International Journal of Climate Research
2023 Vol. 7, No. 1, pp. 46-66
ISSN: 2690-2796
DOI: 10.18488/112.v7i1.3543
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An inclusive study of lightning at various temporal resolutions over North East India using hi-res satellite data

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Article History
Received: 5 April 2022
Revised: 13 September 2023
Accepted: 25 October 2023
Published: 8 December 2023

Keywords
Lightning flash density
North East India
TRMM LIS
CAPE
Topography
Convective storms.

ABSTRACT

Average lightning flash rate density (LFD) values for North East India (NEI) are analyzed for the 16-years (1998–2013) period based on high resolution TRMM LIS data. The number of lightning flash strokes are most active from March to October with the highest number of lightning strokes happening during the months of April and May, with the monsoon months witnessing the maximum spatial density shifting to the plains area. After October, LFD begin to decrease across the entire region. The highest LFD with a value of 56.65 flashes km-2 year-1, observed along an escarpment in the southern parts of Meghalaya plateau. The minimum is found in the semiarid high altitude districts along the Tibetan border in north with a value of 0.74 flashes km-2 year-1. We observed considerable Convective Available Potential Energy (CAPE) with moderately high LFD during the monsoon season, indicating the importance of these quantities in monsoon convections over this region. The low-level wind flow has a significant impact on the LFD distributions during the entire year. The Himalayas to the North and Bay of Bengal to the south enhance local convergence and convection resulting in lightning. Results of this study can be used in relation to lightning safety standards.

Contribution/Originality: The study comprehensively analyzes lightning activity in NEI, linking spatial and temporal patterns with environmental factors. It explores seasonal and regional variations, and identifies flash rate density in western NEI using latest TRMM LIS data. Additionally, the research outlines future research directions, enriching our understanding of NEI's lightning patterns.

1. INTRODUCTION

Lightning occurs in cumulonimbus clouds when an imbalance in electric charge breaks down the electrical resistance of air. Lightning is an unpredictable natural striking force that can hit anytime and anywhere and this is what makes it so hazardous. Lightning has been always acknowledged as one of the most fatal natural calamities which is both powerful and spectacular [1-3]. According to an estimation made by Gomes and Ab Kadir [4] "globally human casualty range from 6000 to 24,000 fatalities per year". But, the number of people who stay alive with lifetime injuries, provisional disabilities and psychological suffering may be several times greater than the dead [4]. Many sectors are affected by lightning including health, property, insurance, electricity, transportation, agriculture, telecommunication, forestry, tourism and recreation [3]. Hence lightning is studied as a significant natural phenomenon across a wide spectrum of scientific disciplines including high-energy physics, risk assessment,

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meteorology, hydrology, climate, atmospheric chemistry to name a few. As a corollary to this, the geographical distribution and characteristics of lightning strikes is of great interest to diverse stakeholders.

Singh and Singh [5] observed "an increasing trend in the number of lightning fatalities with time and considerable inter-annual variations over South Asia" [5]. The regions acknowledged as lightning hot spot (regions of maximum lightning occurrence) over South Asia are the Himalayan foothills, in particular the North-East (NE) and North-West (NW) sides of the Himalayan range [6-11]. In North East India (here after NEI) the high frequency of severe convective local storms and associated lightning represents one of the greatest threats to life and property [12]. Still studies on space -time distribution of lightning activity along with their causes over NEI are somewhat meagre. Observations made by TRMM and GPM over the Tropics in the last two decades and data sharing by NASA have made it possible to do a climatological study of lightning activity over NEI. Thayyen, et al. [13] have studied extreme storms in Leh Himalayas using data from the Tropical Rainfall Measuring Mission (TRMM), LIS, the Tropical Microwave Imager (TMI) and the Precipitation Radar (PR) and observed that cloudburst over the region are always accompanied by deafening thunder and lighting. Sen and Roy [14] observed that on a monthly scale, the frequency of thunderstorm days has a consistent spatially cohesive decreasing trend over east central and northeast India, collocated with the intra-annually shifting maximum of thunderstorm activity. Based on TRMM and GPM data, the climatology of lightning activity has been extensively investigated by many researchers in an effort to identify characteristics of severe storms. At the global scales Lightning flash distribution is studied by Christian, et al. [15]; Cecil, et al. [16] and Albrecht, et al. [17] over land such as Central Tibetan plateau in China by Yang, et al. [18]; Qie, et al. [19] and Orville and Huffines [20] over the oceans and Island studied by Hidayat and Ishii [21]; Altaratz, et al. [22]; Bovalo, et al. [23] and at the regional scale studied by Kandalgaonkar, et al. [6]; Kuleshov, et al. [24] and Poelman [25]. Over India and south Asia the diurnal and spatio-temporal variability of satellite observed lightning activity have been studied by Manohar, et al. [26]; Manohar and Kesarkar [27]; Manohar and Kesarkar [28]; Kandalgaonkar, et al. [29]; Kandalgaonkar, et al. [6]; Tinmaker and Ali [30] and Yadava, et al. [31] identified and correlated the lightning-prone regions with the number of casualties reported over India at the state/union territory level. They observed that the spatial distribution analysis reveals that lightning occurs mostly in hilly regions over India throughout the year (26 flash/sq. km/yr) and, however, causes lesser casualties because of the sparse population over the hilly terrain. Recently [32] studied the wind profiling features received from stratospheric-tropospheric (ST) radar at Guwahati, Assam and identified the storm-induced effects in the wind field-derived variabilities, for possible adaptation as inputs for a thunderstorm predictive model. Using TRMM LIS and OTD data, Christian, et al. [15] and Cecil, et al. [16] developed a global lightning map that portray NEI along with Bangladesh as "an area of high lightning occurrence, and is considered one of the global lightning hotspots" [17, 33]. With a spatial resolution of 2.5° scale [34] observed maximum monthly flash rate of 18 flashes km^{-2} $month^{-1}$, from early April to early May in the Brahmaputra valley in Assam [34]. A number of studies in the past have identified NEI as one of the most lightning prone regions in India [35-41]. Over NEI, Rao, et al. [42] discovered that nearly 80 % of rainfall events are associated with the occurrence of a thunderstorm and lightning. The results from these studies estimate thunderstorm frequency over NEI at more than 90 days in a year.

NEI being prone to frequent occurrence of severe convection leading to lightning necessitates a comprehensive analysis of these events both spatially and temporally using hi-resolution data. A knowledge of different causes and processes responsible for the variation in lightning activity at regional scale can contribute towards an improved understanding of worldwide lightning distribution. However, limited research on lightning activity in NEI and existing studies being based on few years' observation limits proper analysis of the complex character of lightning activity over the region. In-depth study on lightning activities that examines when, where, and how often the convective events produce lightning over NEI, is lacking. The purpose of this work is to further the previous investigations of convection producing lightning activity over NEI thereby allowing a significant update of the

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climatology. The results of this study of lightning flashes over NEI can be useful in developing applications for lightning safety standards and in parametization of lightning in climate models, This work is planned as follows. In Section 2, an overview of the dataset is provided along with a description of the region. In Section 3, we examine an annual lightning flash density map and discuss the general areas of maximum and minimum lightning flash values over NEI. We then examine monthly lightning flash density maps that show seasonal progress of lightning activity, i.e. examine how the lightning flash values change through the seasons. In Section 4, we discuss the observed pattern with dynamic and thermodynamic aspects of lightning over NEI. In Section 5, we summarize our work and provide concluding remarks.

2. DATA

A number of researchers have utilised data from earth-orbiting instruments in an effort to work out approximately global flash rates [15, 17, 43-50].

Optical Transient Detector (OTD) and its successor the Tropical Rainfall Measuring Mission- Lightning Imaging Sensor (TRMM-LIS) provided by National Aeronautics and Space Administration (NASA) offer a worldwide, observed multi-annual time series of lightning flash observations from space [15, 43].

The data from OTD/LIS offer an exclusive observational foundation to develop the lightning climatology for global lightning flash distribution at seasonal (e.g., Christian, et al. [15]) and diurnal cycles [51, 52]. In addition the OTD/LIS data facilitate quantitative analyses of different quantities associated with lightning activity. For example, number of flashes per unit time per unit area (called flash rate densities) observed by OTD/LIS can serve as reference in validating global climate models for parameterized flash densities.

In this study we use 16 years lightning flash data obtained from TRMM-LIS sensor observations for the period January 1998 to December 2013 to develop a lightning climatology for NEI. Lightning flash data have a spatial resolution of 0.1°x0.1° and temporal resolution of hourly, daily and monthly scales. The data was obtained from https://ghrc.nsstc.nasa.gov/lightning/data/data_lis_vhr-climatology.html. The monthly and hourly rainfall of TRMM 3B43 algorithm with spatial resolution 0.25° x 0.25° from the aforementioned period obtained from https://giovanni.gsfc.nasa.gov/giovanni/ was used to observe the seasonal and annual variations of total rainfall and obtained from https://giovanni.gsfc.nasa.gov/giovanni/. From the lightning database of TRMM-LIS for the south Asian region, lightning flashes occurring in the NEIN were isolated, producing a set of about 78 thousand flashes. Lightning flash data in daily, monthly, seasonal scale were summed to produce 16-years averages for each category. The For specific humidity and wind the monthly data at different pressure levels was obtained from ERA5 for the period 1998-2013 from (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=form). Following IMD criteria the four seasons experienced by NEI are winter(December through February), Pre-monsoon(March through May), monsoon(June through September), post-monsoon season(October-November). The results are presented in the next section.

2.1. Region

NEI provides an ideal region to increase our understanding of heavy rain-producing convective storms in the tropics because of the frequency of lighting over this area. Valleys, plateaus, grasslands and mountains located in close proximity lends uniqueness to the topography of the NEI and exerts far-reaching influences on its weather and climate. The terrain provides the ideal set-up for the formation of severe convective storms that affect a wide region in the north-eastern part of South Asia.

All the three major types of land-forms (plateau, mountains and plains.), are found in NEI. The region consists of a flat terrain in the central part, with a range of north-south running mountain ranges over the east and south-eastern parts (called eastern hills), and east-west running mountain ranges in the north (Himalayas) (Figure 1). In south southwest lies the Meghalaya Hills reaching a height of 2000m oriented east-west. Wetlands account for

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around 5 per cent, plateau covers an area of 12 percent and the hills and mountains cover about 60 percent of the total area. The Brahmaputra and Barak plains account for the remaining 23 percent of NEI. The border ranges and the hills and dales topography of the region exert both mechanical and thermodynamic influences on the general and seasonal circulation of winds, distribution of pressure, temperature and precipitation.

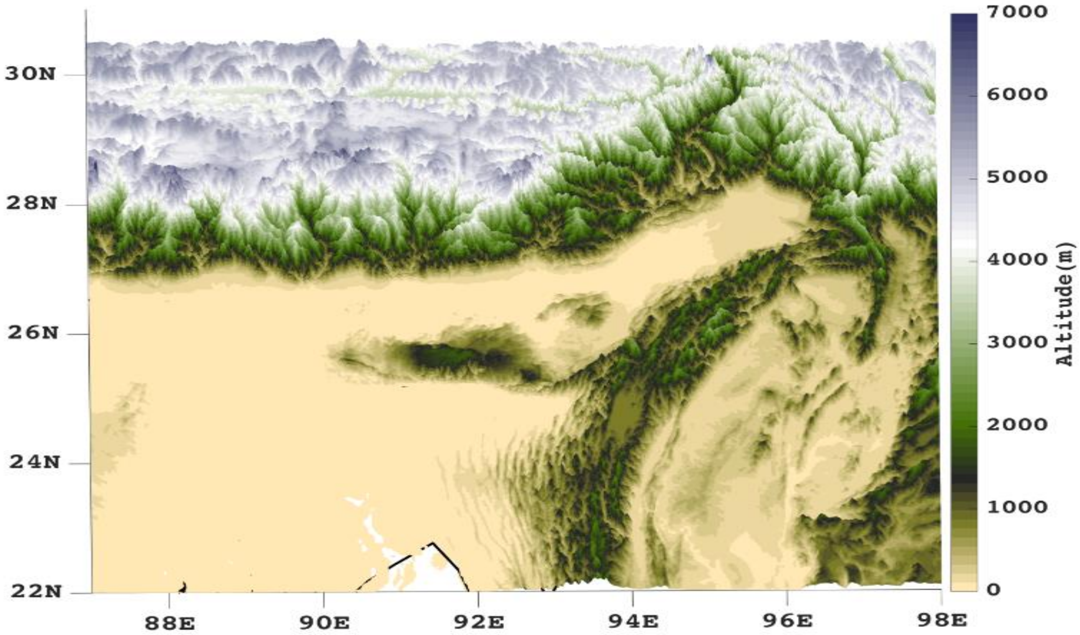

Figure 1. DEM (Digital Elevation Map) of NEIN.

Source: The topographic elevation data is obtained from https://www.ngdc.noaa.gov/mgg/global.

2.2. Analysis Methods

To examine the annual, seasonal and monthly patterns we analyzed lightning flash counts (LFC) for the period 1998-2013 over northeast part of South Asia stretching from 87.5°E-98°E and 21.5°N-30°N. Only flashes that occurred within the geographic boundary of NEIN were taken into account for the purpose of characterizing lightning activity. To identify additional features of lightning over NEI, following Cecil, et al. [53] we employed the quantity Lightning Flash Rate Density(LFD) computed by dividing observed flash counts by the product of view time and area of each grid cell. To obtain the value for any desired timescale, LFD can be multiplied by total seconds in a month, season or year. For our purpose, LFD was computed at a spatial resolution of 0.1° × 0.1° at three temporal scales, i.e. annual, monthly and seasonal. Over the north-eastern part of South Asia a total of 90,859 estimated flashes occurred for the entire period. However only 88% (78,941) of the total flashes occurred over NEI and the remaining occurred over parts of Bangladesh, Bhutan and Myanmar bordering NEI. Next we aggregated the data in daily matrices for further analysis.

3. RESULTS: NEIN TRMM LIS & PR DATA ANALYSIS

The annual distribution of lightning flashes over NEI indicates the southern escarpment of the Meghalaya Plateau to be region of most activity, where the moist marine air first hits the steep slopes. Also, the dominance of lightning activity in western part of NEI as observed from the climatology appears to be a consequence of its geography, topography and terrain. On a seasonal scale, the highest value in the whole plot is 45.6 flashes km^{-2} $season^{-1}$, which is found at 90.25°E &26.25°N (Bilasipara, Dhubri) during pre-monsoon. And the maximum LFRD during monsoon, post-monsoon and winter season is 11.8, 2.2 and 2.9 flashes km^{-2} $season^{-1}$ respectively. The minimum LFRD values for different seasons are viz. pre-monsoon season is 0.14 flashes km^{-2} $season^{-1}$, monsoon 0.29, post-monsoon 0.005 and winter 0.003 flashes $km^{-2}season^{-1}$. The lowest LFRDs were found in the higher reaches (high altitude region) of east Himalayan range within boxes 87.5°E to 98°E and 27°N to 30°N, followed by

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the region in eastern hills of Manipur and Nagaland between 94°E to 98°E and 21.5°N to 30°N (approx.) for almost all seasons.

3.1. Annual Variations

Figure 2(a), the map represents 16-years climatology (annual) of the geographic distribution of detected lightning flashes (expressed as LFRD) and provides an insight into the annual thunderstorm distribution in NEIN with a horizontal spatial resolution of 0.1° x 0.1°. The LFRD distribution indicates that the places of relative areas of lightning maxima and minima are strongly influenced by a variety of combinations of synoptic and mesoscale contributions due to the complex topography of the region and proximity to vast moisture reservoirs. The spatial distribution of LFD over NEI, as shown in Figure 2, agrees with the distribution patterns observed by Albrecht, et al. [17]; Virts, et al. [54]; Christian, et al. [15] using identical TRMM LIS database, but for a shorter duration.

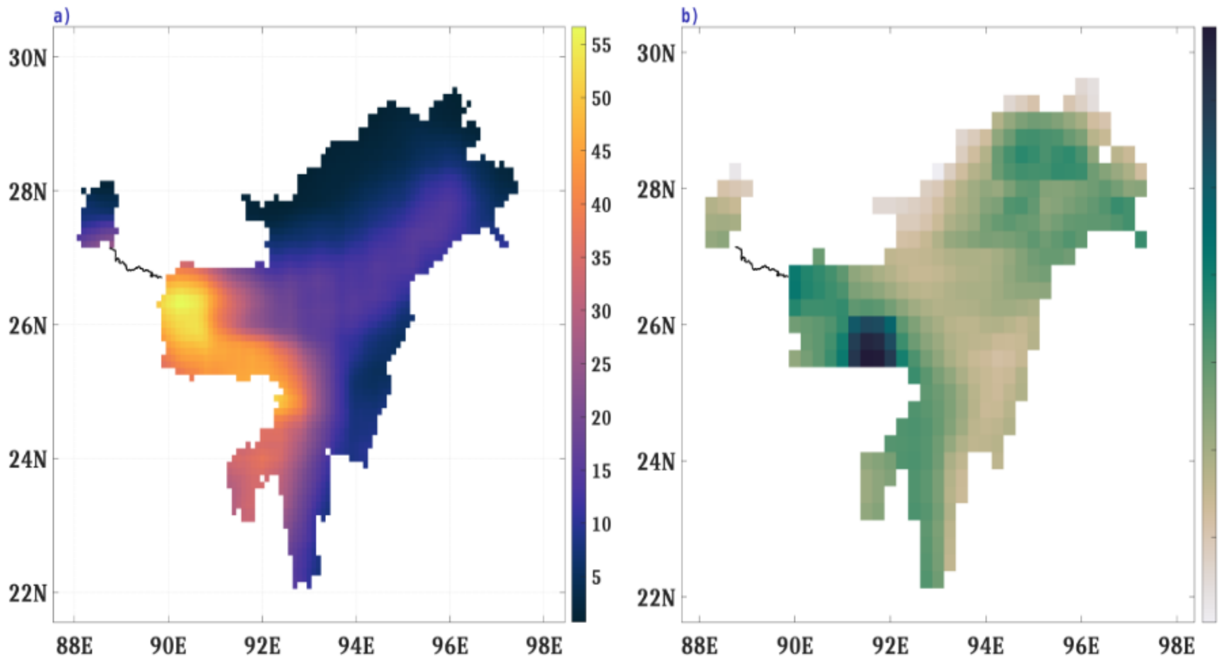

Figure 2. Spatial pattern of annual climatology of a) flash rate density (flashes km^{-2} year^{-1}) b) Precipitation (mm/day) from TRMM LIS and TRMM 3B43 algorithm respectively over NEIN for the period 1998-2013.

A number of interesting features can be seen in the plot of the full region.

- There is a definite trend toward less and less lightning as one goes from southwest to northeast.
- The average annual LFRD was 16.3 flashes km^{-2} year^{-1} over the entire region, and about 38.7 % of the values were <10.0 flashes km^{-2} year^{-1}.
- The highest LFD of 56.6 flashes km^{-2} year^{-1} over NEI is greater than two orders of magnitude when compared with the lowest LFD of ~0.074 flashes km^{-2} year^{-1}.
- On the annual time scale west Assam and Southwest Meghalaya exhibit high lightning frequency during the period of study.
- Higher lightning flash density over south Meghalaya and Arunachal Pradesh during the monsoon might occur due to the interaction between large-scale circulation and the local orography, as observed by Prokop and Walanus [55] who observed that the topographic barrier plays a crucial role in determining the spatial distribution of intense convection and rainfall over the Meghalaya Hills [56].
- The districts of Dhubri, Kokrajhar, Goalpara, and South Salmara-Mankachar lying in western part of Brahmaputra valley and southern districts of Meghalaya have the highest probability of lightning flashes during the year.

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- Most of the minima in lightning activity observed over high altitude regions in East Himalaya and eastern range of hills Manipur, Nagaland bordering Burma, with the least amount observed over the upper Siang and Upper Dibang valley districts in Arunachal Himalayas(29.25°N latitude & 96.35°E longitude) bordering Tibet. The lower occurrence of lightning along NEI's northern limits, (values close to 0 flashes km^{-2} year^{-1}) have a high possibility ofits association to the lower convective activity in the region. A second region with minimum lightning activity is seen over the eastern hilly region, characterised by a series of parallel and sub-parallel north–south-trending ridges of Nagaland and Manipur, which can be attributed to limited low-level moisture, primarily due to the surrounding higher terrain (See Figure 2(a)).
- The Brahmaputra plain compressed between the Siwaliks of Arunachal in the north and Naga Hills, Karbi-Anglong highlands and Meghalaya plateau in the south, have moderate lightning activity over the study period, with an average value of 36 flashes km^{-2} year^{-1}. However the LFRD is uniformly distributed along the entire length of the plain.
- Moderate flash activity (20–30 flashes km^{-2} year^{-1}) was also observed in the states of Mizoram, Tripura Piedmont plain, and Barak valley, a fact that can be explained by the topography and proximity to Bay of Bengal (hereafter BoB). It can also be associated with large-scale convergence zones, such as the ITCZ, according to Christian, et al. [15].
- There is a marked difference in LFRD between regions closer to the BoB i.e. the region first to intercept the moist southerly/southwesterly and the interior high latitude and high altitude parts of the region where atmospheric electrical activity is subdued compared to more central regions of NEIN.
- Areas of flash density maxima do not necessarily occur in the tallest mountain ranges. For example; the Eastern Himalayas in Arunachal Pradesh, reaching to a height of more than 4000m is one of the tallest mountain ranges in NEIN, yet experiences very little lightning. The reason for the low flash densities over this high terrain region is related to the lack of CAPE or moisture over the region concerned.
- Three areas of enhanced lightning activity occur over NEIN.
  A. The first area is located over the south Meghalaya plateau where the flood plains of Bangladesh intersect with the higher terrain of Meghalaya (mountains/plains interface). The concentration of lightning activity in the south indentation of the Meghalaya plateau suggests that the complex shape of the mountain barrier may play a role in the development and distribution of intense mesoscale convection. "The plateau is the first orographic barrier for the humid southwest monsoon winds, on their way from the BoB to the Himalayas" [55].
  B. The second area covers a linear strip plateau associated with west Brahmaputra plains juxtaposed to Tura Hills on the extreme western margin of Meghalaya. The indentation in the western sub-region of NEIN may be the natural preferred end point of trajectories of the BOB Sea air moistened by passage over the wetlands of Bangladesh. Alternatively, the concave indentation in the Himalayan barrier may affect the flow in a way that concentrates low-level convergence in the region of the indentation, as in the case of precipitation maxima in concave indentations on the Mediterranean side of the European Alps [57].
  C. The third area blankets the Cachar plain formed by Barak river and the Tripura plain together with Mizoram foothills lying South of the region. Apart from these, isolated lightning occur over interior regions' of Assam and Nagaland, foothills of Manipur and foothill regions of east Assam.

The annual climatology and distribution of precipitation over NEI, based on the period 1998-2013, and derived from TRMM 3B43 algorithm is shown in Figure 2(b). The area bounded by (24.5°N–26°N) and (91°E–93°E), received the highest precipitation rate, with values exceeding 14 mm day-1. The southern low lying plains bordered by eastern parts of Bangladesh receive moderate precipitation rate of intensity lying between 4-7mm day-1. Central parts of Assam lying on lee of Meghalaya plateau has the least precipitation rate, of less than 4mm day-1. A

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comparison of LFD and precipitation rate (as shown in Figure 2(a) and 2(b)) indicate that areas with high LFD are not necessarily the areas of highest precipitation rates.

Discharges are not frequent (LFRD<0.1flashes km^{-2} year^{-1}) in the east Himalayan region lying in Arunachal Pradesh (23°N–29°N and 92°E–97°E) where a heavy rainfall belt is aligned southeast–northwest. Studies by Williams and Heckman [58] and later by Zipser [59] have observed that convective systems in this region can be characterized as high-precipitation-low-flash [58, 59] which supports our observations.

3.2. Seasonal Variations

Figure 3 (a-d) demonstrates the seasonal maps of time-averaged lightning flash rate over NEIN. Topographic setting of the area marked by orographic barriers to the north and northeast and BoB to the south with the extensive wetlands in the valleys of the region seems to be a major factor in determining the observed spatial distribution of the lightning events at the seasonal scale. With the progress of the season, lightning activity extends east and northward to cover the entire region along with the onset of summer monsoon over NEIN.

The overall distribution pattern shows a well-laid out axis of maxima similar to the annual distribution of LFRD. LFRD values are reasonably high along the foothills of Mizoram, Tripura piedmont plain to the south of NEIN during this season.

3.2.1. Pre-Monsoon Season

Figure 3(b) shows the contours of LFRD during pre-monsoon season over NEIN during 16 year period (1998–2013). The overall distribution pattern shows a well laid out axis of maxima similar to the annual distribution of LFRD. Average LFRD values in the Pre-monsoon season ranges from a minimum of 0.14 flashes km^{-2}season^{-1} (at 96.05°E 29.45°N district of Dibang Valley along the northern boundary with Tibet) to a maximum of 45.6 flashes km-^{2} season^{-1} (at 90.25°E , 26.25°N District of Dhubri lying in western part of NEIN)with a mean of 11.3 flashes km^{-2}season^{-1}.The Brahmaputra valley in the region experiences moderate lightning activity during pre-monsoon season, an average LFRD of 20-30 flashes km^{-2} season^{-1}. LFRD values are reasonably high (~30–40 flashes km^{-2} season^{-1}) along the foothills of Mizoram, Tripura piedmont plain to the south of NEIN during this season.

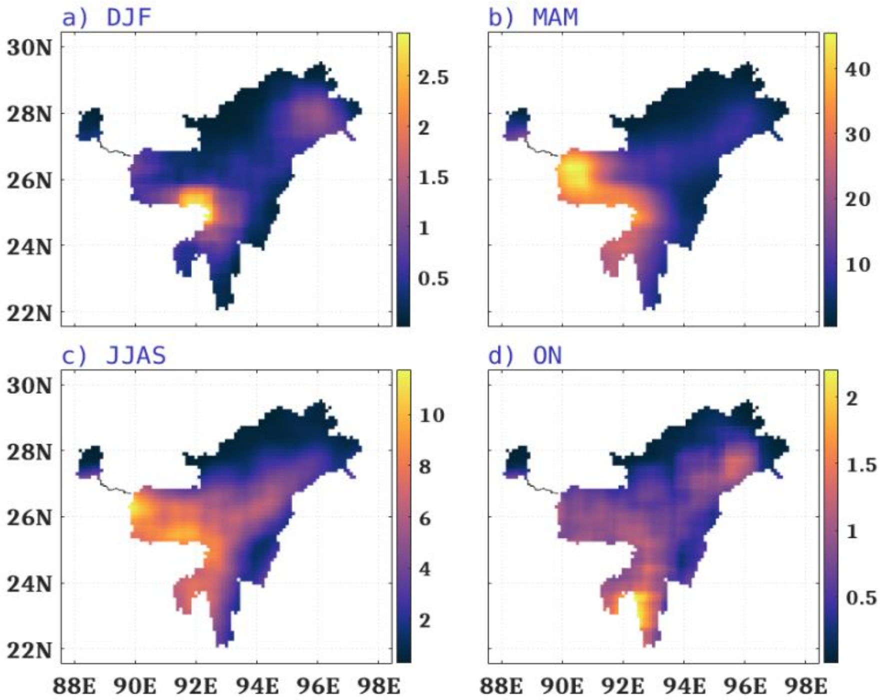

Figure 3. Spatial pattern of seasonal climatology of lightning flash rate density (flashes km^{-2} season^{-1}) over NEIN for the period 1998–2013 from TRMM LIS.

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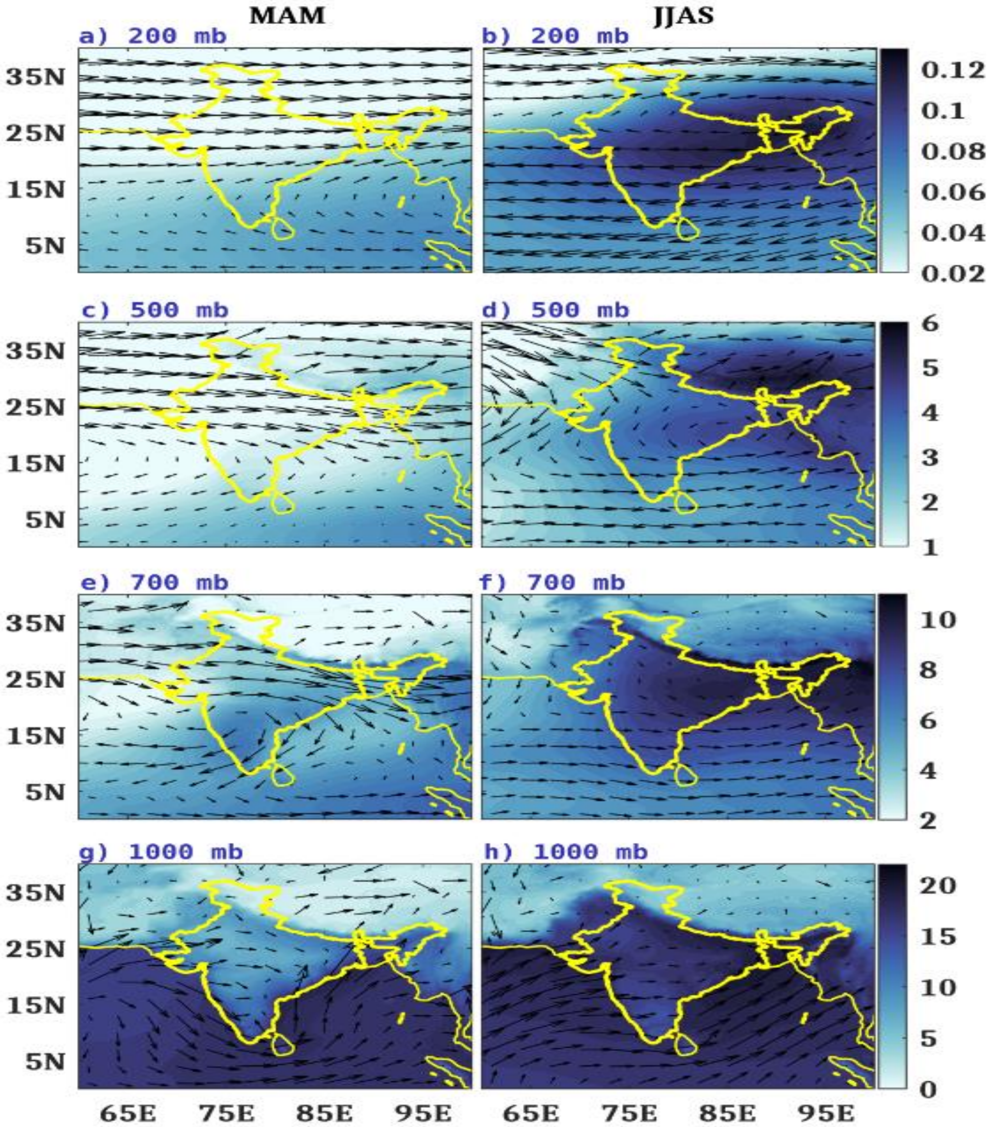

Figure 4. Spatial pattern of wind vector, overlayed on specific humidity at levels (a,b) 200 mb (c,d) 500 mb (e,f) 700 mb (g,h) 1000 mb within longitude 60°E to 100°E and latitude 0°N to 40°N from ERA5 for the period 1998-2013 .[Left panel is for pre-monsoon season (MAM) and right panel is for the monsoon season (JJAS)].

During pre-monsoon season, the specific humidity at 1000 mb is very low over most of the Indian Subcontinent, the exception being NEIN and Bangladesh where it is much higher, the near-surface specific humidity values reach 15-22 g kg^{-1} (see Figure 4(g)). The surface moisture content is low over the higher reaches of Himalaya Mountains along with the Tibetan Plateau (Figure 4(g)). Also, over the eastern hills of Nagaland and Manipur, the values of surface moisture content are low. An area of large specific humidity gradient approximately follows the east coast of India and south coast of Bangladesh to west coast of Burma that divide moist maritime air to the south from dry continental air to the north (Figure 4(g)) and at 700 mb the area of highest moisture extends across the region (Figure 4(e)). Strong west to northwesterlies at 500 mb bring dry (low moisture content) air from the elevated terrain of Afghanistan to the northeastern parts of India (Figure 4(c)). At upper levels, 200mb, there is a strong westerly jet extending northward of 20°N (Figure 4(a)).

In the pre-monsoon season owing to the existence of strong instability in the atmosphere over land the precipitation systems tend to be more convective [33, 60-62]. For the northeast part of South Asia researchers over the years have isolated three mechanisms responsible for the distribution of lightning activities during the pre-monsoon season. They comprise of:

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(a) The terrain effect: orography as observed and identified by Chaudhuri and Middey [63]; Romatschke, et al. [64] and Kandalgaonkar, et al. [6].

(b) Wind discontinuity: Dry line, i.e. presence of wind discontinuity line as shown by Tinmaker and Ali [30]; Weston [60].

(c) Moisture availability: abundant water vapour in the lower troposphere [7, 10].

LFRD distribution over NEI mentioned above is consistent with other lightning studies for India [6, 7, 10, 30, 63, 65]. Studies done by Pathan [66] and later by Qie, et al. [19] and Choudhury, et al. [33] observed that the regions in Bangladesh adjacent to Meghalaya i.e. the Northeastern part of Bangladesh also experience intense thunderstorms associated with higher lightning activity.

3.2.2. Monsoon Season

Convection frequently occurs during the South Asian monsoon (June–September) in NEIN where lightning strikes are also common during the rainy season, when there is a strong monsoonal influence. More than half of the days during this season are days of thunder [67].

Figure 3(c) shows the flash rate density over the NEIN for monsoon season during 16-year period (1998–2013). Overall, mean LFRD value for the season is 3.9 flashes km^{-2}season^{-1} and ranges 0.3 to 11.8 flashes km^{-2}season^{-1}, with highest LFRD found at the location within the box (25.2°N to 26.7°N, 89.8°E to 90.8°E).

In contrast with the lightning distribution during the pre-monsoon season, lightning activities are generally more spread out over the region, particularly to the valleys and foothill regions of NEIN(See Figure 4(b,c)). In other words the region of higher lightning activity spread east ward along the river Brahmaputra during the monsoon season relative to pre-monsoon distribution of higher lightning over western and southern parts of NEI. This expansion may be related to the occurrence of monsoon disturbances that pass through the region and movement of convective systems that is linked to the Madden Julian oscillation (MJO) [6, 68-70].

The monsoon has a significant role in distributing moisture through NEI and the wide spread distribution of thunderstorm activity during the monsoon season can be attributed to the availability of copious moisture in the lower troposphere linked with southwest monsoonal winds and aided by favourable regional topography (Figure 5(h)). This interaction between the moisture laden monsoon flow with the local orography of NEI results in frequent severe thunderstorm and lightning activity. Houze, et al. [71] and Romatschke, et al. [64] have shown that “the location of occurrence of the most extreme convection is closely related to the unique topography of the east Himalayan region”. The same study also observed ‘the form taken by the convection is influenced by the land surface conditions underlying the moist flows, indicating that the terrain plays a key role in releasing and enhancing the convection’ [64, 71]. Apart from these studies, it is well documented that over NEIN cumulonimbus clouds are developed on almost all days during the monsoon season [38, 72].

During the monsoon season due to highly moist marine air mass present in great depth and with suppressed surface temperature over most part of NEIN, the local orography does not allow the highly moist air of low temperature to reach large height. Rather, it turns the moisture into low level clouds and rains. Consequently, the heights of LFC (level of free convection) and of EL (equilibrium level) are low giving rise to low CAPE values(less than 1000 J/Kg) in the monsoon environment. Thus, the chance development of the thunderstorm in this season becomes comparatively less than that in the pre-monsoon season. Vertical air motion in this season is controlled by synoptic scale air motion driven by the horizontal pressure gradient.

3.2.3. Post-monsoon Season

Figure 3(d) illustrates the flash rate density over the NEIN during post-monsoon season (October–November) during 16-year period (1998–2013). Compared to pre-monsoon and monsoon season, lightning activity drops during post-monsoon season, resulting in a completely different spatial pattern of LFRD. The shifting of lightning

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hot spots to new areas, shown in (Figure4(d)), during the post monsoon season has been attributed to western disturbances and onset of north east monsoons by Tinmaker, et al. [73] and Tinmaker, et al. [74]. The LFRD for this season ranges from0.005 to 2.2 flashes km^{-2}season^{-1}. The highest average flash rate density (0.7 flashes km^{-2} season^{-1}) is found at West Phailengin the district of Mamit in South Mizoram. Other spots with higher probability of lightning activity were seen over eastern end of Brahmaputra valley and at isolated places in Meghalaya plateau (western) and Tripura Plains. Kandalgaonkar, et al. [6] observed that the retreat of Inter-tropical Convergence Zone (ITCZ) results in changes in the synoptic scale system, and that lightning activity in east and northeast India is possibly related to this change during monsoon withdrawal. During post-monsoon season, over BoB a number of cyclones and depressions form [75] remnants from these system reaching NEI under the influence of local orography produces a unique convective environment generating lightning. As a result, Tripura (southwest) and Mizoram (south-eastern hilly areas) experience higher lightning compared to other parts of the region. There is less possibility for the encroachment of the moist air from the BoB over interior parts of NEIN and it can be expected that the thunderstorm activity over the region is more controlled by the orographic lifting. Hence the eastern part of Brahmaputra plain which is at higher elevation than the western part records more thunderstorm activity.

3.2.4. Winter Season

Figure 3(a) shows the flash rate density over NEIN during winter season (December-February) for the 16-year period (1998–2013). The spatial distribution of LFD during the winter season resembles the pre-monsoon season LFD but with lesser events. During this season, over the plains, isolated lightning activity is confined to few districts lying in the west of Brahmaputra valley and in eastern part of Assam at the foothill of East end of Himalayas. The highest activity is recorded within the box of 24.6^{O}N to 25.75^{O}N and 91.4^{O}E to 92.9^{O}E over the southern escarpment of Meghalaya plateau and extending into Barak Valley in South Assam. Isolated lightning detected in eastern part of the Brahmaputra Valley in Assam and districts at higher altitude were free of Lightning activities during winter. Lightning activity during winter is noticeably low. In the absence of any other systems present during winter months, orography and western disturbances aid the development of thunderstorms occurring in the months of December, January and February [42].

During winter, wind over NEIN is predominantly northeasterly, reaching over the region from higher latitudes under the influence of Tibetan High. The winds are cold and dry. On occasions during the progress of a western disturbance the wind is moist and predominantly westerly/southwesterly over the NEI [30]. Thus a front of sort is developed along the length of Brahmaputra valley due to the cold and the dry wind of the higher latitudes interacting with comparatively warm and moist wind associated with the Western Disturbances. Such a front like condition is expected to trigger the thunderstorm growth process over the western region and eastern part in the Himalayan foothills. However, the CAPE values under this condition cannot be high and hence the thunderstorms developed during winter are not so intense resulting in very less lightning activity.

3.3. Monthly Variations

No state in NEIN is free of lightning activity in any of the months in a year. Figure 5 shows the monthly cycle of LFRD with two peaks in the month of April (~5 flashes km^{-2} month^{-1}) and September (~1.03 flashes km^{-2} month^{-1}). The LFRD is found to be intensified in the months of March, April and May and is spatially confined to western part of NEIN only (Figure 6(c-e)). Whereas this intensification gets reduced by June (Figure 6(f)) but spread throughout from July till September to central (Brahmaputra valley), Southern (Barak Valley), and touches the Eastern (Foot Hills of Himalaya) part of NEIN (Figure 6(g-i)). By October, the horizontal spread of LFRD starts vanishing with deep patches in Southern (Barak Valley) NEIN (Figure 6(j)). Later, similar type of patches can be seen in South-East and Eastern (Arunachal Pradesh) part of NEIN (Figure 6(k, l)).

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On a monthly scale, peak rainfall activity lags behind peak lightning activity by two months. The lightning activity shows its peaks in the month of April whereas rainfall peaks in July (Figure 5). A secondary peak in lightning activity is observed in the month of September, which is in line with the finding of Tinmaker and Ali [30] but monthly rainfall does not show any such secondary peak.

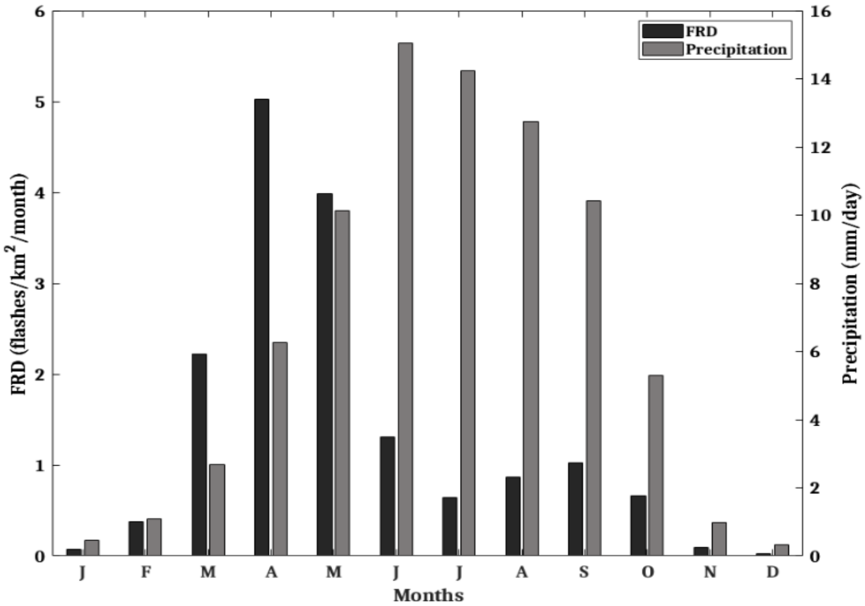

Figure 5. Bar diagram representing the monthly variation of flash rate density (black bars) and Precipitation (grey bars) from TRMM-LIS and TRMM 3B43 respectively over NEIN for the period 1998–2013.

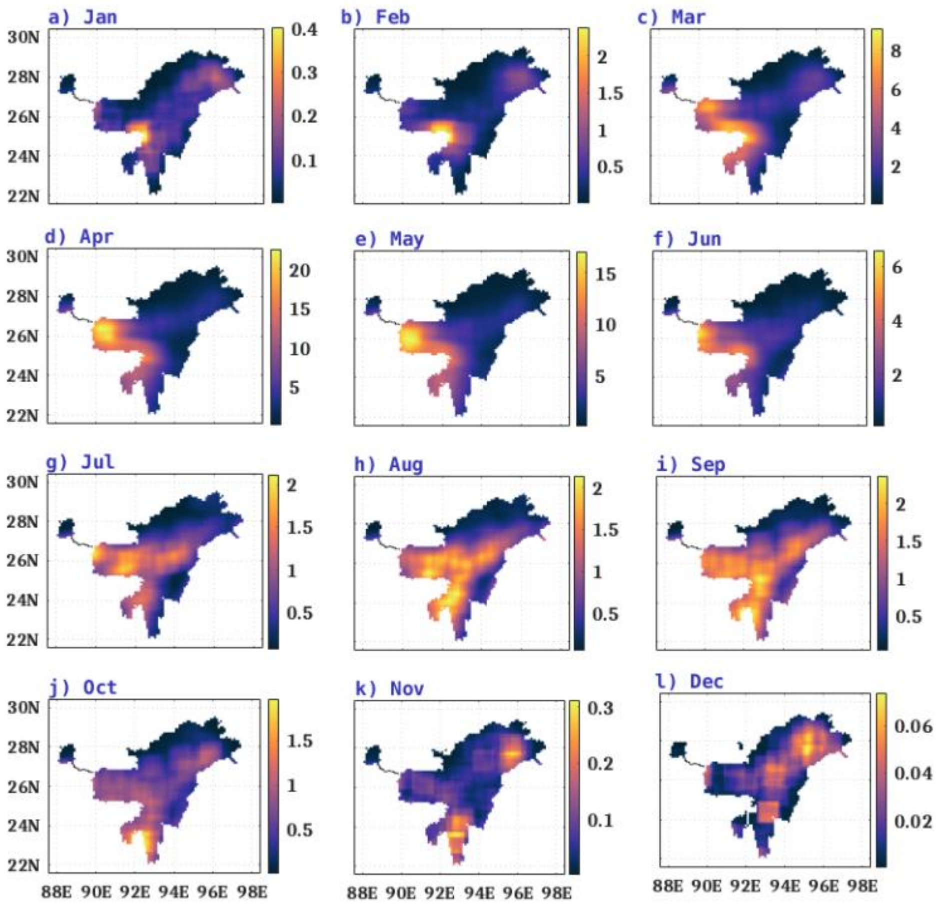

Figure 6. Spatial pattern of monthly climatology of flash rate density (flashes km^{-2} month^{-1}) over NEIN for the period 1998–2013 from TRMM LIS.

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3.4. Diurnal Variations

The amplification of the diurnal pattern occurs mainly due to the contrasting mechanisms of convection between day and night which involve interaction of dynamic flows and the cloud development [76]. The observed diurnal variation of flash (Figure 9) during the pre-monsoon shows high rainfall in sync with high flash only during afternoon/evening and sustains till early morning hours (12-20 UTC), whereas, during early morning to noon the (0-11 UTC) the rainfall is almost double the flash intensity occurring during those hours. During monsoon season the flashes peaks at 13, 18 and 19 UTC, with troughs in between. The rainfall peaks at 6 UTC then again at 18 and 21 UTC. The other two seasons shows very less flashes compared to premonsoon and monsoon season with a fluctuation throughout the hours of the day. But the winter rainfall shows the bell shape distribution with peak at 9 UTC and the flash peaks at 12 UTC. Post monsoon rainfall are more during 6 and 12 UTC accompanied with minimal flashes whereas, flashes are comparatively higher during 0 and 3 UTC.

4. DISCUSSION

In general, cumulonimbus clouds bring into being lightning strikes, which are formed through three mechanisms; "rising of buoyant warm air due to intense surface heating; large heating contrast between adjacent surfaces, or due to orographic lifting of air parcels" [77]. All these processes cause instability within the atmosphere and may set off convection and hence lightning action. Orographic lifting by transferring sensible and latent heat vertically into the atmosphere triggers convection that initiates instability over the area by stronger updrafts leading to lightning flashes.

It was observed that the lightning events peak in pre-monsoon and post-monsoon season when two different air-masses, west to north-west winds of land origin and moist south southwesterly winds from the BoB co-exist over Eastern and North Eastern India (also addressed by Choudhury, et al. [33]) this condition creates instabilities manifested as CAPE. We observed that the least values of LFRD occur when the whole of north-east India is overrun by one air-mass, i.e., during winter when east to north-east winds prevail. Lightning frequency also drops during periods of strong monsoon when moist winds from the BoB prevail. Stull 1988; and later [78] observed that "the introduction of moisture and buoyant forces into the atmospheric boundary layer is directly influenced by the atmospheric forcing such as frictional drag, solar heating and moisture inflow which begin the thermal convection at the surface level" [78]. Our study supports the analysis made by Romatschke, et al. [64] and Choudhury, et al. [33] that the place of occurrence of the deep lightning producing convection in south Asia is intimately related to the land-surface conditions and the topography of the region. The abundant supply of Bay of Bengal (BoB) moisture along with topographically induced local convection creates the conditions for the genesis of thunderstorm and lightning over eastern Himalaya and NEIN Sikka and Narasimha [78]; Houze, et al. [71]; Choudhury, et al. [33]. Goswami, et al. [79] by means of a suite of high-resolution satellite products illustrated that "most of these intense convection (heavy rain events) at almost all stations in NEIN are associated with a mesoscale organization that is embedded in the large-scale organized convection associated with some specific phases of the Intraseasonal variation (ISV) of Indian summer monsoon" [79].

4.1. Topographic Influence on Lightning Density

Medina, et al. [80] stated that in both the NE and NW regions of Himalayan Mountain, the moist extreme convection is closely related to the unique topography of each. Oulkar, et al. [81] also observed the topographical variation in lightning flashes in the Himalayan Range. They have observed that at lower terrain (<500m) the flashes are more compared to a high elevations (terrain slopes). The various mountain ranges and river valleys of NEI play a significant role in the growth and maintenance of severe thunderstorms by modifying local flow in the boundary layer. Bourscheidt, et al. [82] and later [83] observed that 'local orography can create powerful vertical velocity'' and 'affect a change in the density of lightning flash rate through interacting with existing wind and/or

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large-scale processes' Albrecht, et al. [17]; Barros, et al. [84]. Goswami, et al. [79] observed that "among other factors the unique topographic features of NEI is responsible for the occurrence of extreme convection i.e. the steep topographic gradient rather than altitude is responsible for producing deep convections" [79]. In short the study says that the intense convective systems over NEIN are produced by the large-scale-mesoscale interaction due to the mountain ranges. Later another study by Choudhury, et al. [33] observed that along with "the complex topography of NEI, the Tibetan heat low also has a role in triggering the convective activities of the region by increasing the low level convergence".

4.2. Role of Atmospheric Instability in Lightning Distribution

A number of previous studies have established the association between lightning activity and CAPE. For example, Liou and Kar [85] suggested CAPE or surface heating over Taiwan during day –time was controlling lightning activity over that region. Williams [86] found that "the magnitude and distribution of CAPE plays an important role in determining the updraft velocity and vertical distribution of hydrometeors, which participate in the charge generation processes inside thunderclouds leading to lightning activities" [86]. Again Kumar and Kamra [8] noted "the Himalayan range exerts a strong influence on the spatio-temporal distributions of flash rate, surface temperature and CAPE in that region". In the pre-monsoon season, higher values of CAPE are observed over Bangladesh plains lying southwest of NEIN, with moderate CAPE values in the Meghalaya plateau adjacent to Bangladesh (see Figure 7(b)). In spite of low CAPE value over Meghalaya plateau, lightning density is high. This suggests that during pre-monsoon season, over NEI, CAPE alone cannot initiate intense convection with lightning, but on annual scale CAPE and lightning has strong correlation, which was also observed by Choudhury, et al. [87].

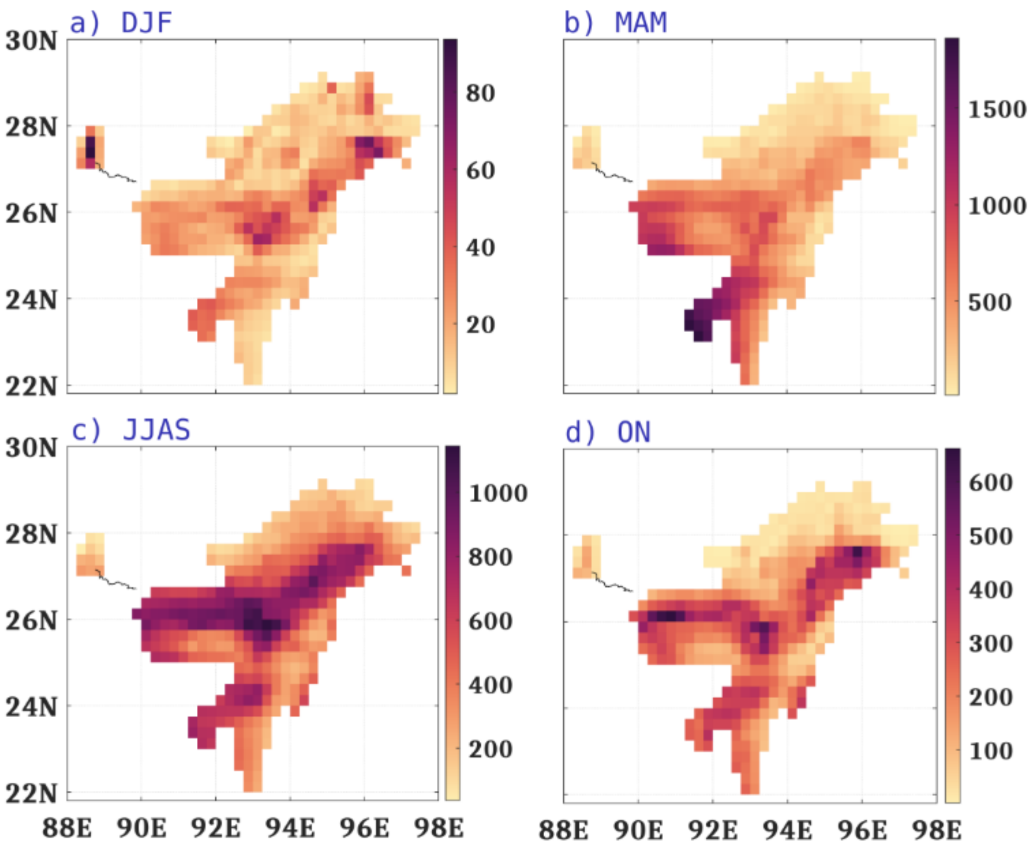

Figure 7. Spatial pattern of seasonal climatology of CAPE (J/kg) from ERA5over NEIN for the period 1998–2013 from ERA5.

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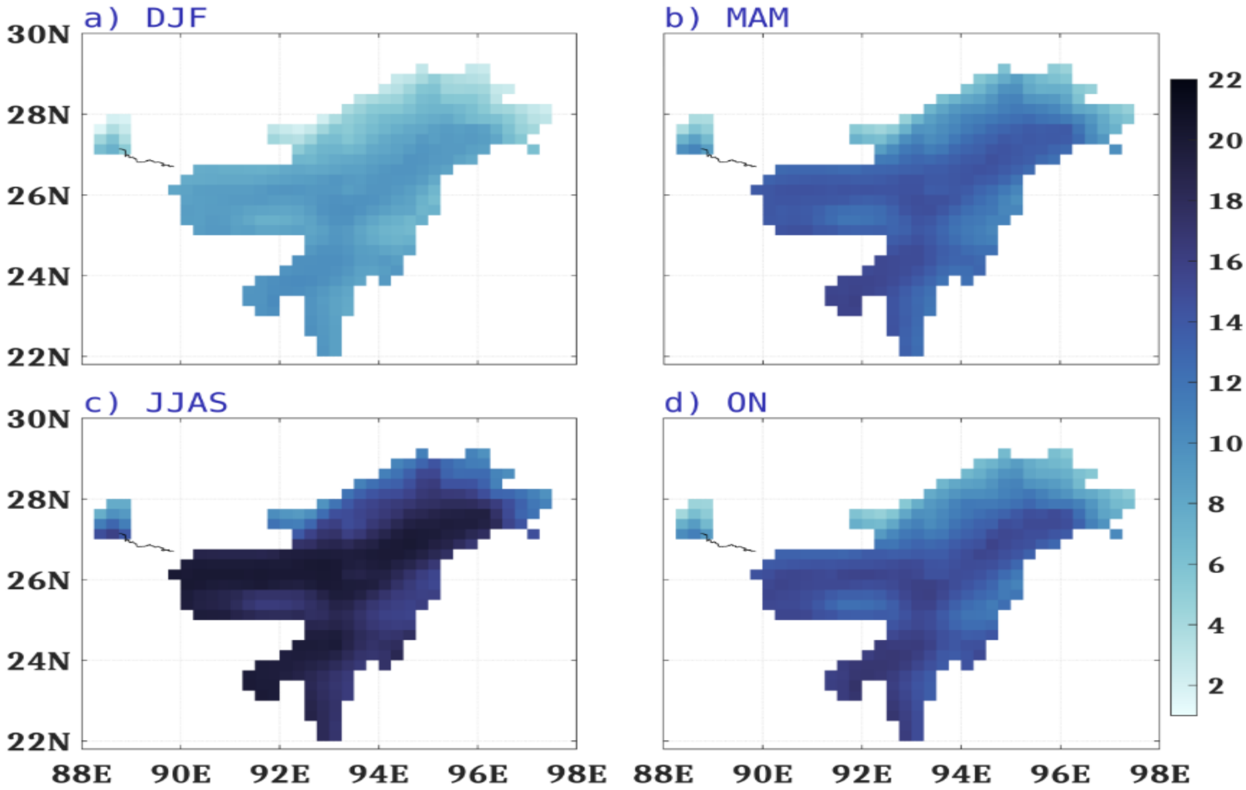

Figure 8. Spatial pattern of seasonal climatology of Wind vector, Overlayed on Specific humidity (g/kg) at 1000 mb from ERA5 over NEIN for the period 1998–2013 from ERA5.

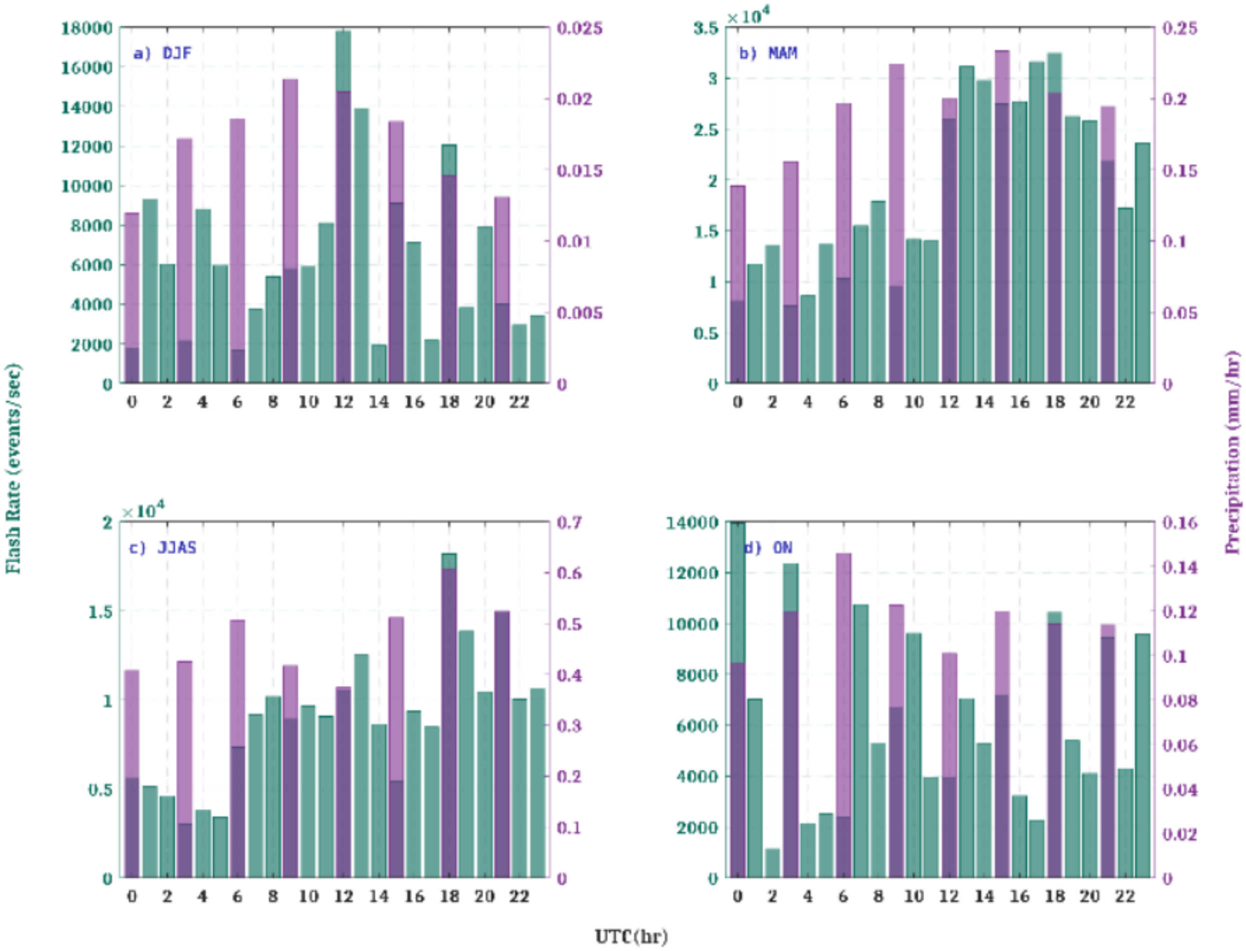

Figure 9. Diurnal variation of Lightning and Precipitation during the four seasons over NEIN for the period 1998–2013 using TRMM dataset.

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From the annual cycle of lightning activity, the increase in LFRD over the region during pre-monsoon months can be inferred from the increase in lapse due to the thermal structure during this time of the year which contributes to increasing the instability. This extreme unstable atmospheric condition in turns gives rise to intense deep convective systems.

During the monsoon season, higher CAPE values were observed over Brahmaputra valley in the centre, western and Southern part of NEI, which is somewhat larger than that in the pre and post-monsoon seasons. As can be seen from Figure 3 (b) the highest lightning activity overlap the region of high CAPE, implying a better correlation between lightning activity and CAPE during the monsoon season as compared to pre-monsoon months, which was also observed by Murugavel, et al. [65] and Pawar, et al. [88] over the Indian region. This correlation suggests the significance of CAPE in development of monsoon convections over the region. However, it has been reported that "in convections coupled with large-scale circulations like monsoon, it is the large scale processes that play important roles in determining the updraft and vertical distribution of hydrometeors inside clouds" [58].

During the post-monsoon months, the distribution of CAPE and lightning activity over NEI is better correlated compared to winter and pre-monsoon season. CAPE values are lowest for the winter months. The lightning activity during this season has large dependence on other factors like orography, the presence of western disturbances and Tibetan low rather than CAPE.

4.3. Wind and Specific Humidity

Climatological representation of surface winds and specific humidity at 1000 mb pressure level obtained from ERA5 is shown in Figure 8(a-d), respectively, over Indian region (60°E to 100°E & 0°N to 40°N) for all the four seasons. Further, these figures demonstrate that during pre-monsoon season the surface winds over NEI are from sea to land and they transport large amount of moisture over the low-lying northeast Indian region. This high moisture content over NEIN along with intense heating of land raises the water content up in the atmosphere and contributes to formation of deep clouds. In spite of low CAPE values, the microphysical process going inside such deep convective clouds plays a major role in the higher lightning activity observed over this region during pre-monsoon season. Figure 8 (a and b) for specific humidity climatology during winter and post -monsoon season also show that moisture content plays a role in the lightning activity observed over NEIN during those seasons too.

5. CONCLUSION

The use of TRMM LIS data in this study provides a comprehensive analysis of the spatial and all possible temporal frequency distribution of lightning flashes over NEI. It also interprets the observed patterns in relation with the characteristics of this area. This study allows a considerably updates the climatological picture of lightning flash over NEI. The observations given in this study of lightning flashes provide a measure of the frequency of intense local convection, identifying the areas more prone to severe weather events. We found that the intense lightning activities are concentrated between the latitudes of 25°N to 27°N and longitudes of 90°E to 91°E approx. , The lightning flashes are mostly associated with intense insolation and corresponding rise in temperature during day time, availability of high moisture content in the lower tropospheric level and prevailing synoptic condition over the NEI during these months and about 90% of the lightning flashes are found to occur during March - September with a peak in the month of April.

During the onset of monsoon, there is a drop in the lightning activity but lightning activity peaks again during the phase when the monsoon withdraws over NEI. There is hardly any lightning during mid-October to mid-. The observed contrast in day-night lightning occurrence with their seasonality indicates the influence of thermal and dynamic effects of local orography on lightning activity. There are significant regional differences between the plains and the mountains and other parts of South Asia. Maximum lightning flash rate density of 55 flashes km^{-2} year^{-1} is observed over the western part of NEI. The topographic and geographic features of NEI together with

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high moisture content in lower atmosphere leads to the high lightning flash rate density over the region. The lightning flash distribution observed from this study can assist Nowcasting systems for alerting severe convective storm (like Nor 'westers) over NEI. However, the conclusions obtained over a period of 16 years may not be representative of lightning activity over NEI, and a set of higher temporal resolution, ground-based campaigns will be very important to investigate lightning flash characteristics, its relationship with local meteorological conditions and the influence of the heating processes in the Tibetan plateau.

Acknowledgment: Authors would like to thank all the data sources (GHRC, GIOVANNI and Copernicus) for making the dataset available for research purpose. PS, BAC and RM would like to thank ICRC, Cotton University, for the support and facilities.

Funding: This study received no specific financial support.
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: Conceived the study, R.M.; analysis and planning P.S.; major contributions B.A.C.; prepared the first draft of the manuscript, R.M.; improved P.S.; critical feedbacks, B.A.C. All authors have read and agreed to the published version of the manuscript.

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