LFRD averaged over the 1998–2013 period for various bins of elevation in the NW and NE regions. The inset shows the same values at 100 m resolution.

elevation of <100 m, the percentage of the flash rate is 61%. For an elevation of <500 m, the percentages of land points and flash rate are 65% and 86%, respectively. The LFRD percentage is very low for elevations of >1500 m in both the NW and the NE regions. Schulz and Diendorfer (1999) also find a similar flash rate–elevation relation in their observations in Austria. The three-dimensional diagram in figure 5 compliments the information that maximum lightning activity (∼50 flashes km^{-2} yr^{-1}) in the NW is bounded by 500–2500 m elevation and significantly decreases at higher elevation. On the other hand, most of the lightning activity is only at lower elevation (<500 m) and is negligibly small at higher elevation in the NE region (figure 5). In the NW region, LFRD is generally maximum in the latitudinal–longitudinal belt of 33–36°N and 71–76°E and peaks at about 35°N and 71°E; 34°N and 75°E; and 33°N and 76°E points. These areas are generally located at high elevation and have large terrain slopes (figures 2 and 3). In the NE region, LFRD is the maximum in the latitudinal–longitudinal belt of 25–27°N and 88–93°E and peaks at about 25°N and 92°E. These are much lower elevation/terrain slope areas as compared to the NW region. The magnitude of peaks is much greater in the NW than in the NE region. Notable are very low values of LFRD above the elevation of about 1000 m in the NE region throughout the whole range of the longitudinal belt considered in this study.

The orography of the NE and NW regions seems to have different effects on the lightning activity during different seasons. Figure 6 illustrates the data of figure 4 separated by season, i.e., separately in the winter (January–February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–December) months. In the

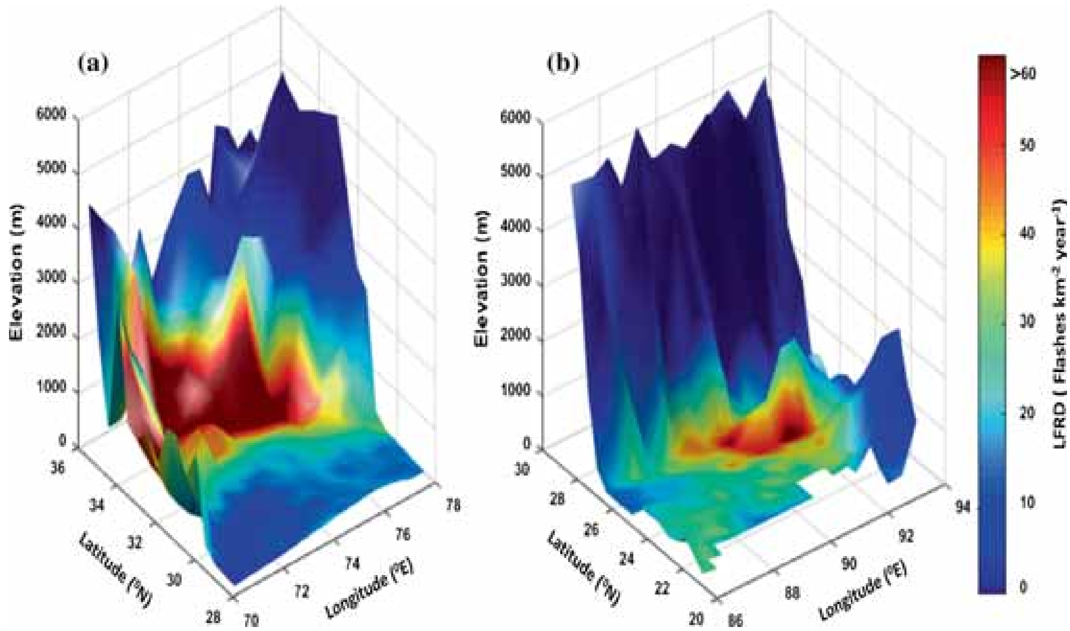

Figure 5. Three-dimensional spatial maps of lightning distribution during the 1998–2013 period in the NW and NE regions.

post-monsoon and winter months, the lightning activity over both the NE and NW regions is <10% (figure 6). The percentage of the flash rate increases to 18% during pre-monsoon months and to 35% for the monsoon months, corresponding to 54% of the analysed land points of <500 m in elevation over the NW region (figure 6). In this region, the effect of elevation between 200 and 2500 m seems to play an important role in the enhancement of the lightning activity during the monsoon season. However, the percentage of the flash rate increases to 55% during the pre-monsoon months, and to 18% during the monsoon months, against 65% of the analysed land points having an elevation of <500 m in the NE region (figure 6). Thus, the change in the flash rate for land points of greater than a given height differs from season to season. The synoptic conditions as well as the supply of sufficient amount of moisture from the Bay of Bengal during the pre-monsoon season give rise to the necessary convergence for the development of thunderstorms and create suitable conditions for the increase in flashes over the NE region (Ranalkar and Chaudhuri 2009).

Similarly, figures 7 and 8 present the percentage of the number of land points and LFRD for various bins of terrain slope over the NW and NE regions on both annual and seasonal scales, respectively. In the NW region, most of lightning occurs in the sloping terrain of <25% (figure 7). However, while for a slope of <2%, there are 66% of land points and a flash rate of 47%, for a slope between 5% and 25%, there are 30% of the land points and a flash rate of 35%. Comparatively, in the NE region for a slope of <2%, there are 65% of the land points and a flash rate of 84% and for a slope a 5–25% there are 29% of the land points and a flash rate of 13% (figure 7). During the monsoon season, the sloping terrain seems to play an important role in the enhancement of the lightning activity in the NW region where a slope of <2%, and the percentage of flash rate is 16% during the pre-monsoon season and 34% during the monsoon season (figure 8). The moist air flowing from the Arabian Sea traverses over the hot and arid Thar Desert and is warmed by the sensible heat flux in the NW region. This air flow may interact with the sloping terrain in the NW in such a way that may enhance the forced ascent and convection and thus enhance the electrical activity. The transportation of sensible and latent heat vertically into the atmosphere by orographic lifting triggers convection and may cause lightning discharges (Kilinc and Beringer 2007). Comparatively, the flash rate is 54% in the pre-monsoon season, 19% in the monsoon season (June–September) and 8% during the post-monsoon and winter seasons for 65% of the land points having a slope of <2% in the moist NE region (figure 8). Galanaki *et al.* (2015) reported that during the winter and spring seasons, the effect of the sloping terrain seems to play an important role in

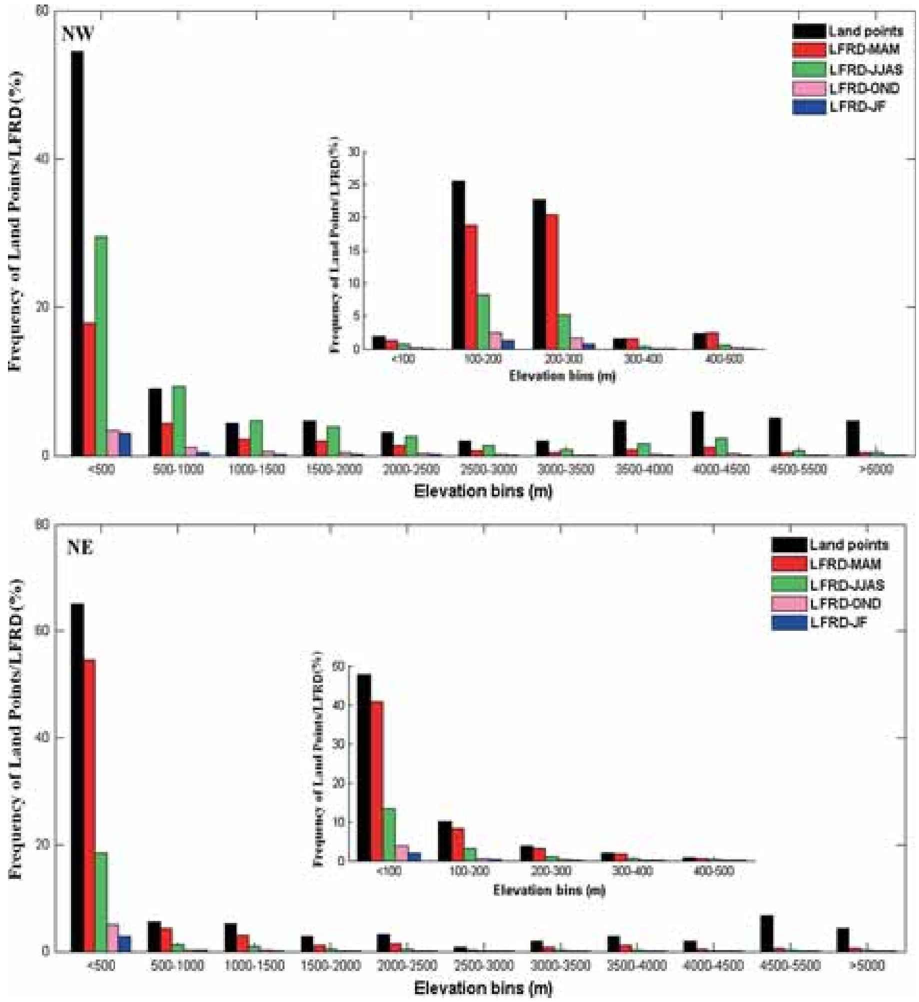

Figure 6. Percentage number of land points and annual LFRD averaged per season for the 1998–2013 period in various bins of elevation in the NW and NE regions. The inset shows the same values at 100 m resolution.

the enhancement of the lightning activity. Our study also corroborates a similar result over the NW region. In the NE region, <2% of the slope plays a more dominant role in the enhancement of the lightning activity.

4.3 *Ratio of the LFRD to the number of land points in a given elevation/terrain slope bin – an indicator of orographic lifting*

Differences in the LFRD-elevation/terrain slope relations between the NW and NE regions may bring out how the orographic lifting impacts the convection and lightning activity in the climatologically opposite environments. Figure 9(a and b) shows the ratio of the percentage change in the LFRD to the percentage number of land points against elevation/terrain slope bins i.e., the change in LFRD per unit change in elevation/terrain slope. In the moist environment of the NE, this ratio is >1 m for an elevation of <1000 m and <1 for an elevation of >1000 m. Furthermore, this ratio is >1 for <5% of the terrain slope and is <1 for >2–5% of the terrain slope. In contrast, in the dry environment of the NW region, this ratio is <1 for an elevation between <200 and >2500 m, and >1 for an elevation between 200–2500 m with a maximum value of ∼2.7 at an elevation of 1000–1500 m. Furthermore, this ratio is <1 for a terrain slope of <2% and mostly >1 for a terrain slope of >2%. Furthermore, in both the NE and NW regions, this ratio shows another secondary maximum at a terrain slope of 30–35% and 35–40%, respectively.

Figure 9(a and b) brings out some important differences on the effect of orography on the lightning activity in the climatologically opposite environments of the NE and NW regions. While the amplitude of the ratio (in both figure 9a and b) varies between 0 and 2 in the NE region, it attains a maximum value of ∼2.7 in figure 9(a)

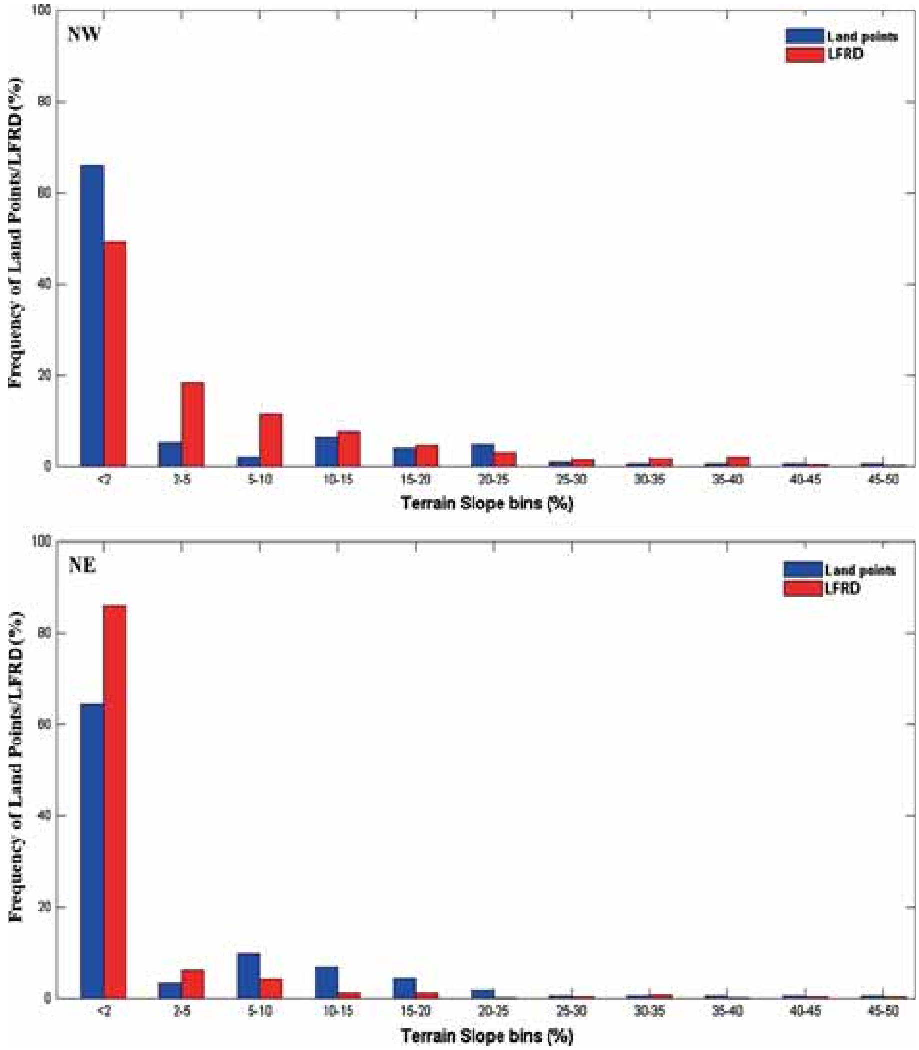

Figure 7. Percentage number of terrain slope and annual LFRD averaged over the 1998–2013 period for various bins of terrain slope in the NW and NE regions.

and ∼6 in figure 9(b) in the NW region. This result implies that both the elevation and terrain slope can enhance the lightning activity in both the NE and NW regions but their impact is much stronger in the dry environment of the NW than in the wet environment of the NE. Furthermore, for increasing the lightning activity, the impact of the terrain slope is stronger than that of elevation in either region. This result is also supported by the finding of Goswami *et al.* (2010) who concluded that a steep topographic gradient rather than altitude is responsible for producing a deep convection which is directly related to the production of lightning.

4.4 *Correlation between LFRD and NDVI*

The two regions of the NE and NW have vast differences in NDVI. Since 50–80% of the area in the NE region is a forest (Dikshit and Dikshit 2014), NDVI over it is more throughout the year with a mean of 0.53 as compared to a mean of 0.32 in the NW. Such a difference in average vegetation results because of dry conditions in the NW and moist conditions with plenty of rain in the NE. Figure 10 shows the variation in the monthly mean of NDVI in the NW and NE regions during the period 1998–2013. NDVI varies from 0.45 to 0.62 over the NE region, whereas in the NW region, it varies from 0.21 to 0.40. Furthermore, the variation in the NDVI is annual with a maximum in the month of October over the NE region and semi-annual with maxima in February and August–September and minima in May and November over the NW region. The maximum in the month of February corresponds to the rabi crops and in the months of August–September to the green cover associated with the monsoon

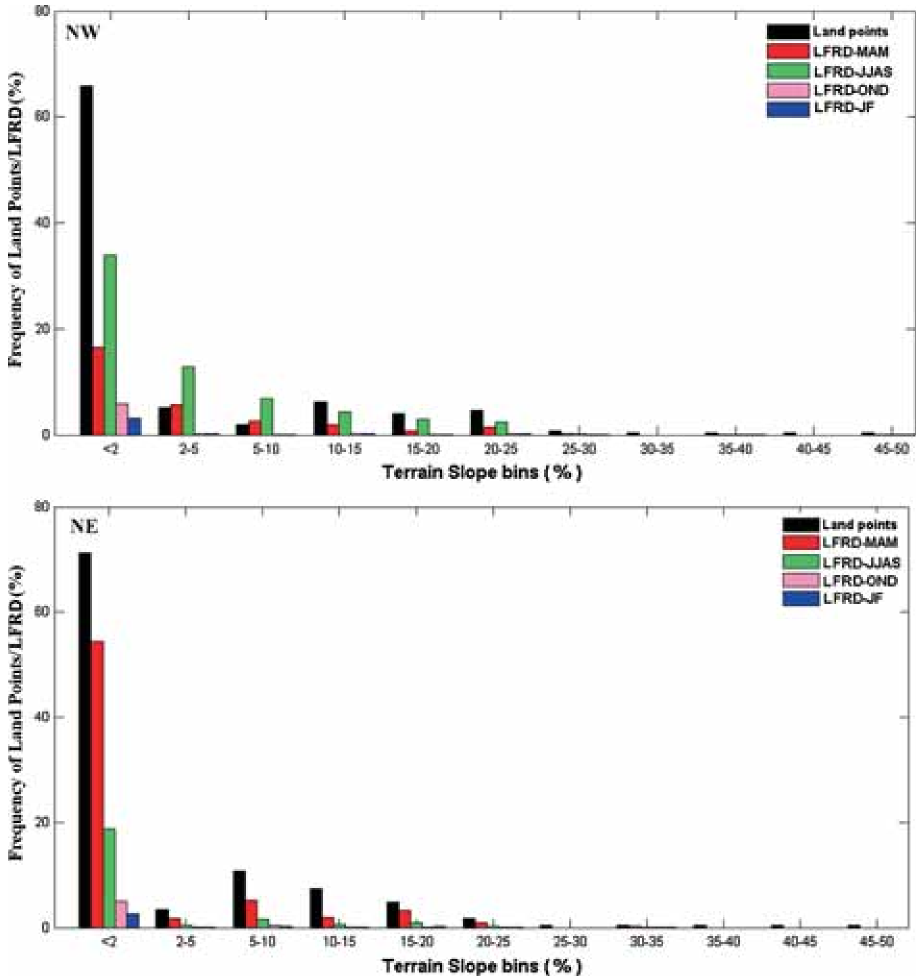

Figure 8. Percentage number of terrain slope and annual LFRD averaged per season for the 1998–2013 period for various bins of terrain slope in the NW and NE regions.

rainfall. Similar variations of NDVI are reported by Kumar *et al.* (2016) for a wide area of the Indo-Gangetic Plain.

In figure 11 are plotted the values of the flash rate and NDVI averaged over the 1998–2013 period for every grid point along with a linear fit for the NE and NW regions. The average values of the correlation coefficient of the LFRD and NDVI are only 0.38 in the NE region and it is 0.43 in the NW region. The correlation between LFRD and NDVI in the NE and NW regions is not very high even on a seasonal scale (figure 12). The values of R_t for Pearson's product moment correlation coefficients calculated for linear relation between seasonal and annually averaged LFRD and NDVI in the NE and NW regions are shown in table 1. However, in spite of a weak correlation and a large scatter in the data, it is noticeable that lightning activity consistently shows an increasing trend with NDVI in all seasons in both regions (figure 12). This fact indicates the possibility of a positive correlation existing between NDVI and the flash rate in view of the fact that lightning activity depends on several other parameters. Nature and growth patterns of vegetation growing at different elevation in contrasting environments widely differ from each other. Also, such differences in vegetation may widely differ in different seasons. Such differences may grossly affect the exchange of moisture content between the land surface and the atmosphere. This is likely to influence the cloud electrification and the lightning activity (Pielke 2001). Therefore, any consistent correlation between the averaged values of NDVI and LFRD may be significant and needs to be further analysed in more detail. So, it must be added here that the impact of NDVI on the distribution of lightning needs to be further investigated in more detail with respect to different vegetation growing at different elevation in contrasting environments.

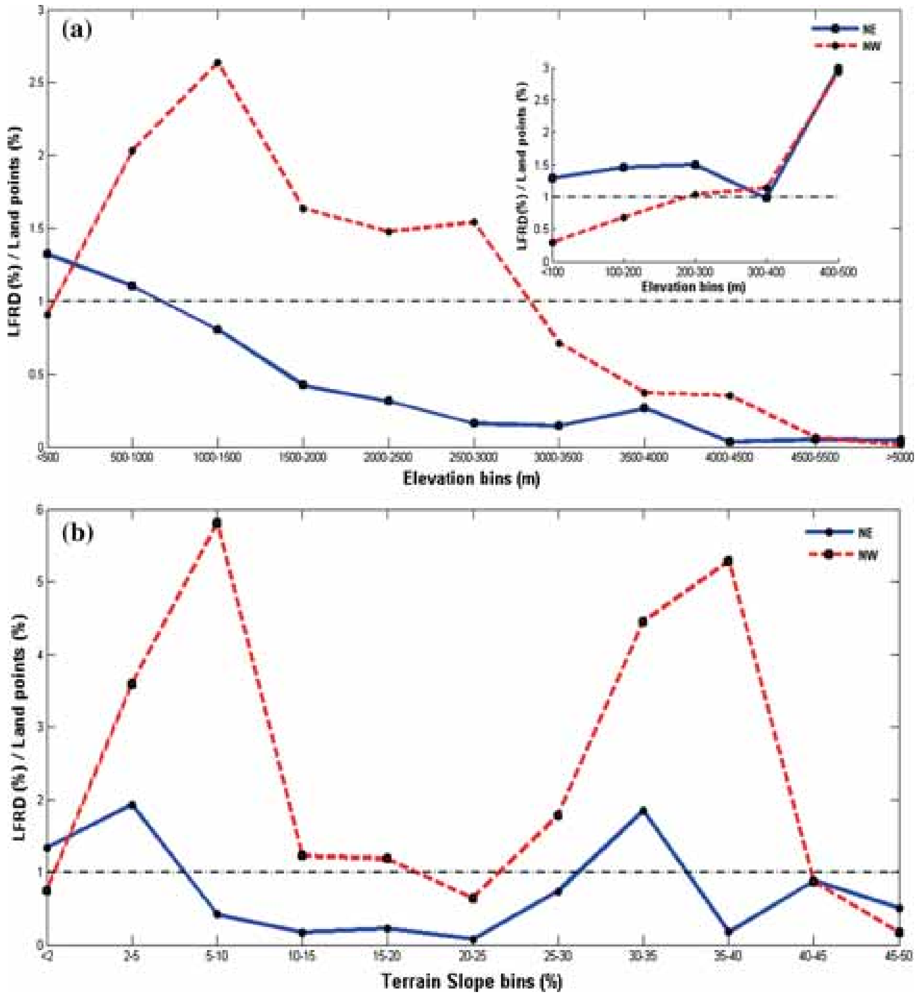

Figure 9. Ratio of the LFRD to the number of land points per elevation/terrain slope bin against (**a**) elevation bins and (**b**) terrain slope bins in the NW and NE regions.

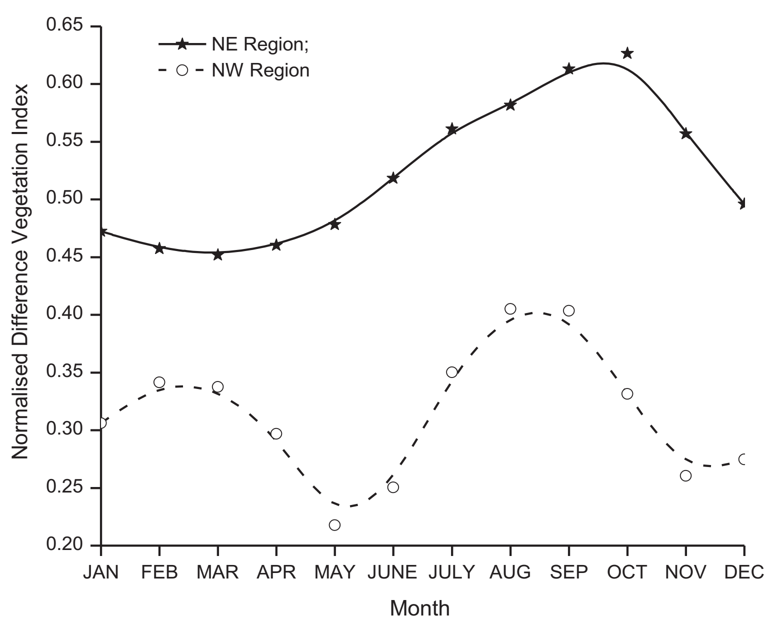

Figure 10. Seasonal variations of the monthly mean value of NDVI averaged over the 1998–2013 period in the NW and NE regions.

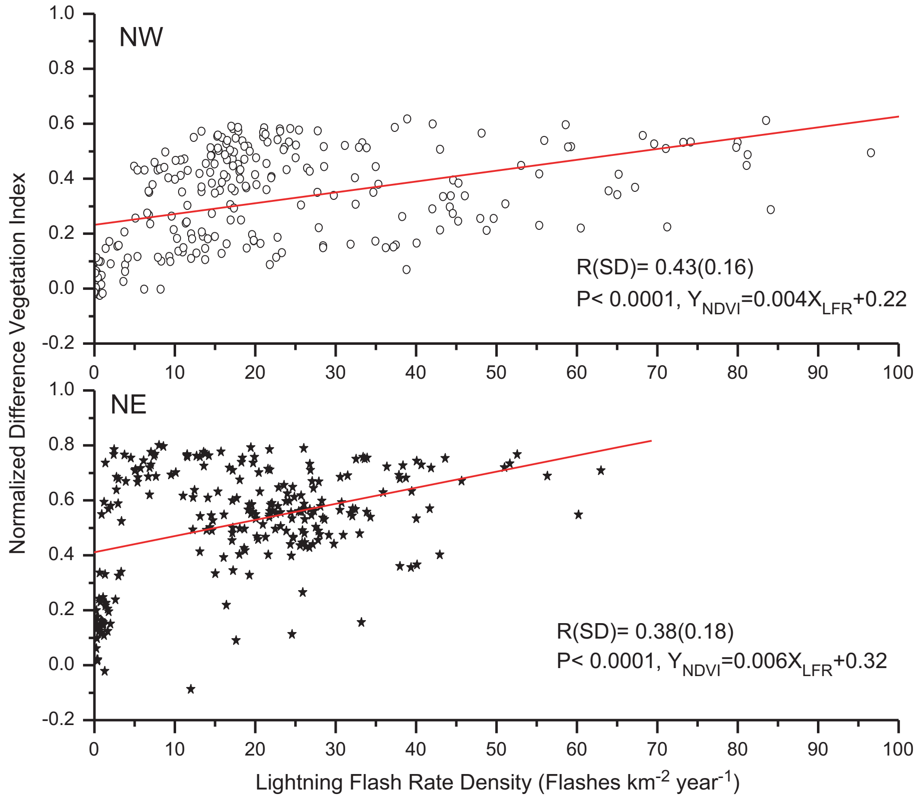

Figure 11. Correlation between the monthly averaged values of the LFRD and NDVI for the 1998–2013 period in the NW and NE regions, where R is the value of the Pearson's correlation coefficient, SD is the standard deviation and P is the significance level.

Table 1. *Values of* R_t *for Pearson product moment correlation coefficient for the seasonally and annually averaged values of the LFRD and NDVI.*

	Annual	Winter	Pre-monsoon	Monsoon	Post-monsoon
NW	0.44	0.65	0.44	0.47	0.26
NE	0.38	0.32	0.33	0.26	0.25

5. Discussion

While projecting for the change in lightning activity in a warmer world in a scenario of global warming, Price (2009) concluded that areas that experience surface drying in future will experience increased lightning activity. This conclusion is in conformity with the result of Williams *et al.* (2005) that lightning activity increased as the thunderstorm cloud base height increased which implies drier surface conditions where such thunderstorm develops. The occurrence of predominately positive lightning in a drier environment also supports it (Carey and Buffalo 2007). The analysis of Penki and Kamra (2013) also confirms more lightning in the drier NW region than in the wet NE region in the Himalayas. Also, several climate models predict an increase in lightning activity as the climate dries (Price and Rind 1994; Grenfell *et al.* 2003; Shindell *et al.* 2006). However, as emphasised by Price (2009), a lightning–climate relationship for different locations may be influenced by several factors such as topography, vegetation, aerosol suspended in the atmosphere, atmospheric circulation patterns, ocean currents, etc. For example, the main difference between African and South American lightning activity has been explained due to Africa being hotter and drier than South America (Williams and Satori 2004). The greater continentality of Africa is attributed to its greater elevation, and to the asymmetry of the synoptic scale delivery of moisture to the region. Hence, caution is needed in using any single climatic variable as a proxy for climate–lightning relationships about long-term changes in the climate (Lindzen *et al.* 1995). This study is a step in that direction.

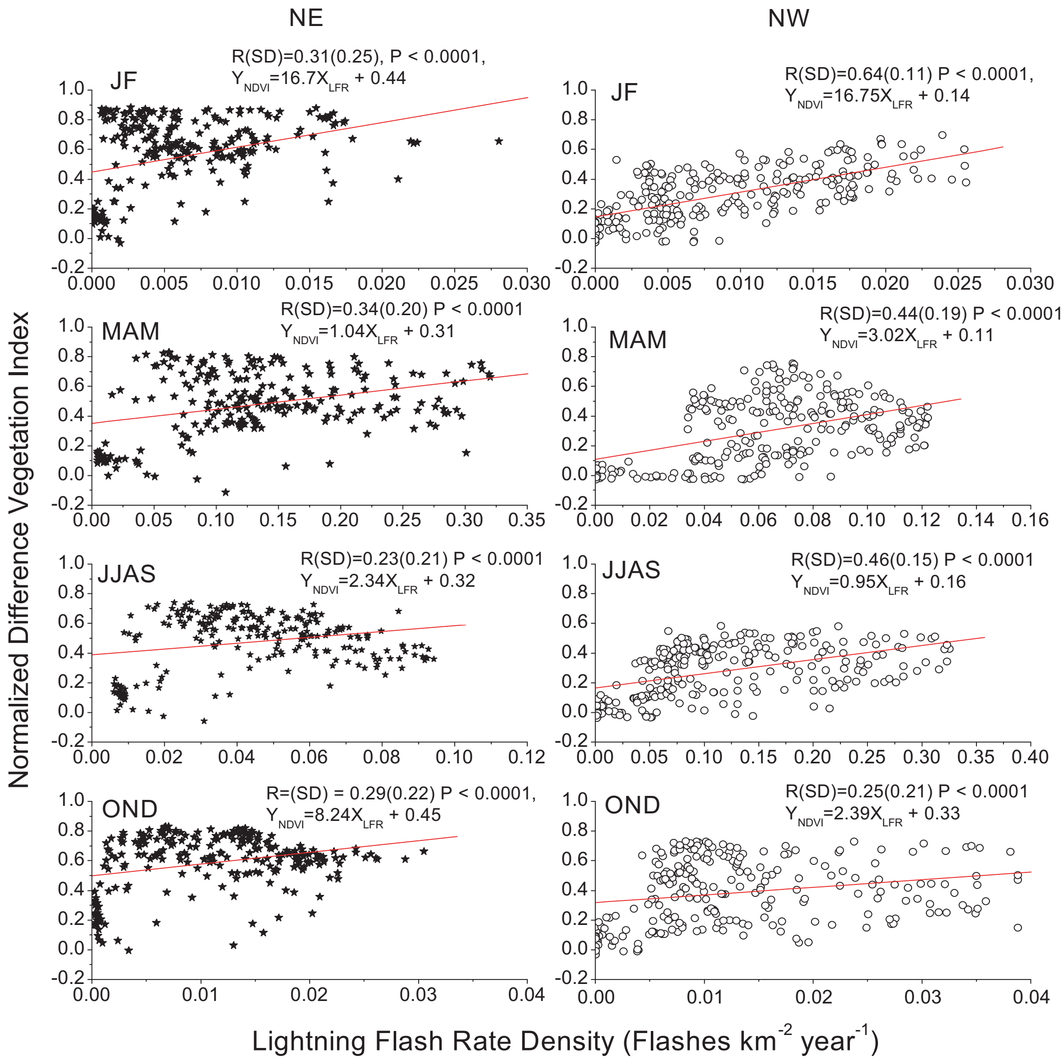

Figure 12. Correlation between the monthly averaged values of the LFRD with NDVI for different seasons during the 1998–2013 period in the NW and NE regions, where R is the value of the Pearson's correlation coefficient, SD is the standard deviation and P is the significance level.

Bonan (2008) reported that forest areas have deeper roots, hold more water and have higher latent heat fluxes. Also, Pielke (2001) suggested that the highest leaf area in the forest permits more transpiration of water vapour into the air and, subsequently, produces higher CAPE and deeper convection. They attributed this effect to the existence of large latent heat fluxes in the forested area and their potential to enhance convection. This may turn into enhanced lightning activity in the forested areas such as at the lower elevations in the moist environment of the NE region.

It must be mentioned here that in addition to the land surface conditions investigated in this paper, several other processes such as the land surface–atmosphere interactions and the microphysical and dynamical characteristics of clouds are also significant and perhaps major contributions in determining the lightning activity in a region. The influence of such processes places a limitation on the significance of the quantitative estimates of the conclusions reached in this study. Therefore, the results of this study need be taken only as guidelines. Numerical modelling, including all such effects may help in isolating the relative contributions of different factors on lightning activity in a region.

6. Conclusions

In the NW region, the lightning flash rate is the maximum during the month of June whereas in the NE region, it has two maxima, one in April and another, secondary maxima, in September. The dry NW region is more susceptible to lightning activity where terrain slope/elevation is more even when there is little or no vegetation cover. However, lightning activity is more in the moist region of NE at a lower terrain slope/elevation and higher vegetation cover. In the moist environment of the NE, 86% (84%) of LFRD occurs at elevations of <500 m (terrain slope <2%) and then sharply falls off at higher elevations (terrain slope). Most of the lightning in the NE occurs in the pre-monsoon season. On the other hand, in the dry environment of the NW, only 49% (47%) of LFRD occurs at elevations of <500 m (terrain slope <2%) and then rather gradually falls off at higher elevations (terrain slope). Unlike in the NE, most of the lightning in the NW region occurs in the monsoon season. Moreover, the ratio of the percentages of LFRD to the elevation points is much higher in the NW than in the NE above an elevation of a ∼1000 m. Furthermore, while this ratio continuously decreases with elevation in the NE, it attains a maximum at an elevation of 1000–1500 m and then decreases with elevation in the NW. Also, the variation of this ratio is much higher in the NW than in the NE at all slopes above 2%. Furthermore, variation of this ratio with terrain slope shows two maxima in each region, at 2–5% and 30–35% of terrain slope in the NE and at 5–10% and 35–40% of terrain slope in the NW. The variation of NDVI is annual in the NE but semi-annual in the NW. The correlation coefficient of the LFRD with NDVI is higher in the NW than in the NE on both regional and annual scales. It is significant that in spite of large scatter in data, the LFRD always shows an increasing trend with the increase in NDVI on annual and seasonal scales in both the NE and NW regions.

In summary: (i) both the elevation and terrain slope enhance the lightning activity in both the NW and NE regions; (ii) the impacts of elevation and slope on LFRD are stronger in the dry environment of the NW than in the humid environment of the NE; (iii) the impact of terrain slope in increasing the LFRD in either region, which is stronger than that of elevation; (iv) the LFRD is better correlated with NDVI in the dry NW than the humid NE region; and (v) LFRD is more at a higher elevation in the NW where vegetation is less but at a lower elevation in the NE where vegetation is more.

Acknowledgements

This research study conducted by the Indian Institute of Tropical Meteorology Pune was funded by the Ministry of Earth Sciences (MoES), Government of India. AKK acknowledges the support under the INSA Honorary Scientist Programme. We are grateful to GIOVANNI NASA, TRMM and SRTM teams for providing the data through their websites.

References

Albrecht R I, Goodmann S J, Buechler D E, Blakeslee R J and Christian H J 2016 Where are the lightning hotspots on earth? *Bull. Am. Meteorol. Soc.* ES227–ES252, https://doi.org/10.1175/BAMS-D-14-00193.1.

Barros A P, Kim G, Williams E and Nesbitt S W 2004 Probing orographic controls in the Himalayas during the monsoon using satellite imagery; *Nat. Hazards Earth Syst. Sci.* **4** 29–51, https://doi.org/10.5194/nhess-4-29-2004.

Boccippio D J, Goodman S J and Heckman S J 2000 Regional differences in tropical lightning distributions; *J. Appl. Meteorol.* **39** 2231–2248, https://doi.org/10.1175/1520-0450(2001)0402.0.CO;2.

Boccippio D J, William J K and Blakeslee R J 2002 Performance assessment of the optical transient detector and lightning imaging sensor. Part I: Predicted diurnal variability; *J. Atmos. Ocean Technol.* **19** 1318–1332, https://doi.org/10.1175/1520-0426(2002)019<1318:PAOTOT>2.0.CO;2.

Bonan G 2008 *Ecological Climatology (Concept and Application)*; Cambridge University Press, Cambridge, pp. 271–276, ISBN: 978-0521-69319-6.

Bourscheidt V, Pinto O, Naccarato K P and Pinto I R C A 2009 The influence of topography on the cloud-to-ground lightning density in South Brazil; *Atmos. Res.* **91** 508–513, https://doi.org/10.1016/j.atmosres.2008.06.010.

Carey L D and Buffalo K M 2007 Environmental control of cloud-to-ground lightning polarity in severe storms; *Mon. Weather Rev.* **135** 1327–1353.

Cecil D J, Buechler D E and Blakeslee R J 2014 Gridded lightning climatology from TRMM-LIS and OTD: Dataset description; *Atmos. Res.* **135–136** 404–414, https://doi.org/10.1016/j/atmosres.2012.06.028.

Cecil D J, Buechler D E and Blakeslee R J 2015 TRMM-LIS climatology of thunderstorm occurrence and conditional lightning flash rates; *J. Clim.* **28** 6536–6547, https://doi.org/10.1175/JCLI-D-15-0124.1.

Christian H J, Blakeslee R J, Boccippio D J, Boeck W L, Buechler D E, Driscoll K T, Goodman S J, Hall J M, Koshak W J, Mach D M and Stewart M F 2003 Global frequency and distribution of lightning as observed from space by the optical transient detector; *J. Geophys. Res.* **108** 4005, https://doi.org/10.1029/2002JD002347.

Cummins K L 2014 Mapping the impact of terrain on lightning incidence and multiple ground contacts in cloud-to-ground Flashes'; In: *XV International Conference* *on Atmospheric Electricity*, 15–20 June, 2104, Norman, Oklahoma, USA.

Dikshit K R and Dikshit J K 2014 Natural Vegetation: Forests and Grasslands of North-East India (Chapter-9); In: *Asian Human Environmental Research* (eds) Dikshit K R and Dikshit J K, Springer, Dordrecht, pp. 213–255, https://doi.org/10.1007/978-94-7055-3_9.

Dissing D and Verbyla D L 2003 Spatial patterns of lightning strikes in interior Alaska and their relations to elevation and vegetation; *Can. J. Res.* **33** 770–782, https://doi.org/10.1139/X02-214.

Egger J and Hoinka K P 1992 Fronts and orography; *Meteorol. Atmos. Phys.* **48** 3–36, https://doi.org/10.1007/BF01029557.

Galanaki E, Kotroni V, Lagouvardos K and Argiriou A 2015 A ten-year analysis of cloud to-ground lightning activity over the eastern Mediterranean region; *Atmos. Res.* **166** 213–222, https://doi.org/10.1016/j.atmosres.2015.07.008.

Goswami B N 1987 A mechanism for the west-north-west movement of monsoon depressions; *Nature* **326** 376–378, https://doi.org/10.1038/326376a0.

Goswami B B, Mukhopadhyay P, Mahanta R and Goswami B N 2010 Multiscale interaction with topography and extreme rainfall events in the northeast Indian region; *J. Geophys. Res.* **115** D12114, https://doi.org/10.1029/2009JD012275.

Grenfell J L, Shindell D T and Grewe V 2003 Sensitivity studies of oxidative changes in the troposphere in 2100 using the GISS GCM; *Atmos. Chem. Phys. Discuss.* **3** 1805–1842.

Holle R 2016 The number of documented global lightning facilities; In: *6th International Conferences Lightning Meteorology*, 18–21 April, 2016, Vaisala, San Diego, California, USA.

Houze R A Jr 2012 Orographic effects on precipitating clouds; *Rev. Geophys.* **50** RG1001, https://doi.org/10.1029/2011RG000365.

Houze R A Jr, Wilton D C and Smull B F 2007 Monsoon convection in the Himalayan region as seen by the TRMM precipitation radar; *Quart. J. Roy. Meteorol. Soc.* **133** 1389–1411, https://doi.org/10.1002/qj.106.

Huete A, Didan K, Miura T, Rodriguez E P, Gao X and Ferreira L G 2002 Overview of the radiometric and biophysical performance of the MODIS vegetation indices; *Remote Sens. Environ.* **83** 195–213, https://doi.org/10.1016/S0034-4257(02)00096-2.

Kandalgaonkar S S, Tinmaker M I R, Kulkarni J R, Nath A, Kulkarni M K and Trimbke H K 2005 Spatio-temporal variability of lightning activity over the Indian region; *J. Geophys. Res.* **110** D11108, https://doi.org/10.1029/2004JD005631.

Kaufmann R K, Zhou L, Myneri R B, Tucker C J, Slayback D, Shabanov N V and Pinzon J 2003 The effect of vegetation on surface temperature: A statistical analysis of NDVI and climate data; *Geophys. Res. Lett.* **30** 2147, https://doi.org/10.1029/2003GL018251.

Kilinc M and Beringer J 2007 The spatial and temporal distribution of lightning strikes and their relationship with vegetation type, elevation, and fire scars in the northern territory; *J. Clim.* **20** 1161–1173, https://doi.org/10.1175/JCLI4039.1.

Kotroni V and Lagouvardos K 2008 Lightning occurrence in relation with elevation, terrain slope, and vegetation cover in the Mediterranean; *J. Geophys. Res.* **113** D21118, https://doi.org/10.1029/2008JD010605.

Kumar S, Siingh D, Singh R P and Singh A K 2016 Influence of meteorological parameters and atmospheric pollutants on lightning, rainfall and normalized difference vegetation index in the Indo-Gangetic Plain; *Int. J. Remote Sens.* **37** 53–77, https://doi.org/10.1080/01431161.2015.1117680.

Kumar S, Siingh D, Singh R P, Singh A K and Kamra A K 2018 Lightning discharges, cosmic rays and climate; *Sur. Geophys.* **39** 861–899, https://doi.org/10.1007/s10712-018-9469-z.

Lindzen R S, Kirtman B, Kirk-Davidoff D and Schneider E K 1995 Seasonal surrogate for climate; *J. Clim.* **8** 1681–1684.

Mabuchi K, Sato Y and Kida H 2005 Climatic impact of vegetation change in the Asian tropical region. Part I: Case of the Northern hemisphere summer; *J. Clim.* **18** 410–428, https://doi.org/10.1175/JCLI-3273.1.

Medina S, Houze R A, Kumar A and Niyogi D 2010 Summer monsoon convection in the Himalayan region: Terrain and land cover effects; *Quart. J. Roy. Meteorol. Soc.* **136** 593–616, https://doi.org/10.1002/qj.601.

Mills B, Unrau D, Pentelow L and Spring K 2010 Assessment of lightning-related damage and disruption in Canada; *Nat. Hazards* **52** 481–499, https://doi.org/10.1007/s11069-009-9391-2.

Monmonier M S 1982 *Computer-Assisted Cartography*; Prentice-Hall, Englewoord Cliffs, New Jersey, 214p.

Orville R E and Silver A C 1997 Lightning ground flash density in the contiguous United States – 1992 to 1995; *Mon. Weather Rev.* **125** 631–638, https://doi.org/10.1175/1520-0493(1991)119<0573:LGFDIT>2.0.CO;2.

Penki R K and Kamra A K 2013 The lightning activity associated with the dry and moist convections in the Himalayan Regions; *J. Geophys. Res.* **118** 6246–6258, https://doi.org/10.1002/jgrd.50499.

Pielke Sr R A 2001 Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall; *Rev. Geophys.* **39** 151–177, https://doi.org/10.1029/1999RG000072.

Price C 2009 Will drier climate result in more lightning? *Atmos. Res.* **91** 479–484, https://doi.org/10.1016/j.atmosres.2008.05.016.

Price C and Rind D 1994 Possible implications of global climate change on global lightning distributions and frequencies; *J. Geophys. Res.* **99** 10,823–10,831.

Qie X, Toumi R and Yuan T 2003 Lightning activities on the Tibetan plateau as observed by the lightning imaging sensor; *J. Geophys. Res.* **108** 4551, https://doi.org/10.1029/2002JD003304.

Qie X, Wu X, Yuan T, Bian J and Lu D 2014 Comprehensive pattern of deep convective systems over the Tibetan Plateau–South Asian monsoon region based on TRMM data; *J. Clim.* **27** 6612–6626, https://doi.org/10.1175/JCLI-D-14-00076.1.

Ramage C S 1971 Monsoon meteorology; In: *International Geophysics Series*, Vol. **15**; Academic Press, San Diego.

Ramesh Kumar P and Kamra A K 2012 Spatio-temporal variability of lightning activity in the Himalayan foothills;

J. Geophys. Res. **117** D24201, https://doi.org/10.1029/2012JD018246.

Ranalkar M R and Chaudhuri H S 2009 Seasonal variation of lightning activity over the Indian subcontinent; *Meteorol. Atmos. Phys.* **104** 125–134, https://doi.org/10.1007/s00703-009-0026-7.

Romatschke U, Medina S and Houze R A Jr 2010 Regional, seasonal, and diurnal variations of extreme convection in the south Asian region; *J. Clim.* **23** 419–439, https://doi.org/10.1175/2009JCLI3140.1.

Saha U, Siingh D, Kamra A K, Galanaki E, Maitra A, Singh R P, Singh A K, Chakraborty S and Singh R 2017 On the association of lightning activity and projected change in climate over the Indian sub-continent; *Atmos. Res.* **183** 173–190, https://doi.org/10.1016/j.atmosres.2016.09.001.

Santos J A, Reis M A, De Pablo F, Rivas-Soriano L and Leite S M 2013 Forcing factors of cloud-to-ground lightning over Iberia: Regional-scale assessments; *Nat. Hazards Earth Syst. Sci.* **13** 1745–1758, https://doi.org/10.5194/nhess-13-1745-2013.

Schulz W and Diendorfer G 1999 Lightning characteristics as a function of altitude evaluated from lightning location network data; In: *Proceedings of the International Conference on Lightning and Static Electricity*, Society of Automotive Engineers, Toulouse, France.

Sellers P J, Mintz Y, Sud Y C and Dalcher A 1986 A simple biosphere model (SiB) for use with general circulation models; *J. Atmos. Sci.* **43** 505–531, https://doi.org/10.1175/1520-469(1986)043<0505:ASBMFU>2.0.CO;2.

Shilong P, Jingyun F, Wei J, Qinghua G, Jinhu K and Shu T 2004 Variation in a satellite based vegetation index in relation to climate in China; *J. Veg. Sci.* **15** 219–226, https://doi.org/10.1658/1100-9233(2004)015[0219:VIASVI]2.0.CO;2.

Shindell D T, Faluvegi G, Unger N, Aguilar E, Schmidt G A, Koch D M, Bauer S E and Miller R L 2006 Simulations of preindustrial, present-day, and 2100 conditions in the NASA GISS composition and climate model G-PUCCINI; *Atmos. Chem. Phys.* **6** 4427–4459.

Siingh D, Singh R P, Singh A K, Kulkarni M N, Gautam A S and Singh A K 2011 Solar activity, lightning and climate; *Sur. Geophys.* **32** 659–703, https://doi.org/10.1007/s10712-011-9127.

Siingh D, Ramesh Kumar P, Kulkarni M N and Singh A K 2013 Lightning, convective rain and solar activity-over south/Southeast Asia; *Atmos. Res.* **120–121** 99–111, https://doi.org/10.1016/j.atmosres.2012.07.026.

Siingh D, Buchunde P S, Singh R P, Nath A, Kumar S and Ghodpage R N 2014 Lightning and convective rain study in different parts of India; *Atmos. Res.* **137** 35–48, https://doi.org/10.1016/j.atmosres.2013.09.018.

Sikka D R 1977 Some aspects of the life history, structure and movement of monsoon depressions; *Pure Appl. Geophys.* **115** 1501–1529, https://doi.org/10.1007/BF00874421.

Sikka D R and Narasimha R 1995 Genesis of the monsoon trough boundary layer experiment (MONTBLEX); *Proc. Indian Acad. Sci.-Earth Planet. Sci.* **104** 157–187, https://doi.org/10.1007/BF02839270.

Siqueira M B, Katul G and Porporato A 2009 Soil moisture feedbacks on convection triggers: The role of soil–plant hydrodynamics; *J. Hydrometeor.* **10** 96–112, https://doi.org/10.1175/2008JHM1027.1.

Stull R B 1988 *An Introduction to Boundary Layer Meteorology*; Springer, Berlin, https://doi.org/10.1007/978-94-009-3027-8.

Wagner G, Fuelberg H E, Kann D, Wynne R and Cobb S 2006 A GIS-based approach to lightning studies for west Texas and New Mexico; In: *Proceedings of the Second Conference on Meteorological Applications of Lightning Data*, Society AM, Atlanta, 2006.

Williams E R 1992 The Schumann resonance: A global tropical thermometer; *Science* **256** 1184–1187, https://doi.org/10.1126/science.256.5060.1184.

Williams E R 2005 Lightning and climate: A review; *Atmos. Res.* **76** 272–287, https://doi.org/10.1016/j.atmosres.2004.11.014.

Williams E R and Satori G 2004 Lightning, thermodynamic and hydrological comparisons of the two tropical continental chimneys; *J. Atmos. Sol.-Terr. Phys.* **66** 1213–1231.

Williams E R, Mushtak V C, Rosenfeld R, Goodman S J and Boccippio D J 2005 Thermodynamic conditions favorable to superlative updrafts, mixed phase microphysics and lightning flash rate; *Atmos. Res.* **76** 288–306, https://doi.org/10.1016/j.atmosres.2004.11.009.

Zhang W, Meng Q, Ma M and Zhang Y 2011 Lightning casualties and damages in China from 1997 to 2009; *Nat. Hazards* **57** 465–476, https://doi.org/10.1007/s11069-010-9628-0.

Zipser E J, Cecil D J, Liu C, Nesbitt S W and Yorty D P 2006 Where are the most intense thunderstorms on Earth? *Bull. Am. Meteorol. Soc.* **87** 1057–1071, https://doi.org/10.1175/BAMS-87-8-1057.

Ziv B, Saaroni H, Yair Y, Ganot M, Baharad A and Isasrachi D 2009 Atmospheric factors governing winter thunderstorms in the coastal region of the eastern Mediterranean; *Theor. Appl. Climatol.* **95** 301–310, https://doi.org/10.1007/s00704-008-0008-6.

Corresponding editor: Prashant K Srivastava