Spatio-temporal Variability of Lightning Climatology and Its Association With Thunderstorm Indices Over India

Unashish Mondal
Central University of Rajasthan

Subrat Kumar Panda (✉ subrat.atmos@curaj.ac.in)
Central University of Rajasthan

Someshwar Das
Central University of Rajasthan

Devesh Sharma
Central University of Rajasthan

Spatio-temporal Variability of Lightning Climatology and its Association with Thunderstorm Indices over India

Unashish Mondal, S. K. Panda, Someshwar Das and Devesh Sharma

Department of Atmospheric Science
School of Earth Sciences
Central University of Rajasthan, Kishangarh
Dist: Ajmer, State: Rajasthan (305 817), INDIA

Corresponding Author email: S. K Panda, subrat.atmos@curaj.ac.in

Abstract

Lightning is an electrical discharge - a'spark' or 'flash' as charged regions in the atmosphere instantly balance themselves through this discharge. It is a beautiful and deadly naturally occurring phenomenon. In June 2020, more than a hundred people died in the state Bihar of India only in three days' span due to lightning events. In this work, Lightning Imaging Sensor (LIS) information from the Tropical Rainfall Measuring Mission (TRMM) satellite with a very high spatial resolution of 0.1 X 0.1 degree has been utilized to create the climatology of India for 16 years from 1998 to 2013. Diurnal, monthly, and seasonal variations in the occurrence of lightning flash rate density have also been analyzed. TRMM satellite low-resolution monthly time series (LRMTS) with 2.5-degree resolution datasets have been used for lightning trend analysis.

The diurnal lightning event mainly occurs in the afternoon/evening (1400-1900 Hrs) time duration around 0.001 flashes/km^2/hr. The highest lightning occurred in May (0.04 flashes/km^2/day) and the least in December (0.005 flashes/km^2/day). The distribution of lightning flash counts by season over India landmass is mainly in pre-monsoon (MAM) ranges from 0.248 – 0.491 flashes/km^2/day, and monsoon (JJA) ranges from 0.284 – 0.451 flashes/km^2/day and decreases afterward. Spatially, the distribution of lightning flashes mainly at North-Eastern region along with Bangladesh, Bihar, Jharkhand, Orissa, and Jammu& Kashmir region. The CAPE and K Index have positively correlated with the flash rate density seasonally but CAPE is more significantly correlated. This study also focused on finding of lightning hotspots region of India district wise and Rajouri district in Jammu and Kashmir got the highest lightning with 121 flashes/km^2/yr.

Keywords: TRMM, Lightning flash density, K-Index, CAPE, Climatology

1. Introduction

Lightning is a ubiquitous naturally occurring phenomenon associated with a combination of atmospheric and surface events, including severe weather, which can pose a significant threat to agriculture, electric power networks, property, and living beings. As a result, in atmospheric science, disaster planning and management, and the power utility/energy sector, the spatial pattern of lightning occurrence is of great interest. Lightning mainly occurs due to thunderstorms which are small synoptic weather events produced due to strong convection (Dowdy et al., 2020). When the collision between the hail particles with other smaller ice particles occurs because this smaller ice particle gains a positive charge and loses a negative charge, respectively. When the charge is built high enough, rapid electricity discharge occurs to equalize the charged region called lightning. (Dwayr & Uman 2014). The lightning frequency depends on the microphysical and kinematics property of the thunderstorms and the available buoyant energy in the environment. It mostly happens in a cumulonimbus cloud, which requires high surface heating, buoyant warm air rises, great heat contrast between surfaces, frontal lifting, or orographic lifting of air parcels (Tapper and Sturman, 1996). Therefore, it can be used to increase our understanding of the structure and variability of thunderstorms at local, regional levels over land and the ocean.

Lightning is one of the most dangerous atmospheric hazards (Mushtaq et al., 2018). The phenomenon of thunderstorms events causes massive destruction and loss of life and property (Dowdy et al., 2016, Bhardwaj et al., 2017). It occurs more than 3 billion times or 100 times per second (Okafor 2005) all around the earth, and the most prone region for lightning is a tropical region of the earth. (Cecil et al., 2014). The range of lightning causalities due to lightning is 6000-24000 per year, mostly in developing countries than the developed countries (Holle 2016). On June 26, 2020, the lighting event in Bihar caused more than 120 deaths in 3 days. As per the study (Swagata et al., 2020, op Singh 2015, illiyas2014), more than 2000 people die due to lightning per year in India, around 9 percent of deaths due to natural calamities. The most prone lightning area in India is the whole north-eastern region, Bihar, Orissa, Jammu Kashmir, and Uttarakhand. Furthermore, most lightning deaths happen in Maharashtra, Orissa, and Madhya Pradesh due to population density (Swagata et al., 2020).

The cloud-to-cloud flashes are 5 -10 times more than cloud-to-ground flashes. Lightning detection from the satellite relies on the sudden release of electrical energy during lightning, generating a rapid heating and shock wave (thunder). The electromagnetic radiation detected by the LIS sensor 128 x 128 charge-coupled device (Goodman et al., 1988) the viewing area of the sensor is 668 x 668 km with 4.4 km of nadir. (Boccippio et al., 2002; Christian et al., 2003). The Lightning Imaging Sensor (LIS) aboard the Tropical Rainfall Measuring Mission (TRMM) produced lightning observations that allowed researchers to examine the electrical, microphysical, and kinematic characteristics of tropical thunderstorms in addition to the hotspot placement over the area. (Document describing the ATBD-algorithm of the Lis sensor). Because it covers the whole region, even areas where there is no ground network coverage, the use of a satellite sensor is a vital instrument for the study of lightning. (Cecil et al., 2014; Dewan et al., 2018b; Taszarek et al., 2019, Lizandro et al., 2020). Many studies take place on lightning and its correlation with other indices over the Indian region (Saha et al., 2016, Murugavel et al., 2014, Tinmaker et al., 2014 Kandalgaonkar et al., 2003, 2005; Pawar et al. 2012; Ranalkar and Chaudhari et al., 2009; Penki and Kamra et al., 2013). With the increase in CAPE, the lightning activity also increases; South Asia is one of the highest lightning impacted regions (>30 fl /km^2) analyzed by (Albrecht et al., 2016), mainly Himalayan foothills. With the change in CAPE in the foothills of Himalayan, it would change the lightning flash rate by 22% (Ramesh Kumar and Kamra et al., 2012). Lightning prediction is now a challenging area of research (Tiwari et al., 2014) examined the prediction skill of large-scale seasonal mean temperature variability in inter annual timescale over India using GCM products. The spatial characteristics and statistical scores are used to evaluate the performance of each model in simulating NASA's NEX-GDDP-simulated summer monsoon rainfall over homogeneous monsoon regions of India (Kumar et al., 2020)

Using LIS satellite lightning data, Kandalgaonkar et al. (2005) calculated that a 1-degree increase in temperature would increase lightning activity by 20-40%. As a result, several kinds of research have been conducted on South Asia to understand better the geographical and temporal variation of lightning and related variables using ground and satellite-based data. During monsoon, CAPE is an essential factor for lightning activities (Murugavel et al., 2014, Pawar et al., 2012). However, there is no relationship between the CAPE and lightning activities in the north-

eastern India region due to topographic forcing. (Pawar et al., 2010). A study done by (Siingh et al., 2014) shows that the CAPE varies all over India, mainly due to orography and vegetation cover.

Lightning is linked to thermodynamic variables such as instability, adequate moisture, and lifting force, in addition to human influences. (Saha et al., 2012, 2014, Kumar et al., 2016)

CAPE is an index that is used to evaluate atmospheric instability. (Romps et al., 2014; Galanaki et al., 2015). The available potential energy transformed into kinetic energy is shown in CAPE, which is used to estimate thunderstorm occurrences. This aids in the separation of charges in thunderclouds. (Williams et al., 1993); thus, it shows a good correlation with lightning flashes (Galanaki et al., 2015). K index is proved to help indicate the air mass thunderstorm. As the K index value increases, the probability of a thunderstorm increase (Tinmaker et al., 2017). The K index is based on the temperature lapse rate, lower tropospheric humidity, and the vertical extent of the wet layer. A study done by (Umakanth et al., 2020) shows that the K index value during the pre-monsoon season shows the intense thunderstorm occurrence over the region, suggesting that it provides a good indication in forecasting thunderstorms.

This study presents lightning intensity's spatial and temporal distribution by calculating flash rate density over the Indian region. The correlation between lightning intensity and indices such as CAPE and K index investigated seasonally. The lightning trend analysis has also been calculated spatially for the India region seasonally. This study also examined the hotspots region in India with the highest flash rate density that will help us provide early warning and arrangements for the safety of the people, live stocks, and property. Section 2 discusses the study area geography, datasets description, and methodology in detail. Next, Section 3 describe the results and discussion part of the research paper, which contains lightning climatology, the correlation between lightning events and indices, lightning hotspots region, and lightning trend analysis. Section 4 presents the conclusion. Finally, the last section, 5, contains references.

2. Data and Methodology

2.1 Study Region

India is located in south Asia between 8°4' north and 37°6' north latitude and 68°7' east and 97°25' east longitude, north of the equator. With a size of 3.28 million square kilometres, it is the world's 7th largest nation. With a population of 1.21 billion people (2011 census), it is ranked second.

The Indian Ocean borders India on the south, with the Arabian Sea to the west, the Bay of Bengal to the east, and the Himalayas to the north. According to the Koppen classification, India's climate is split into six primary climate types and microclimates, making it the world's most climatically diverse country; India is primarily a tropical country. The Himalayas and the Thar desert mostly influence India's climate by attracting the monsoon-laden southwest wind; The rainfall India receives is around 117 cm, out of which 80% of rainfall is observed during monsoon month of June to September (Praveen 2020). As per the study, most lightning strikes in India happen in pre-monsoon and monsoon periods, and deaths due to lightning happen in India (Singh 2015, Swagata et al.,2020, NCRB report).

2.2 Data

2.2.1 TRMM satellite datasets

The lightning datasets used in this study are derived from a satellite sensor that is a tropical rainfall measurement mission (TRMM) which is a NASA-JAXA cooperative mission with a low inclination equatorial orbit satellite project that is part of NASA's ESE (Earth Science Enterprise). This is the first mission to understand the tropical and subtropical rainfall from a global perspective, which was the least understood parameter. In 1995 NASA launched Optical Transient Detector (OTD), a low earth orbit satellite at 740 km of altitude using a 70-degree inclination to detect lightning from space with a storm-scale resolution both day and night of 1300km x 1300km for each 3 min satellite overpass (Boccippio et al. 2002 and Christian et al. 2003). LIS combines a high-speed charge-coupled device (CCD) detection array with a narrow band filter centered at 777nm. (Boccippio et al., 2002; Christian

et al., 2003) To detect and locate lightning with a storm-scale resolution of 5-10km, around over tropical region (35N-S) coverage. For measurement and observation of lightning flash rates for individual storms, the LIS field of view (FOV) in the 90s (Cecil et al., 2014)

LIS can detect the total lightning throughout day and night with efficiency varying between 69% to 88%, respectively. (both within the cloud and from the cloud to the surface) by measuring the radiant energy released by lightning. The overarching goal of LIS was to provide more information on the characteristics of tropical marine and continental convective clouds, laying the groundwork for establishing a worldwide thunderstorm and lightning climatology. TRMM's height was increased from 350 km to 400 km in August 2001, resulting in a larger field of vision. It also gives a more extended sample period, increasing the overall number of flashes but not the rate of flashes. Both OTD and LIS are low earth orbit satellites; LIS has a narrower field of view (FOV) than the Optical Transient Detector (OTD) sensor, but it has higher detection effectiveness (Bond et al. 2002), reaching 88 percent at night (Cecil et al., 2014). The gridded climatology is built with the merging of TRMM-LIS and OTD (Cecil 2014).

This research uses very high-resolution climatology (0.1°) data from January 1, 1998, to December 31, 2013; the entire dataset is downloaded from the NASA Earth Observing System Data and Information System (EOSDIS) Global Hydrology Resource Center (GHRC): https://doi.org/10.5067/LIS/LIS/DATA306. The LIS/OTD data of Low-Resolution Monthly Climatology Time Series (LRMTS) in the grid resolution of 2.5° × 2.5° for 1996–2014 are obtained from the website (http://thunder.msfc.nasa.gov/data/data_lis.html) for the Indian sub-continent.
The very high-resolution datasets consist of five gridded data sets: very high-resolution full climatology (VHRFC), very high-resolution diurnal cycle (VHRDC), very high-resolution monthly climatology (VHRMC), very high-resolution seasonal climatology (VHRSC), and very high-resolution annual climatology (VHRAC) were processed by (Albrecht et al. 2016).
The datasets (daily, monthly, or seasonal) were already treated with a 49-day and 1-degree boxcar moving average to eliminate diurnal cycle and smooth regions with low flash rates to make the findings more robust.

2.3 Methodology

The LIS TRMM (0.1 degree) very high-resolution gridded lightning climatology data collection (Albrecht et al., 2016) was used to compute the cloud-to-ground lightning flash density over India, to analyze the spatial-temporal distribution of lightning in India. The extraction and plotting of the data available in NetCDF format with a resolution of 0.1° × 0.1°, over the Indian region analyzed with the geographic information system (ArcGIS) by preparing thematic maps to examine the flash rate density. According to the earth observation system (EOS/TRMM) data requirements, the seasonal dataset (VHRSC) comprises four seasons (winter (December-January-February), pre-monsoon (March-April-May), monsoon (June-July-August), and post-monsoon (September-October-November). Furthermore, the LIS-OTD (2.5 degrees) low-resolution monthly time series gridded climatology from 1996 to 2012 have been used (Cecil et al. 2014 and Christian et al., 2003).
The CAPE with 2-degree resolution and K Index with 0.25 degree have been used for the correlation purpose. The datasets mentioned above have different spatial resolutions. The two datasets are generally averaged for correlation purposes, and interpolation has been done with the coarse resolution dataset.
The lightning hotspot analysis, done by the superimposition of the lightning flash rate density dataset on the district-state map of India, thus finding out the hotspot location district-wise (Lizandro et al., 2020; Albrecht et al., 2016).

2.3.1 Indices
The gridded values of the monthly averaged K Index (Umakanth et al., 2020, Tinmaker et al., 2017) are among the most significant stability indices for predicting atmospheric convective activity, i.e., is CAPE (Dewan et al., 2018; Murugavel et al., 2012, Saha et al., 2016) has been used for the study. The data was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-5 database; ERA5 is monthly averaged data on single levels from 1979 to the present with gridded monthly mean and a spatial resolution of 0.25° downloaded from January 1, 1998, to December 31, 2014. The monthly averaged CAPE with a spatial resolution of 2.0° × 2.0° is obtained from National Centres for Environmental Prediction/National Center for Atmospheric Research

(NCEP/NCAR) reanalysis product (Kalnay et al., 1996) provided by the ESRL PSD, Boulder, Colorado, USA (website: http://www.esrl.noaa.gov/psd.html) for the period 1996–2012. CAPE is utilized at the surface level to depict tropical areas more adequately. (Tinmaker 2019, Dewan et al., 2018; Saha et al., 2017). The monthly mean of the CAPE is utilized to determine the connection with the flash rate density. (Mao et al., 2020 and Lizandro 2020).

$$CAPE \ = \ \int_{Zf}^{Zn} g \ \left[\frac{Tv,parcel - Tv,env}{Tv,env} \right] \ dz \qquad\qquad [1]$$

The following formula is used to calculate CAPE: (where Tv, parcel and Tv, env are the virtual temperatures of the parcel and environment, respectively). The levels of free convection and neutral buoyancy are indicated by the letters Zf and Zn. The CAPE parameter's threshold levels indicate the likelihood of severe weather activity. (Grieser 2012).

The K index threshold value indicates the risk of severe weather activity (Johnson 1982). The K-index may also be used to predict the likelihood of a thunderstorm. It is calculated by subtracting the temperature from the dew point temperature at various atmospheric pressure levels., as shown below (George 1960).

The formula is:

$$K\text{-Index } (°C) = (T_{850} - T_{500}) + Td_{850} - (T_{700} - Td_{700}) \qquad\qquad [2]$$

$$[A] \qquad\qquad [B] \qquad\quad [C]$$

(T is the temperature in degree Celsius, and Td is the dewpoint temperature at the given pressure level in hPa.); where component [A] shows the static instability between 850hPa and 500hPa, component [B] shows the moisture at 850hPa, and component [c] shows the dryness of the airmass at 700hPa.

The index is most effective in flat regions at low to moderate elevations; it is less effective at higher heights. The meaning of the index value changes depending on the season and place (e.g., tropics or mid-latitude, summer or winter). The typical values differ by region; however, it can be advantageous and informative for predicting thunderstorms.

3. Results and Discussions

This section described the spatial-temporal distribution and seasonal variation of CAPE, K Index, flash rate density, and their trends for 1996-2013 over the India region. This section discussed the lightning hotspot region in India and the correlation between lightning flash rate density with CAPE and K Index.

3.1 Seasonal Climatology of Satellite Datasets

The seasonal analysis over the India region, for the period of 1998-2013 has been done by using the very high-resolution seasonal climatology (0. 1 degree) dataset with the pre-defined seasons from NASA-GHRC datasets, i.e., is (winter-(DJF), pre-monsoon-(MAM), monsoon-(JJA), post-monsoon- (SON). The highest lighting occurs in India during the pre-monsoon (MAM) and post-monsoon season (JJA) (Swagata et al., 2020). Lightning hotspots in India have more lightning activity (>15 fl day–1) during the monsoon months (May–October, peaking in September; and less from November to March (Albrecht et al., 2016)

As figure 2 depicts, during the pre-monsoon MAM season highest lightning occurs in India's north-eastern region, around 0.248-0.491 flashes/km^2/day, wherein West Bengal, Orissa, Bihar, Kashmir, Uttarakhand, and Kerala states which are around 0.129-0.247 flashes/km^2/day. Due to the low-pressure zone and excessive heat in the north-eastern region of India, including Bangladesh, convection increases so the chances of thunderstorms. The moisture availability in the Bay of Bengal, thunderstorm lightning increases in the north-eastern region in the pre-monsoon season (Saha et al., 2016). According to Wu et al. (2016), Backward trajectory analysis confirms that moisture transport from the Arabian Sea and the Bay of Bengal are two critical transport pathways for the summer monsoon intense convective systems at the western end of the southern Himalayan front. In monsoon season (JJA) Kashmir

region gets the maximum lightning range in 0.284-0.451 flashes/km^2/day. During the monsoon season, convection and accompanying lightning occurrences moved from the north-eastern to the north-western lower Himalayan foothills. According to a study conducted by Upal Saha (2016), the maximum lightning flashes are detected over the north-western section of the Himalayas and much more over the eastern, north-eastern region Himalayas along the foothills of the Himalayas. Cecil et al. (2005), Zipser et al. (2006), and Houze et al. (2007) recognized the western Himalayas as an area with the most severe thunderstorms on earth. Houze et al. (2007) discovered that the most severe convective storms occur upwind or at the mountain foothills, where the moist south westerly monsoon flow from the Arabian Sea meets the descending dry air from the Afghan or Tibetan Plateaus, implying a similarity to dryline convection. Moreover, higher latitudes got more lightning than lower latitudes by Ranalkar and Chaudhuri (2009), which justifies the study entirely.

Furthermore, some parts of Himachal Pradesh and Punjab also get heavy lightning. In post-monsoon (SON), the maximum lightning occurs in Jammu & Kashmir 0.0852-0.143 flashes/km^2/day, Punjab and Himachal Pradesh around 0.0438-0.0851 flashes/km^2/day. During the retreating monsoon season, due to western disturbances across northern India. In winter (DJF), the most prone lightning area is north-western, including Jammu Kashmir, Punjab, 0.0166-0.312 flashes/km^2/day Himachal Pradesh Haryana, Uttar Pradesh, and some part of Rajasthan 0.00613-0.165 flashes/km^2/day. However, the lightning intensity is moderate.

3.2 Monthly Climatology of Satellite Datasets

The monthly flash rate climatology is examined using the very high-resolution monthly climatology (VHRMC: 1998-2013) and Low-resolution monthly time series (LRMTS: 1996-2013) datasets. As per the fig.3, we analyze that the Flashes are less during the winter months till March and gradually increase from April and show it peak in May. It is in maximum range during June, July, and August, and after that, it decreases gradually from September. Lightning is sensitive to the surface temperature (William 1994), and the study done by (Kumar 2018) on the central part and north-eastern part of India analyzed that the increase in land temperature during daytime is one of the regions of lightning in pre-monsoon months.

The overall lighting is high during the monsoon and post-monsoon months. The graph shows the monthly mean flash rate density measured in flashes/km^2/day. In March, the northeast region, i.e., Meghalaya, Tripura, Assam, got the maximum lightning 0.139-0.294 flashes/km^2/day, which increases to 0.431- 0.752 flashes/km^2/day in April, and in May, the flashes are around 0.257-0.552 flashes/km^2/day in the north-eastern region above Bangladesh area cover Assam and also in Kashmir region lightning flashes maximum than rest of India. In August, the lightning flashes are maximum in Kashmir, around 0.253-0.457 flashes/km^2/day, and in October, the southern part of India, i.e., Tamilnadu, and some part Orissa, Bihar, and Kashmir, has the maximum lighting than rest of India. In November, some parts of western ghat and Kerala got lightning. Lightning events occur during September. October and November are due to the north-eastern monsoon. The lightning flash count is less than the other months but significant for the area around 0.0308-0.0562 flashes/km^2/day.

As per figure 4, the low-resolution monthly time-averaged datasets from 1996 to 2013 show the mean, maximum, and minimum flash rate density over the India region yearly and show the highest flashes occur during the May month gradually decrease after that in coming months.

3.3 Diurnal Climatology of Satellite Datasets

During the daytime efficiency of the LIS, the sensor is less than at night because of the reflection from the top of the clouds and due to sunlight illumination being much brighter than the lightning. The very high-resolution diurnal climatology data (0.1 degrees) is used to calculate the diurnal flashes with the LIS detection efficiency ranging from 69% during the afternoon to 88% at night. (Christian et al., 2000; Boccippio et al., 2002; Christian et al., 2003; Cecil et al., 2014, Albrecht et al., 2016). The flash rate for the diurnal climatology is calculated in flashes/km^2/hr. Over the India region, the minimum flashes occur during morning time from 09 am to 11 am, and the peak of the flash detects during the noontime from 03 pm to 07 pm and decreases after that. Below figure 5 represents the diurnal flash rate over the Indian region.

3.4 Correlation

The correlation maps may be quite valuable to obtain regional changes in climate patterns across the Indian subcontinent. Changing climates can deliver mixed benefits and threats to societies, with a disproportional distribution of both. The correlation between lightning flash rate density with convective available potential energy and K index will provide an opportunity to investigate the lightning intensity and prime cause related to it further. The spatial correlation analysis was done for 16 years from 1996-2012 seasonal basis over the Indian region.

3.4.1 Seasonal spatial correlation between flash rate density and CAPE

As figure 6 shows, during the winter season months DJF, the spatial correlation between the convective available potential energy and lightning flash rate density is positively correlated with each other in the range from -0.11 to 0.77. The north-western region, which covers Rajasthan, Haryana, and Punjab, in north Jammu and Kashmir, the whole north-eastern region, West Bengal and Orissa are positively correlated in the range of 0.44 to 0.77. The regions where it is negatively correlated are Gujarat and some parts of the southern region, including Tamil Nadu and Andhra Pradesh. The rest of the region is moderately correlated. During the pre-monsoon season, the MAM majority region of India is positively correlated, which includes north-western, central, and southern India in the range of 0.65 to 0.83. The less correlated region in India's north and north-eastern region is in the range of 0.076 to 0.048. In the monsoon season JJA, the southern region, and the north-eastern region are highly correlated in the range of 0.34 to 0.89. Moreover, the negatively correlated region is Himachal Pradesh, Uttarakhand, Uttar Pradesh, and Jammu & Kashmir, around -0.66 to 0.16. During the post-monsoon SON, only Jammu & Kashmir is negatively correlated around -0.31 to 0.15. rest of India is moderately correlated. The high correlation shows in the eastern ghat and the north-eastern region around 0.65 to 0.94.

3.4.2 Seasonal spatial correlation between flash rate density and K Index

Figure 7 clearly describes that during the winter season DJF, the region above the tropic of cancer that covers the entire half of India, is positively correlated in the range of 0.43 to 0.83, the highest correlation shown in the eastern ghat, foothills of the Himalayas, and the north-western region of India. The regions which are negatively correlated are Gujarat and Tamil Nadu, around -0.33 to 0.15. The rest of the region is moderately correlated. In the pre-monsoon season MAM, the majority of India is positively correlated around 0.66 to 0.83. The regions which are negatively correlated are Jammu & Kashmir and North-eastern states around 0.12 to 0.48. During the monsoon season JJA, the Himalaya foothill is negatively correlated to the north-eastern region, around -0.8 to -0.021. The north and north-western parts are moderately correlated. Southern India shows a correlation of 0.17 to 0.49. This clearly shows that the correlation between the K Index and flash rate density during the monsoon season is not good. During the post-monsoon season SON, the region which shows the poor correlation in the western ghat. The rest of India is positively correlated, and the region that shows a high correlation is northern India, the north-eastern region, where the correlation is around 0.79 to 0.93.

3.5 Lightning Trend Analysis

The seasonal trend analysis of flash rate density using low-resolution monthly time series for 1996-2013. LRMTS dataset with the 2.5-degree resolution is robust for analyzing trends. The seasonal trend analysis of lightning activity and lightning event spatial distribution have been studied over the Indian region.

Due to the wide range of meteorological and environmental conditions and their interactions with topography and landforms, clouds with a wide range of microphysical and dynamical characteristics, thunderclouds forming in different seasons produce a wide range of lightning occurrences in different areas. Lightning activity and its link with pre-monsoon and moist convections, large-scale dynamics, and surface fluxes over the Indian region around the Bay of Bengal and the Arabian Sea have previously been examined by many researchers over the Indian region (Kandalgaonkar et al., 2005, Saha et al., 2014, Chakraborty et al., 2015).

In the winter season DJF, the positive lightning trend is shown in the north-western region of India, including Jammu Kashmir, Rajasthan, Haryana, Uttar Pradesh, Punjab, Uttarakhand, with an increase of 0.001 to 0.004 flashes/

km^2/day and also in the North-eastern region by 0.001 flashes/ km^2/day. The negative trend is shown in the West Bengal, Bihar, and Orissa region by -0.008 to -0.005 flashes/ km^2/day. The MAM pre-monsoon season positive trend is shown in the north-eastern region of India about 0.04 to 0.045 flashes/ km^2/day. J&K increases around 0.03 to 0.045 flashes, and in West Bengal, Bihar, Orissa, around 0.025 to 0.035 flashes/km^2/day. In the southern region of Kerala and Karnataka positive trend is shown by 0.02 to 0.03 flashes/ km^2/day. A negative trend is shown in the Kutch region of Gujarat by -0.005 flashes/ km^2/day. The JJA monsoon season positive lightning trend is shown in J &K around 0.06 to 0.03 flashes/ km^2 /day and north-western part around 0.03 to 0.04 flashes/km^2/day. Chhattisgarh, Orissa, and West Bengal increases by 0.01 to 0.03 flashes/ km^2/day. There is no negative trend found in the monsoon season in any part of India. There was a positive trend in the SON post-monsoon season in Tamil Nadu, Kerala, Karnataka, around 0.003 to 0.009 flashes/ km^2/day. A negative trend in the north-western part included Rajasthan, Madhya Pradesh, Gujarat by -0.021 to -0.015/ km^2/day. Figure 8 clearly shows the spatial trend analysis of lightning over the Indian region.

3.6 Lightning Hotspots Region of India

The region of lightning hotspots in India presented in this study is above 50 flashes /km^2 /yr. Many studies have been done to present the lightning hotspots over the globe (Albrecht et al.,2016, Cecil et al., 2014), but this analysis will present India's district-wise lightning hotspot regions. The lightning hotspots region is mainly located in Jammu Kashmir, Himachal Pradesh, Uttarakhand, the north-eastern state of India, i.e., Meghalaya, Assam, Tripura west Bengal, Orissa, Jharkhand, Bihar, and Kerala. The Foothills of the Himalayas also come under the lightning hotspots.

Figure 9 clearly shows the region where most of the lightning hotspots are located in the northern part of India rather than the southern peninsula. Rajouri district in Jammu and Kashmir has the highest lightning activity zone, around 121.40 flashes/km^{-2}/yr^{-1}. Below is the list of 50 districts with a lightning hotspot of India where lightning is more than 50 flashes /km^{-2}/yr^{-1}, seven districts from Jammu & Kashmir, six from Meghalaya, six from West Bengal, and six from Kerala. There are a total of 52 districts and also the plot to show the lightning hotspot district-wise. Because vast meteorological and environmental factors and their interactions with topography and landforms lead to the creation of clouds with a broad range of microphysical and dynamical features, thunderclouds growing in different seasons show a wide variety of lightning occurrences in different regions. Table 3 mentioned the district-wise list of the top 50 lightning hotspots region of India.

4. Conclusions

Lightning is one of the most dangerous and hazardous natural phenomena which causes heavy destruction to the human life and property. Lightning mainly occurs in the tropical region of the planet earth. India is situated in the tropical region and due to its location, some of the highest lightning events took place in this region. Because of lightning every year many human fatalities happen in India. There are many researches have been taken place in the past and still carry on to lessen the impact of lightning. This study also been done to provide some insights for further research perspectives.

This study has used the satellite datasets from Tropical Measurement Mission Rainfall (TRMM) LIS data and ERA-5 reanalysis datasets, to produce the lightning climatology diurnal, monthly, and seasonally over India region for 16 years from 1998-2013. The spatial plot of seasonal flash rate density shows the region where lightning events are high and low as per the season. The highest lightning events took place in pre-monsoon and monsoon season around 0.49 and 0.45 flashes/km^2/day. The affected region is northern India, foothills of Himalaya and the north eastern region including Orissa and Kerala. During post-monsoon the whole eastern ghat and Kerala is the region where lightning events are high. In winter the north western region got the highest lightning events. The major lightning events states are the north-eastern region, Jammu and Kashmir, West Bengal, Orissa, Bihar, Uttarakhand, Uttar Pradesh, and Kerala.

As per the study in May month India gets the highest lightning intensity which is around 0.045 flashes/km^2/day and continue till August and afterward it decreases gradually. The diurnal variation of lightning intensity is highest

during the afternoon from 1500 to 1900 hrs which is around 0.0012 flashes/km^2/hr and minimum during 700 to 1200 hrs in the morning around 0.0002 flashes/km^2/hr.

A set of spatial correlation plots were created seasonally, to revealing key geographical and temporal features of lightning with the thunderstorm indices i.e., convective available potential energy (CAPE) and K index respectively to understand the connection between indices and flash rate density. The result shows the positive correlation of flash rate density with both the indices but Among the two variables, the CAPE is significant with the lightning. During pre-monsoon and monsoon, the correlation of K index is very low which is around 0.49 whereas CAPE is 0.83 respectively. The CAPE is highly correlated in the eastern ghat during the post-monsoon season around 0.94. The CAPE is high in India's eastern, south-eastern, and south-western regions due to an adequate supply of moisture for the formation of convective instability and thunderstorms. Due to the orographic, the formation of thunderstorms is high in the Northern region of India, so lightning events are also more than the rest of India despite less CAPE value over the region. (Tahir et al., 2015). The eastern part of India has a high CAPE value due to the Bay of Bengal sea, which has more moisture for convection than the Arabian sea. (Chakraborty et al., 2015). Because India is located in a tropical location, high insolation occurs during the pre-monsoon and monsoon seasons, and owing to the availability of moisture; convective events occur throughout this season. The CAPE value is high in the region where the monsoon trough lies during the monsoon season. (Saha et al., 2016)

The spatial seasonal trend analysis of flash rate density over the India region shows a very minimum trend in lightning during the period of climatology. The study provides the specific result that only in pre-monsoon the positive trend analysis shows in north eastern region of India and northern India adjoining Pakistan and the negative trends is shown in central India include southern Rajasthan, Madhya Pradesh in post-monsoon season.

This study also calculates the lightning hotspots region where the lightning event is more than 50 flashes/km^2/year in India district wise. There are more than 50 districts where the lightning is more than 50 flashes/km^2/year, mostly these regions are located in Jammu & Kashmir, Himachal Pradesh, north-eastern states, West Bengal and Kerala. The Rajouri district in Jammu & Kashmir got the highest lightning around 121 flashes/km^2/yr. This result clearly depicts that northern region of India is more lightning prone than the southern region. The topography of the region plays the most crucial part for the formation of lightning.

Declarations

is supported from MoES project (MoES/16/09/2018-RDEAS/THUMP-4) sponsored by Ministry of Earth Science (MoES), Government of India.

References:

Albrecht RI, Goodman SJ, Buechler DE, Blakeslee RJ, Christian HJ (2016) Where are the lightning hotspots on earth? Bulletin of the American Meteorological Society. 97(11), 2051-2068

Blakeslee RJ, Lang TJ, Koshak WJ, Buechler D, Gatlin P, Mach DM, Christian H (2020) Three years of the Lightning Imaging Sensor onboard the International Space Station: Expanded global coverage and enhanced applications. Journal of Geophysical Research: Atmospheres, 125(16), e2020JD032918

Bond DW, Steiger S, Zhang R, Tie X, Orville RE (2002) The importance of NOx production by lightning in the tropics. Atmospheric Environment, 36(9), 1509-1519

Boccippio DJ, Koshak WJ, Blakeslee RJ (2002) Performance assessment of the optical transient detector and lightning imaging sensor. Part I: Predicted diurnal variability. Journal of Atmospheric and Oceanic Technology, 19(9), 1318-1332

Christian HJ, Latham J (1998) Satellite measurements of global lightning. Quarterly Journal of the Royal Meteorological Society, 124(549), 1771-1773

Christian HJ, Blakeslee RJ, Boccippio DJ, Boeck WL, Buechler DE, Driscoll KT, Stewart MF (2003) Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. Journal of Geophysical Research: Atmospheres, 108(D1), ACL-4

Cecil DJ, Buechler DE, Blakeslee RJ (2014) Gridded lightning climatology from TRMM-LIS and OTD: Dataset description. Atmospheric Research, 135, 404-414

Cecil DJ, Buechler DE, Blakeslee RJ (2015) TRMM LIS climatology of thunderstorm occurrence and conditional lightning flash rates. Journal of Climate, 28(16), 6536-6547

Dewan A, Ongee ET, Rafiuddin M, Rahman MM, Mahmood R (2018) Lightning activity associated with precipitation and CAPE over Bangladesh. International Journal of Climatology, 38(4), 1649-1660

de Abreu LP, Gonçalves WA, Mattos EV, Albrecht RI (2020) Assessment of the total lightning flash rate density (FRD) in northeast Brazil (NEB) based on TRMM orbital data from 1998 to 2013. International Journal of Applied Earth Observation and Geoinformation, 93, 102195

Dewan A, Ongee ET, Rahman MM, Mahmood R, Yamane Y (2018) Spatial and temporal analysis of a 17-year lightning climatology over Bangladesh with LIS data. Theoretical and Applied Climatology, 134(1), 347-362

Dwyer JR, Uman MA (2014) The physics of lightning. Physics Reports, 534(4), 147-241

Dowdy AJ (2020) Climatology of thunderstorms, convective rainfall and dry lightning environments in Australia. Climate Dynamics, 54(5), 3041-3052

Grieser, J (2012) Convection parameters. Selbstverl

Goodman SJ, Buechler DE, Wright PD, Rust WD (1988) Lightning and precipitation history of a microburst-producing storm. Geophysical Research Letters, 15(11), 1185-1188

Galanaki E, Kotroni V, Lagouvardos K, Argiriou A (2015) A ten-year analysis of cloud-to-ground lightning activity over the Eastern Mediterranean region. Atmospheric Research, 166, 213-222

Holle RL (2016) The number of documented global lightning fatalities. In International Conference on Lightning Protection (ICLP 2016) (pp. 1-4)

Illiyas FT, Mohan K, Mani SK, Pradeepkumar AP (2014). Lightning risk in India: Challenges in disaster compensation. Economic and Political Weekly, 23-27

Kandalgaonkar SS, Tinmaker MIR, Kulkarni JR, Nath A, Kulkarni MK, Trimbake HK (2005) Spatio-temporal variability of lightning activity over the Indian region. Journal of Geophysical Research: Atmospheres, 110(D11)

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Joseph D (1996) The NCEP/NCAR 40-year reanalysis project. Bulletin of the American meteorological Society, 77(3), 437-472

Kumar S, Siingh D, Singh RP, Singh AK (2016) The influence of meteorological parameters and atmospheric pollutants on lightning, rainfall, and normalized difference vegetation index in the Indo-Gangetic Plain. International Journal of Remote Sensing, 37(1), 53-77

Kumar P, Kumar S, Barat A, P Parth Sarthi, Ashutosh KS (2020) Evaluation of NASA's NEX-GDDP-simulated summer monsoon rainfall over homogeneous monsoon regions of India. Theoretical and Applied Climatology 141, 525–536 https://doi.org/10.1007/s00704-020-03188-2

Kandalgaonkar SS, Tinmaker MIR, Kulkarni JR, Nath A (2003. Diurnal variation of lightning activity over the Indian region. Geophysical Research Letters, 30(20)

Lal DM, Pawar SD (2011) Effect of urbanization on lightning over four metropolitan cities of India. Atmospheric Environment, 45(1), 191-196

Mao J, Li M (2020) Interannual variations in spring lightning activity and convective rainfall over South China during the TRMM era. Theoretical and Applied Climatology 142, 483–495 https://doi.org/10.1007/s00704-020-03322-0https://doi.org/10.1038/s41598-020-67228-7

McVicar TR, Roderick ML, Donohue RJ, Li LT, Van Niel, TG, Thomas A, Dinpashoh Y (2012) Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. Journal of Hydrology, 416, 182-205

Mushtaq F, Lala MGN, Anand A (2018) Spatio-temporal variability of lightning activity over J&K region and its relationship with topography, vegetation cover, and absorbing aerosol index (AAI). Journal of Atmospheric and Solar-Terrestrial Physics, 179, 281-292

Murugavel P, Pawar SD, Gopalakrishan V (2014) Climatology of lightning over Indian region and its relationship with convective available potential energy. International Journal of Climatology, 34(11), 3179-3187

Muhammad Tahir K, Yin Y, Wang Y, Babar ZA, Yan D (2015) Impact assessment of orography on the extreme precipitation event of July 2010 over Pakistan: A numerical study. Advances in Meteorology, 2015

Moncrieff MW, Miller MJ (1976) The dynamics and simulation of tropical cumulonimbus and squall lines. Quarterly Journal of the Royal Meteorological Society, 102(432), 373-394

Okafor UV (2005) Lightning injuries and acute renal failure: a review. Renal failure, 27(2), 129-134

Pawar SD, Lal DM, Murugavel P (2012) Lightning characteristics over central India during Indian summer monsoon. Atmospheric Research, 106, 44-49

Penki RK, Kamra AK (2013) The lightning activity associated with the dry and moist convection in the Himalayan Regions. Journal of Geophysical Research: Atmospheres, 118(12), 6246-6258

Pawar SD, Murugavel P, Gopalakrishnan V (2010) Anomalous electric field changes and high flash rate beneath a thunderstorm in northeast India. Journal of Earth System Science, 119(5), 617-625

Praveen B, Talukdar S, Shah F (2020) Analyzing trend and forecasting of rainfall changes in India using non-parametrical and machine learning approaches. Sci Rep 10, 10342 (2020)

Ranalkar MR, Chaudhari HS (2009) Seasonal variation of lightning activity over the Indian subcontinent. Meteorology and Atmospheric Physics, 104(1), 125-134

Ramesh Kumar P, Kamra AK (2012) Spatio-temporal variability of lightning activity in the Himalayan foothills. J. Geophys. Res. 117, D24201. http://dx.doi.org/10.1029/2012JD018246

Romps DM, Seeley JT, Vollaro D, Molinari J (2014) Projected increase in lightning strikes in the United States due to global warming. Science, 346(6211), 851-854

Saha U, Maitra A, Midya SK, Das GK (2014) Association of thunderstorm frequency with rainfall occurrences over an Indian urban metropolis. Atmospheric Research, 138, 240-252

Saha U, Midya SK, Sarkar H, Das GK (2012) Sharp depletion of absolute humidity associated with squall over Kolkata (22 34′ N, 88 26′ E): a possible method of forecasting squall. Pacific Journal of Science and Technology 13(1), 683-688

Saha U, Siingh D, Kamra AK, Galanaki E, Maitra A, Singh RP, Singh R (2017) On the association of lightning activity and projected change in climate over the Indian sub-continent. Atmospheric Research, 183, 173-190

Siingh D, Buchunde PS, Singh RP, Nath A, Kumar S, Ghodpage RN (2014) Lightning and convective rain study in different parts of India. Atmospheric Research, 137, 35-48

Sturman AP, Tapper NJ (1996) The weather and climate of Australia and New Zealand. Oxford University Press, USA

Taszarek M, Allen J, Púčik T, Groenemeijer P, Czernecki B, Kolendowicz L, Schulz W (2019) A climatology of thunderstorms across Europe from a synthesis of multiple data sources. Journal of Climate, 32(6), 1813-1837

Tapper NJ (1996) The weather and climate of Australia and New Zealand. Oxford University Press, USA

Tinmaker MIR, Aslam MY, Chate DM (2014) Climatology of lightning activity over the Indian seas. Atmosphere-Ocean, 52(4), 314-320

Tinmaker MIR, Aslam MY, Chate DM (2017) Association of rainfall and stability index with lightning parameter over the Indo-Gangetic Plains. American Journal of Climate Change, 6(03), 443

Tinmaker MIR, Ghude SD, Chate DM (2019) Land-sea contrasts for climatic lightning activity over Indian region. Theoretical and Applied Climatology 138, 931–940 (2019). https://doi.org/10.1007/s00704-019-02862-4

Tiwari PR, Kar SC, Mohanty U C, Dey S, Kumari S, Sinha P (2016). Seasonal prediction skill of winter temperature over North India. Theoretical and Applied Climatology, 124(1-2), 15-29.

Umakanth N, Satyanarayana GC, Simon B, Rao MC, Babu NR (2020) Long-term analysis of thunderstorm-related parameters over Visakhapatnam and Machilipatnam, India. Acta Geophysica, 68, 921-932

Williams E, Renno N (1993) An analysis of the conditional instability of the tropical atmosphere. Monthly Weather Review, 121(1), 21-36

Yadava PK, Soni M, Verma S, Kumar H, Sharma A, Payra S (2020) The major lightning regions and associated casualties over India. Natural Hazards, 101(1), 217-229

Zhang D, Cummins KL, Bitzer P, Koshak WJ (2019) Evaluation of the performance characteristics of the lightning imaging sensor. Journal of Atmospheric and Oceanic Technology, 36(6), 1015-1031

Zipser EJ, Cecil DJ, Liu C, Nesbitt SW, Yorty DP (2006). Where are the most intense thunderstorms on earth? Bulletin of the American Meteorological Society, 87(8), 1057-1072

ATBD, V. (2013). Joint polar satellite system (JPSS) visible infrared imaging radiometer Suite (VIIRS) sensor data records (SDR) algorithm theoretical basis document (ATBD). Goddard Space Flight Center, Greenbelt, Maryland, Tech. Rep. Joint Polar Satell. Syst.(JPSS) Ground Project Code, 474474-00053. Accessed 12 October 2021
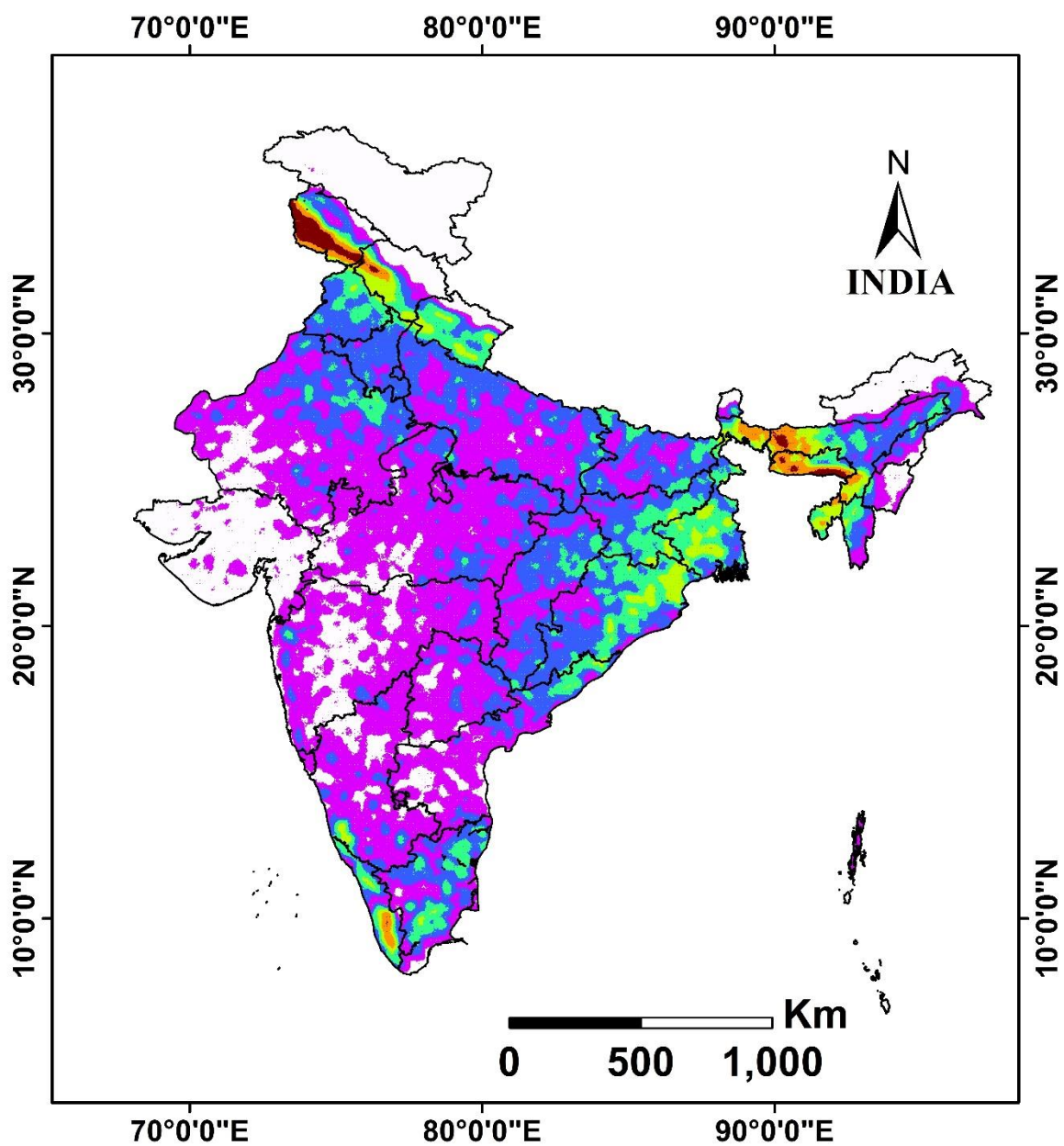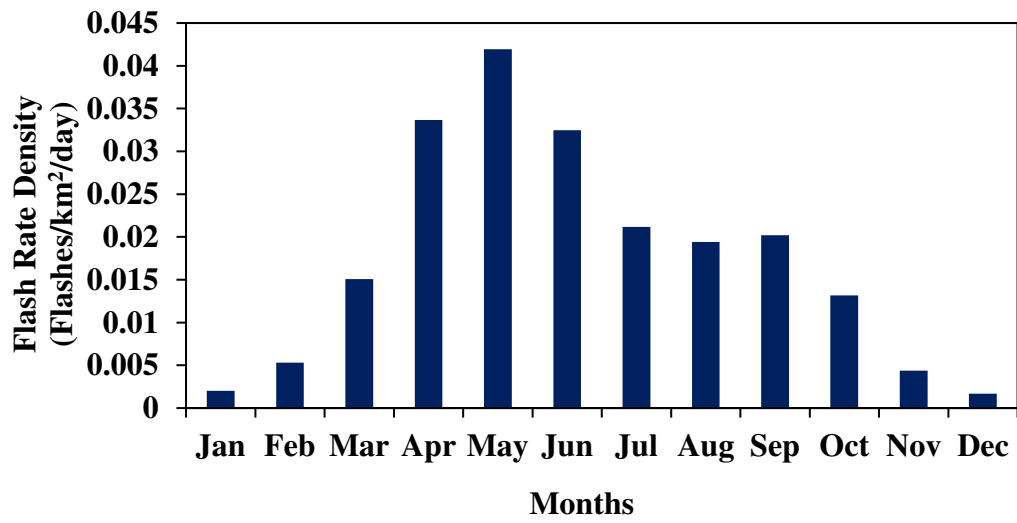
Fig. 1 Study area of lightning flash rate density over India region based on (0.1 degree) over India region during the period 1998-2013 using Lightning Imaging Sensor- Tropical Rainfall Measurement Mission (LIS-TRMM) datasets
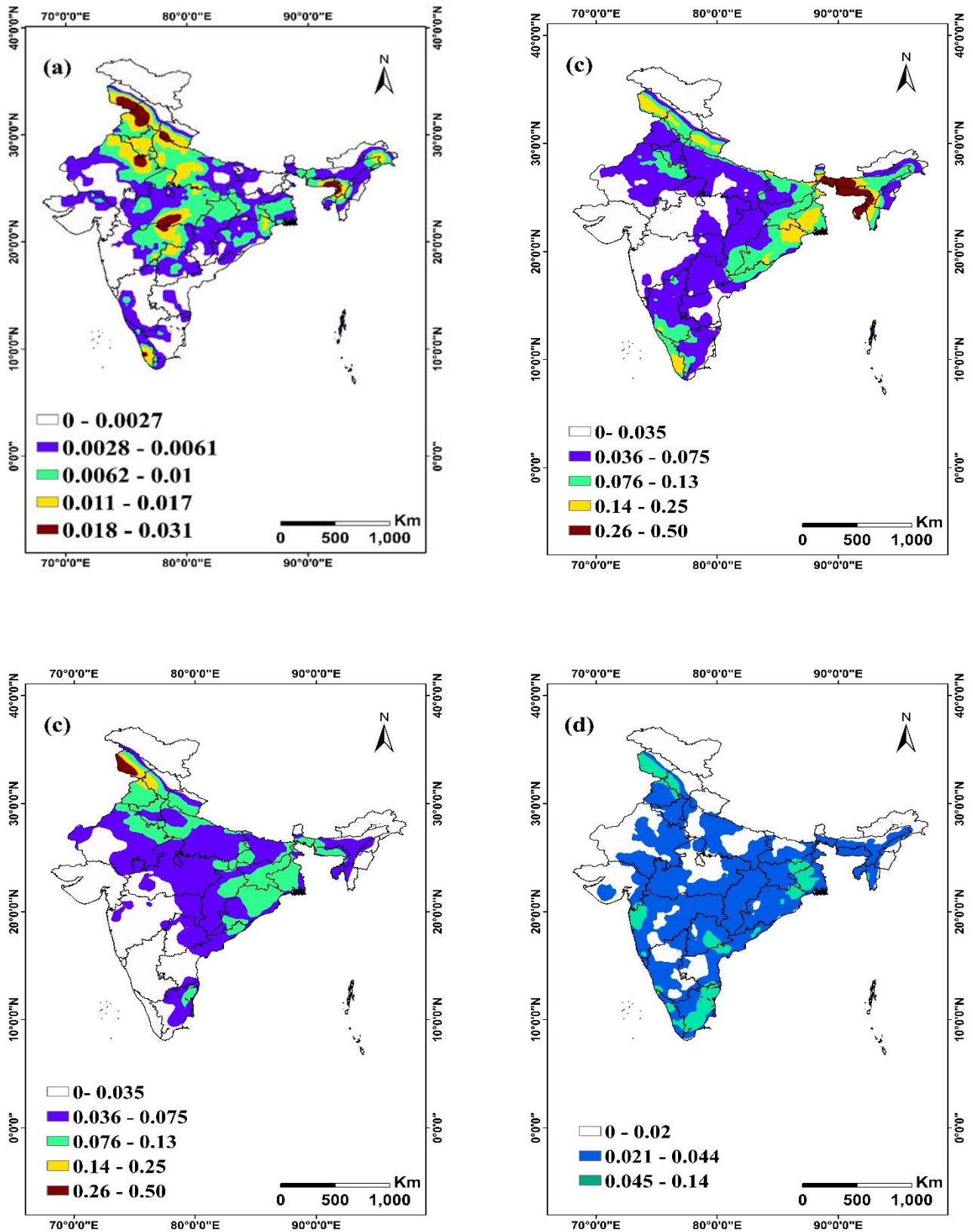
**Fig. 2** Seasonal climatology of lightning flash rate (flashes/ km^2 /day) of **(a)** DJF, **(b)** MAM, **(c)** JJA, and **(d)** SON, during the period 1998–2013 over the Indian sub-continent based on (0.1 degree) using Lightning Imaging Sensor-Tropical Rainfall Measurement Mission (LIS-TRMM) datasets

Fig. 3 Climatology monthly variation of mean of Flash Rate Density (FRD) unit (flashes/km^2/hr) over Indian region from 1998-2013 based on (0.1 degree) over India region during the period 1998-2013 using Lightning Imaging Sensor- Tropical Rainfall Measurement Mission (LIS-TRMM) datasets
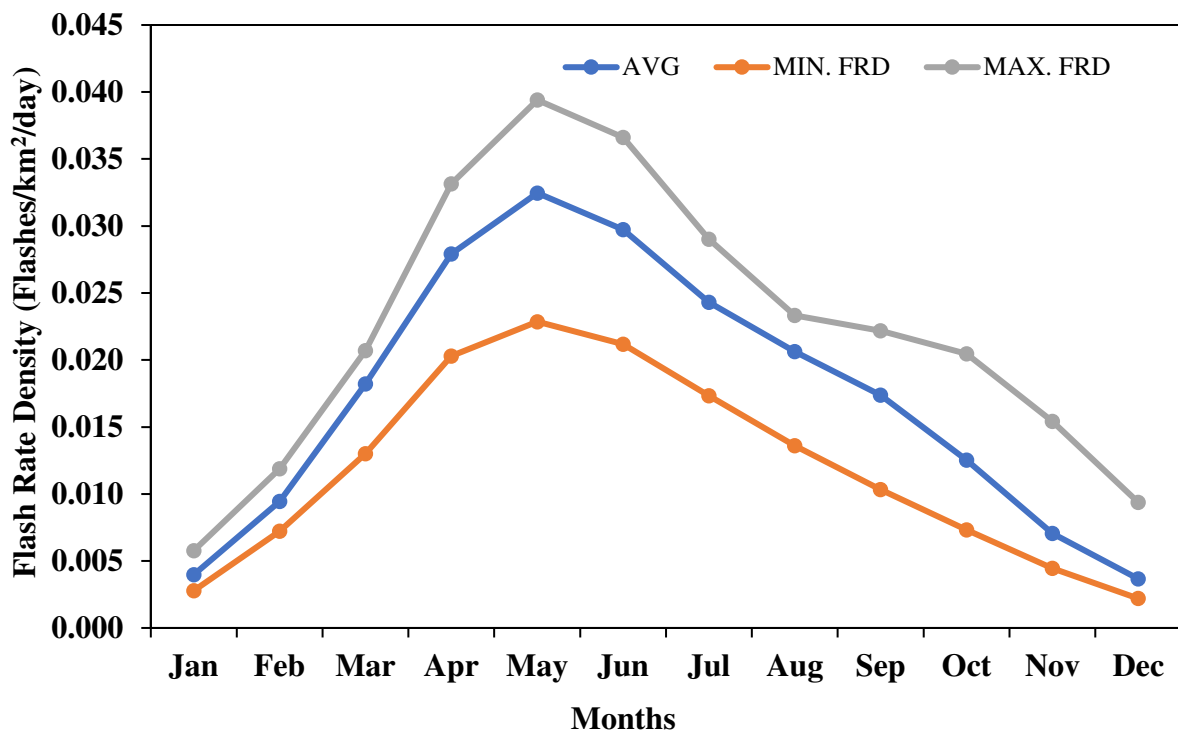
Fig. 4 Monthly mean average, minimum, and maximum flash rate density unit (Flashes/km2/day) over India region during the period 1998-2013 using (2.5 degree) Low Resolution Monthly Time Series (LRMTS), Lightning Imaging Sensor- Optical Transient Detector (LIS-OTD) datasets
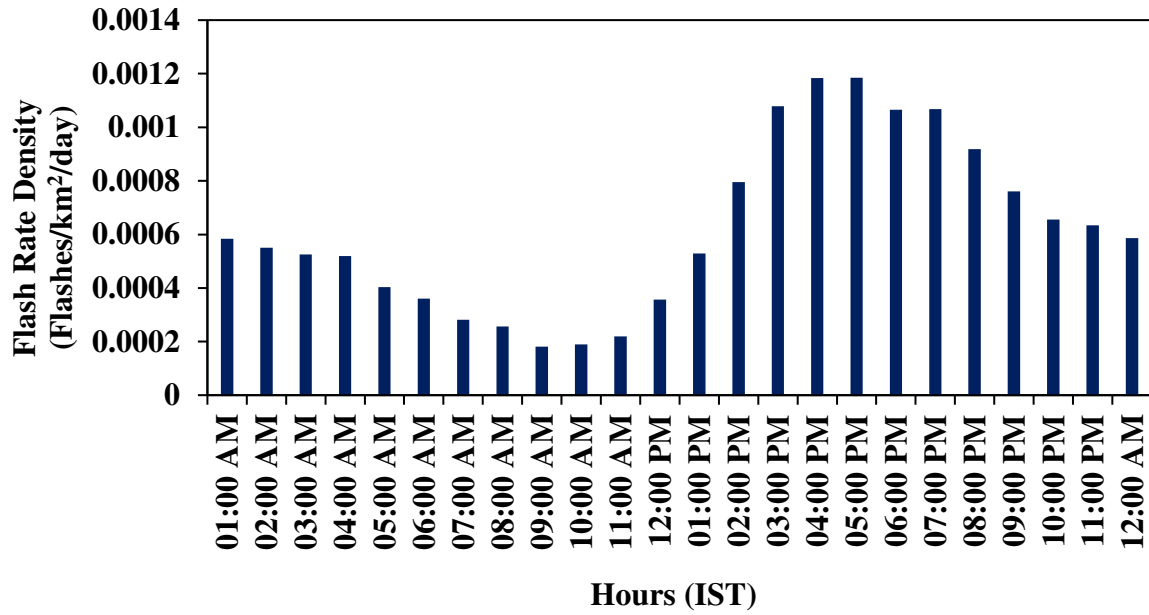
Fig. 5 Climatology diurnal variation of mean Flash Rate Density (FRD) unit (flashes/km^2/hr) over Indian region from 1998-2013 based on (0.1 degree) over India region during the period 1998-2013 using Lightning Imaging Sensor- Tropical Rainfall Measurement Mission (LIS-TRMM) datasets
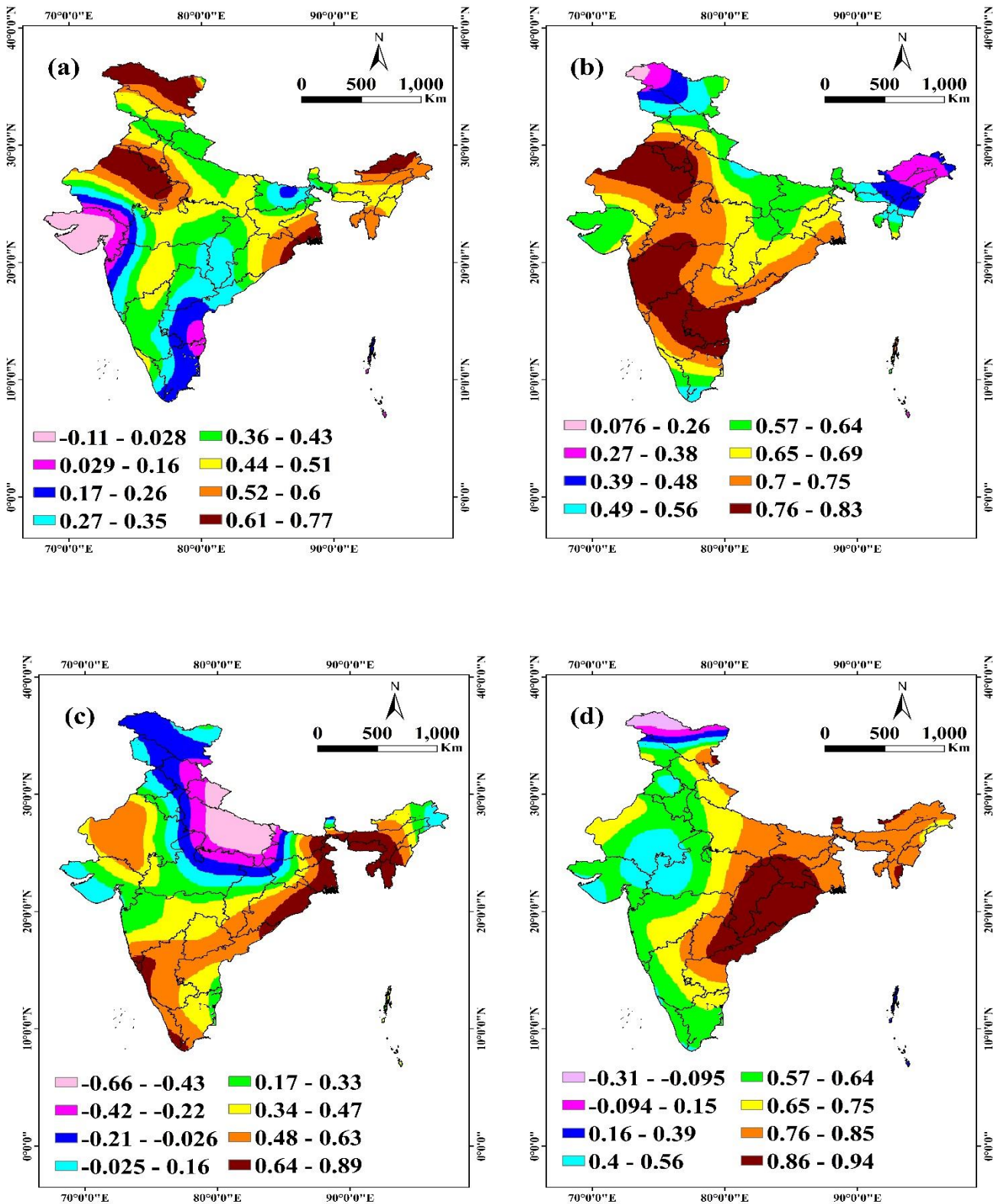
Fig. 6 Seasonal spatial correlation between convective available potential energy (CAPE) and lightning flash rate density (FRD) of **(a)** DJF, **(b)** MAM, **(c)** JJA, and **(d)** SON, over India region during the period 1996-2012
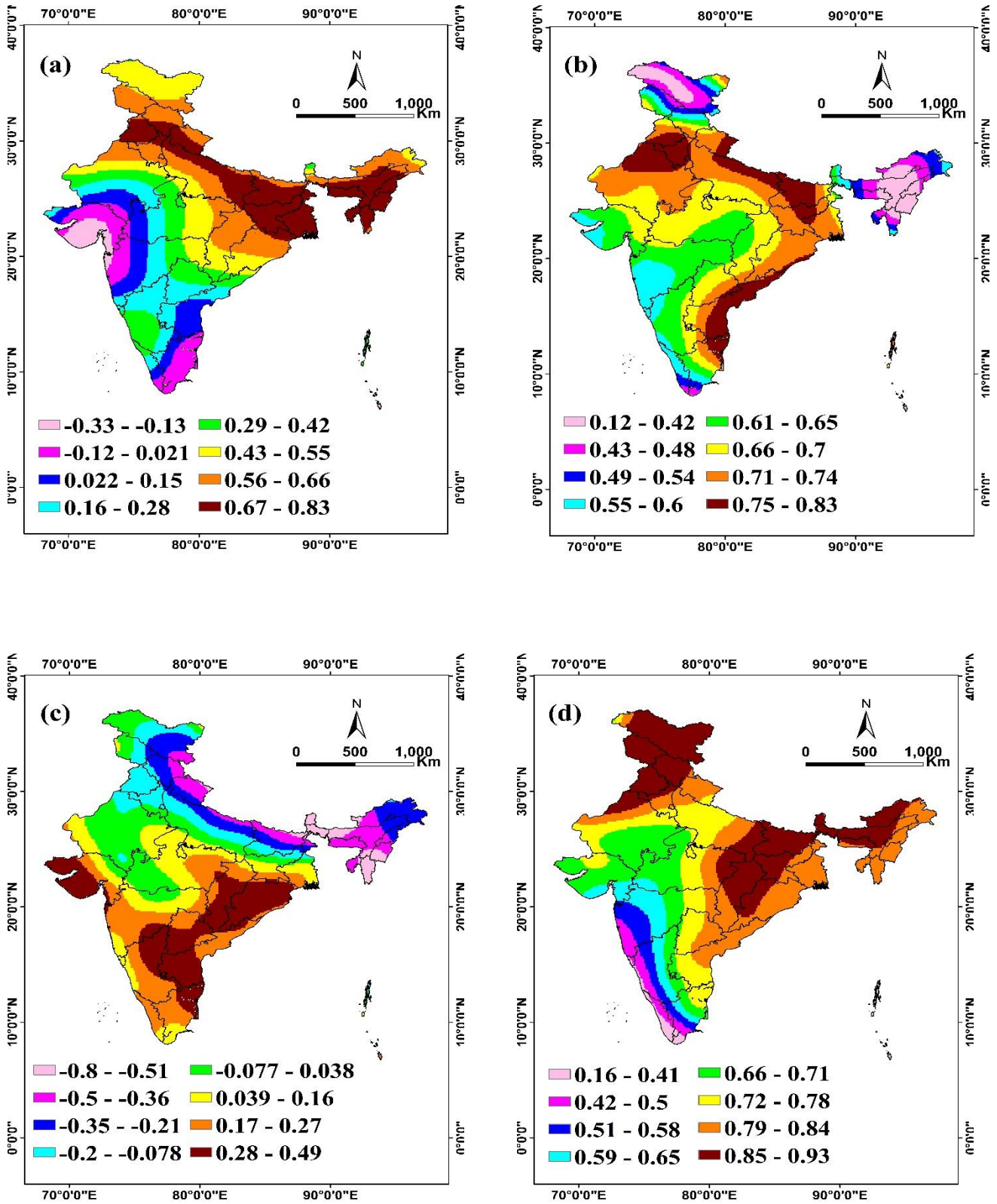
Fig. 7 Seasonal spatial correlation between K Index (KI) and lightning flash rate density (FRD) of **(a)** DJF, **(b)** MAM, **(c)** JJA, and **(d)** SON, over India region during the period 1996-2012
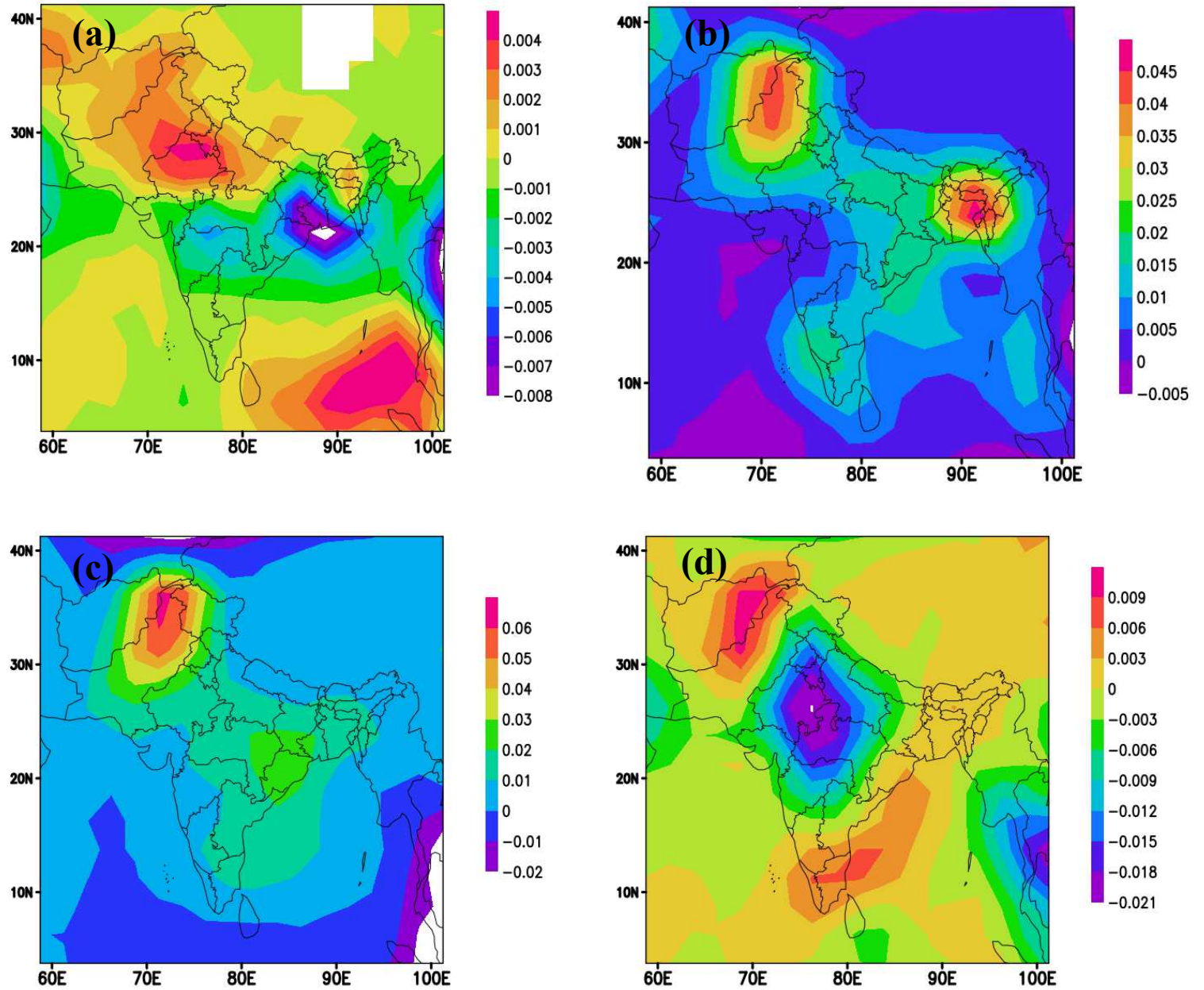
Fig. 8 Seasonal spatial trend of lightning flash rate density (FRD) of **(a)** DJF, **(b)** MAM, **(c)** JJA, and **(d)** SON, over India region during the period 1996-2014 using (2.5 degree) Low Resolution Monthly Time Series (LRMTS), Lightning Imaging Sensor- Optical Transient Detector (LIS-OTD) datasets
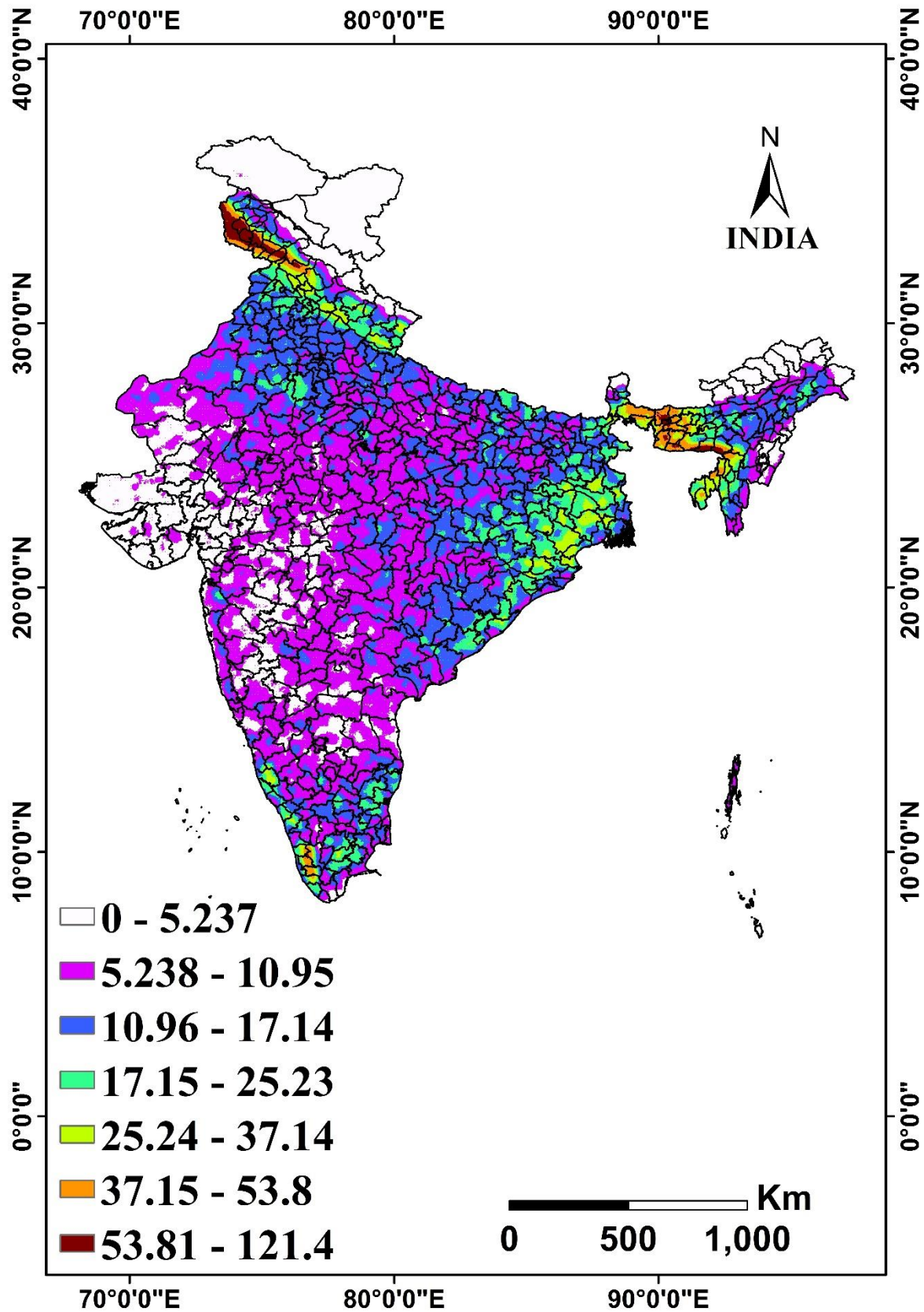
Fig. 9 Lightning hotspots region districts wise of India based on (0.1 degree) over India region during the period 1998-2013 using Lightning Imaging Sensor- Tropical Rainfall Measurement Mission (LIS-TRMM) datasets

Table 1 Resolution Gridded Lightning Climatology Data Parameters

File Identifier	Dataset name	Description	Units	Dimensions*	Bin sizes	Smoothing
VHRFC	VHRFC_LIS_FRD	Mean annual flash rate density	flashes/km^2/year	400 x 330	0.1° x 0.1°	none
VHRDC	VHRDC_LIS_FRD	Mean local time flash rate density	flashes/km^2/hr	400 x 330x 24	0.1° x 0.1° x 1 h	1° x1° boxcar moving average
VHRMC	VHRMC_LIS_FRD	Mean monthly flash rate density	flashes/km^2/day	400 x 330x 12	0.1° x 0.1° x 1 month	49-day and 1° x1° boxcar moving average
VHRSC	VHRSC_LIS_FRD	Mean seasonal flash rate density	flashes/km^2/day	400 x 330x 4	0.1° x 0.1° x 1 trimester	49-day and 1° x1° boxcar moving average
LRMTS	LRMTS_COM_FR	Monthly time series of flash rate (weighted more toward LIS than other products)	flashes/km^2/day	18x16x72	1 month x 2.5-degree x 2.5-degree	Weighted average of LRTS_OTD_FR and LRTS_LIS_FR

*Dimensions over the India region

Table 2 CAPE parameters indicating thunderstorm chances

CAPE	Thunderstorm chances
Less than 300 J/kg	Little or no convective potential
Ranging between 300 and 1000 J/Kg	Weak convective potential
Ranging between 1000 AND 2500 J/Kg	Moderate convective potential
Greater than 2500 J/Kg	Strong convective potential

Table 3 K index parameters indicating thunderstorms chances

K-index	Thunderstorm Probability
<20 ˚C	No thunderstorms
20-25˚C	Isolated thunderstorms
26-30 ˚C	Widely scattered thunderstorms
31-35 ˚C	Scattered thunderstorms
>35 ˚C	Numerous thunderstorms

Table 4 Top 50 lightning hotspots in India, indicating its position in the ranking, the name of the nearest city and state, latitude and longitude position on TRMM LIS 0.1° climatology grid, and FRD.

DISTRICT	ST_NM	Min_lon	Max_lon	Min_lat	Max_lat	Max_vhrfc
Rajouri	Jammu & Kashmir	74.15	74.65	33.15	33.55	121.40
Reasi	Jammu & Kashmir	74.65	75.05	32.95	33.45	115.25
East Khasi Hills	Meghalaya	91.45	92.05	25.15	25.55	101.78
Jaintia Hills	Meghalaya	92.05	92.75	25.05	25.65	94.99
Kottayam	Kerala	76.45	76.95	9.45	9.75	92.94
Kathua	Jammu & Kashmir	75.25	75.85	32.35	32.75	92.80
Kangra	Himachal Pradesh	75.75	76.95	31.75	32.35	92.59
Punch	Jammu & Kashmir	73.95	74.45	33.45	33.95	90.11
Udhampur	Jammu & Kashmir	75.05	75.75	32.65	33.05	84.19
Karimganj	Assam	92.25	92.55	24.25	24.85	83.00
West Garo Hills	Meghalaya	89.85	90.35	25.25	25.85	79.46
Jammu	Jammu & Kashmir	74.55	75.05	32.55	32.95	77.42
Dhubri	Assam	89.75	90.45	25.65	26.35	77.33
Goalpara	Assam	90.25	91.05	25.95	26.15	77.08
Jalpaiguri	West Bengal	88.45	89.85	26.35	26.95	77.03
Kokrajhar	Assam	89.95	90.35	26.15	26.85	76.62
Idukki	Kerala	76.65	77.35	9.35	10.25	75.72
East Garo Hills	Meghalaya	90.15	90.95	25.45	25.95	74.51
West Khasi Hills	Meghalaya	90.85	91.75	25.25	25.75	73.90
Samba	Jammu & Kashmir	74.95	75.25	32.45	32.75	71.72
Chamba	Himachal Pradesh	75.85	76.85	32.25	33.15	69.78
Ernakulam	Kerala	76.25	76.75	9.85	10.25	68.45
Kollam	Kerala	76.55	77.25	8.85	9.15	68.26
South Tripura	Tripura	91.35	91.85	23.05	23.75	66.85
South Garo Hills	Meghalaya	90.25	90.95	25.15	25.45	66.03
Cachar	Assam	92.55	93.15	24.45	25.05	65.87
Pashchim Medinipur	West Bengal	86.65	87.85	21.85	22.95	65.44
Chirang	Assam	90.45	90.85	26.45	26.85	65.03
Koch Bihar	West Bengal	88.85	89.85	26.05	26.45	64.49
Gurdaspur	Punjab	74.95	75.85	31.65	32.45	62.65
Pathanamthitta	Kerala	76.55	77.25	9.15	9.45	62.25
Bhadrak	Odisha	86.35	86.95	20.85	21.15	58.50
Bongaigaon	Assam	90.45	90.75	26.25	26.45	58.22
Kamrup	Assam	91.05	91.75	25.75	26.45	58.17
Hugli	West Bengal	87.65	88.45	22.65	23.15	57.55
Maldah	West Bengal	87.85	88.45	24.75	25.45	56.85
Birbhum	West Bengal	87.15	87.95	23.55	24.55	55.85
Una	Himachal Pradesh	76.05	76.45	31.35	31.85	55.12
Tamenglong	Manipur	93.25	93.85	24.55	25.35	54.58

Puri	Odisha	85.25	86.35	19.55	20.15	54.22
Kendujhar	Odisha	85.25	86.35	21.05	22.05	54.21
Dima Hasao	Assam	92.65	93.45	25.05	25.75	54.12
Mayurbhanj	Odisha	85.75	87.05	21.35	22.55	53.81
Dindigul	Tamil Nadu	77.35	78.25	10.05	10.75	53.67
Cuttack	Odisha	84.95	86.25	20.05	20.65	52.46
Dhenkanal	Odisha	85.15	85.95	20.55	21.15	52.28
Barpeta	Assam	90.75	91.25	26.15	26.65	51.67
North Tripura	Tripura	91.95	92.25	23.75	24.35	51.21
Dhalai	Tripura	91.85	92.15	23.55	24.15	50.46
Pashchimi Singhbhum	Jharkhand	85.05	85.95	22.05	22.85	50.36
Dakshina Kannada	Karnataka	74.85	75.65	12.55	13.15	50.22