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Lightning activity in India an important cause of fatalities

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सार– चरम मौसम की घटनाओं ने पूरे वर्ष देश को कई तरह से प्रभावित किया, जैसे भारी वर्षा, ऊष्ण लहरें, शीत लहरें और तड़ित गिरना। तड़ित गिरने की गतिविधि अत्यधिक अस्तव्यस्त करने वाली, अप्रत्याशित और प्रकृति में यादृच्छिक होती है। जलवायु परिवर्तन पर अंतर-सरकारी पैनल (IPCC) की रिपोर्ट-2013 में 21वीं सदी के अंत तक 1-5 डिग्री सेल्सियस की वैश्विक गर्मी बढ़ने का अनुमान लगाया गया है। क्या यह बदलता परिदृश्य तड़ित गिरने से होने वाली मौतों में हाल की वृद्धि के लिए जिम्मेदार है? ग्रीनहाउस गैसों (GHG) की बढ़ी हुई सांद्रता इस परिवर्तन से निकटता से संबंधित है। सतह के तापमान में थोड़ी सी वृद्धि से भी आंधी और तड़ित गिरने की गतिविधियों में वृद्धि होती है। IPCC की रिपोर्ट सीधे तौर पर तड़ित गिरने की गतिविधियों और इसके भविष्य के अनुमानों से नहीं करती है क्योंकि इसे जलवायु मॉडल द्वारा ठीक से हल नहीं किया गया है।

अतः, इस कार्य में हमने ऊपरी क्षोभमंडलीय जल वाष्प, संवहनीय उपलब्ध संभावित ऊर्जा (CAPE), बादल बर्फ, एरोसोल और सतह के तापमान के संदर्भ में तड़ित की गतिविधियों की प्रवृत्तियों का विश्लेषण किया है। इस कार्य में ये प्राचल उष्णकटिबंधीय वर्षा मापने वाले मिशन माइक्रोवेव इमेजर (TRMM) पर लगे लाइटनिंग इमेजिंग सेंसर (LIS) के तड़ित चमक डेटा, भारत मौसम विज्ञान विभाग (IMD) के ग्रिडेड तापमान डेटा, मॉडरेट रेजोल्यूशन इमेजिंग स्पेक्ट्रोरेडियोमीटर (MODIS) और TRMM लेवल-2 वर्षा रेडार डेटा के साथ सकारात्मक और नकारात्मक दोनों तरह से सहसंबंधित हैं।

यह देखा गया है कि सतह के तापमान की तुलना में ऊपरी वायुमंडल के तापमान में अधिक वृद्धि एक स्थिर वायुमंडल का सूचक है और इसलिए कम गर्ज के साथ तूफान आता है। तड़ित की गतिविधियों को ट्रिगर करना वायुमंडल में जल वाष्प के संवहनी परिवहन से संबंधित हो सकता है जो पृथ्वी की सतह से उत्सर्जित अवरक्त विकिरण को अवशोषित करता है; यह बदले में वायुमंडल को निचले स्तरों पर स्थिर करता है और वायुमंडल में ऊपरी स्तरों पर ऊष्ण करता है। विश्लेषण के परिणाम दर्शाते हैं कि CAPE का गर्ज के साथ तूफान सेल के भीतर अस्थिरता से प्रेरित बिजली की गतिविधि के साथ सकारात्मक संबंध है। अतः, हम कह सकते हैं कि वैश्विक औसत वायुमंडल के स्थिरीकरण के परिणामस्वरूप बहुत अधिक विस्फोटकता होती है, जिससे अधिक बिजली की गतिविधि उत्पन्न होती है और संभवतः अधिक मौतें होती हैं।

ABSTRACT. Extreme weather events affected the country throughout the year in many ways, like heavy rainfall, heat waves, cold waves & lightning. Lightning activity is highly chaotic, unpredictable and random in nature. The Intergovernmental Panel on Climate Change (IPCC) report - 2013 projects the global warming of 1-5 ºC by the end of 21^{st} Century. Is this changing scenario responsible for the recent increase of deaths due to lightning? The increased concentration of greenhouse gases (GHGs) is closely related to this change. Small increase in surface temperature leads to an increase in thunderstorm and lightning activities. IPCC report directly not dealing with lightning activities and its future projections as it is poorly resolved by climate models.

Therefore, in this work we have analysed the trends of the lightning activities in reference to upper tropospheric water vapour, convective available potential energy (CAPE), cloud ice, aerosols and surface temperature. These parameters are correlated both positively and negatively with lightning flash data of Lightning Imaging Sensor (LIS) aboard on tropical rainfall measuring mission microwave imager (TRMM), gridded temperature data of India Meteorological Department (IMD), Moderate Resolution Imaging Spectroradiometer (MODIS) and TRMM Level-2 Precipitation Radar data.

It is seen that more upper troposphere temperature rise than surface temperature is an indicator of a stable atmosphere and hence fewer thunderstorms. The triggering of lightning activities can be related to the convective transport of water vapour in the atmosphere which absorbs the infrared radiation emitted by the surface of the earth; this in turn stabilizes the atmosphere at lower levels and warming at upper levels in the atmosphere. Results of the analysis shows that CAPE is positively correlated with lightning activity induced by the instability within the thunderstorm cell. Therefore, we can say that stabilization of the global mean atmosphere results in much more explosive producing more lightning activity and perhaps lead to more fatalities.

Key words- Lightning, Liquid water path, Thunderstorm, Climate change.

1. Introduction

The lightning associated with thunderstorms can directly result in loss of life and damage to infrastructure (Holle, 2008, Mills *et al*., 2010, Cardoso *et al*., 2011 and Zhang *et al*., 2011) as well as lead to the occurrence of hazards such as wildfires (Vazquez *et al*., 1998, Wotton, *et al*., 2005, Kasischke *et al*., 2006 and Dowdy & Mills., 2012). Lightning is an atmospheric hazard which is chaotic in nature can be predicted seasonally with the support of slowly varying remote sensing forces (Mallick *et al*., 2022).

On Geostationary satellites like Meteosat Third Generation-Imager (MTG-I), lightning Imager (LI) have great potential for severe weather monitoring (Grandell *et al*., 2010) the lightning instruments provides near real time information on total lightning, intercloud (IC) and Cloud to ground (CG) with a latency on the order of 1 minute. Similarly, Geostationary Lightning Mapper (GLM) on National Oceanic Atmospheric Administration (NOAA), Geostationary Operational Environmental Satellite (GOES) 16/17 and later on GOES- T/U and Lightning Image Mapper (LMI) on the Chinese Fengyun-4 (FY-4) satellite series (Yang *et al.*, 2017) will establish geostationary ring of Lightning Imagers. Assimilation of this high-resolution data of geostationary satellite data provides high temporal refresh cycles by providing three-dimensional fields of water vapor and cloud observations for numerical weather prediction (NWP) models.

Nowadays new techniques and methods such as artificial intelligence and machine learning schemes that are able to use large amounts of complex data sources, are also being developed offering new opportunities for nowcasting (Boukabara *et al*., 2019) especially for such chaotic events. Keeping in view of the urgent needs of information of lightning an important of public safety and extensive damages caused by lightning both private and public services working together to track the locations of lightning and heavy precipitation to generate warning with sufficient lead time (Nag *et al*., 2015).

The advent of improved lightning observations, including space-based observations, now also provides the opportunity to support climate monitoring. Lightning is therefore recognized by Global Climate Observing System (GCOS) as a new ECV (Aich *et al*., 2018, WMO, 2020). Thunderstorms can sometimes be associated with hazards such as extreme rainfall, winds and hail occurrence (Elsner *et al*., 2014). Thunderstorms are also a major driver of the global atmospheric distribution of water thereby influencing both long and short-wave radiation (Amerasekera *et al*., 1997, Price, 2000., Soden, 2000 and Williams, 2005) with the global distribution of upper-tropospheric ice broadly consistent with thunderstorm behaviour (Kent *et al*., 1995). The post-strike effects of lightning are very crucial and create traumatic conditions in humans and it also produces nitrogen oxides, which are strong greenhouse gases (Price, 1993, 2013, Price *et al*., *1997*). Lightning flash data are obtained from two NASA satellite sensors: the Lightning Imaging Sensor (LIS) and the Optical Transient Detector (OTD), Boccippio *et al*., 2002, Christian *et al*., 2003). Results are examined in relation to the potential for seasonal forecasting of lightning and thunderstorm activity, including through the use of hindcast.

Present work brought out the trends of lightning activity, surface temperature, upper tropospheric water vapour, cloud ice, Convective Available Potential Energy (CAPE) and AOD correlation of these parameters with lightning activity using lightning flash rate data of Lightning Imaging Sensor aboard TRMM, gridded temperature data of IMD, aerosol data acquired by MODIS.

2. Data and methodology

The datasets used in this study have been taken from India Meteorological Department (IMD) for gridded temperature data (Srivastava *et al.*, 2009) & thunderstorm days in each season. Lightning flash rate data for the period (1996-2004) has been taken from Lightning Imaging Sensor (LIS) aboard Tropical Rainfall Measuring Mission (TRMM) at 4x4 km spatial resolution in NETCDF-4 format. The convective and stratiform rainfall data has been analysed from the L2 TRMM data sets (TRMM_2A23_7) downloaded from Goddard Earth Sciences Data and Information Services Center (https://disc.gsfc.nasa.gov/). The aerosol optical depth, cloud optical thickness, ice water path & Upper Troposphere Water Vapour (UTWV) data has been taken from Moderate Resolution Imaging Spectroradiometer (MODIS) level 2 data sets (MOD06 /MOD08/MOD35) at

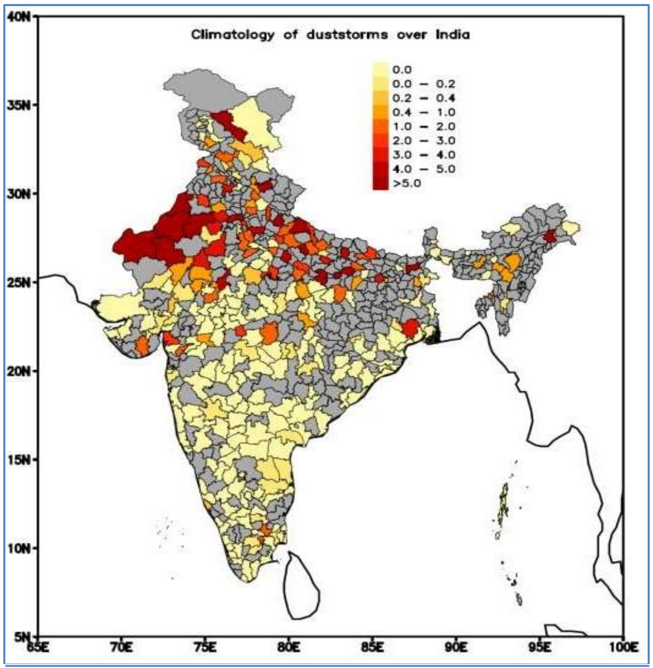

Fig. 1(a). Climatology of Dust storms over India. (Source: IMD-Pune).

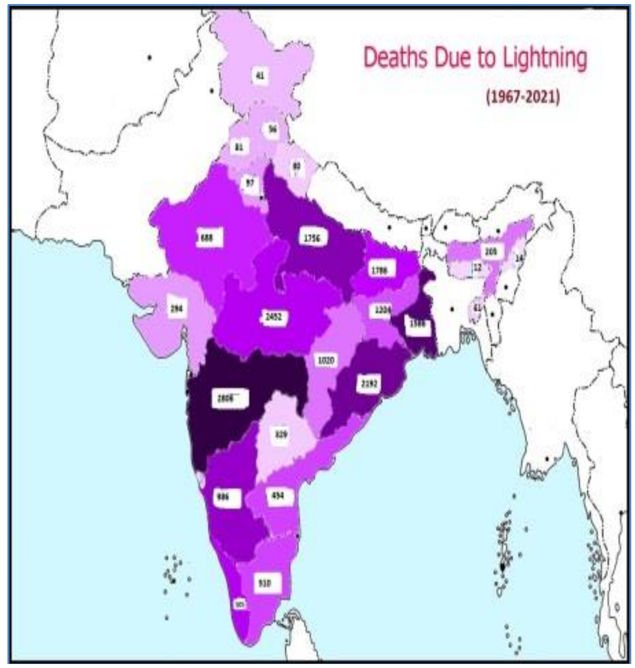

Fig. 1(b). Deaths due to lightning (1967-2021) based on the IMD, Disastrous Weather Events (DWE), Annual Reports. 1967-2021.

1x1 km (https://ladsweb.modaps.eosdis.nasa.gov/). For final analysis all data sets TRMM as well as MODIS at 4 x 4 km resolution has been generated

Therefore, in order to address this issue, we have processed and analysed trends of lightning activity, surface temperature, upper tropospheric water vapour, cloud ice, Convective Available Potential Energy (CAPE) and aerosol Optical depth (AOD) from the above data sets. We have also examined the correlation of the above said parameter parameters with lightning activity. The data analysis is done for different seasons of India (winter, pre-monsoon, monsoon & post monsoon seasons). The period of different data sets are as follows: LIS lightning flash data, Surface temperature, Aerosol Optical depth, (1996-2014), Upper Tropospheric Water Vapour, cloud optical thickness, Ice water Path, aerosol Optical depth, Convective and stratiform rainfall (1996-2014).

3. Results and discussions

Extreme weather events and associated losses affect the country every year. The increasing awareness and latest state of art techniques improves the forecasting skill and accuracy substantially. However, the prediction and impact due to lightning is still a challenging task. The thunder events normally accompanied with dust storms also if the weather system takes sufficient moisture. The convective development during pre, monsoon and post monsoon seasons also leads to lightning activities and caused several deaths every year (Ray *et al*., 2021). The dust storm climatology made from climatological tables of observatories in India (1981-2010) published by IMD Pune, Ministry of Earth Sciences (IMD, 2015) is shown in Fig. 1(a). Normally the dust storm prone zones behave in similar fashion like convective zone therefore lightning events also behave almost in similar manner. However, there is no such one to one correspondence but if the dust storm picks up the moisture then its development may be rapid and can be cause of lightning activity.

The disaster weather events (DWE state-wise records compiled by IMD (https://imdpune.gov.in/library/publication.html) and National Crime Record Bureau from 1967-2021 (https://www.ncrb.gov.in/accidental-deaths-suicides-in-india-adsi.html). The total number of deaths due to lightning in different states of India are shows in Fig. 1(b). This record can be manifold as the compilation of such events in many places remained unnoticed. It is seen from Fig. 1(b) that the fatalities due to lightning are highest in Maharashtra (2806) followed by Madhya Pradesh (2452), Odisha (2152), Bihar (1786), Uttar Pradesh (1756), West Bengal (1586). Jharkhand (1204), Karnataka (986), Rajasthan (688), Tamilnadu (510), Kerala (505), Andhra Pradesh (454), Telengana (329), Gujrat (294), Assam 92-5), Haryana & Delhi (97), Punjab (81), Tripura (61), Uttarakhand (56) and J&K (41). The cases of lightning reported in the NE regions are less as compared to Northern, Central and Southern parts of India but due to unique demography and source of origin different type of weather systems it needs special attention or study separately.

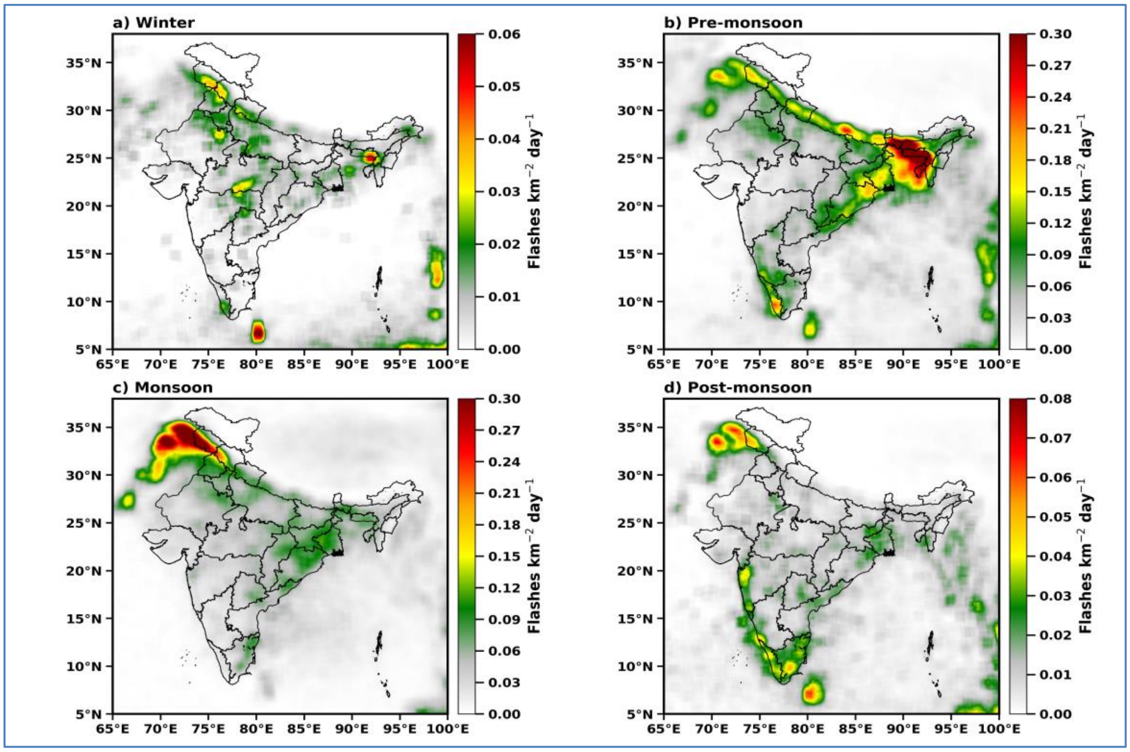

Fig. 2. High Resolution Seasonal Climatology of Lightning. (a) Winter(Jan-Feb), (b) Pre-monsoon(Mar-May), (c) Monsoon(Jun-Sep) and (d) Post-monsoon (Oct-Dec). [Source: TRMM data].

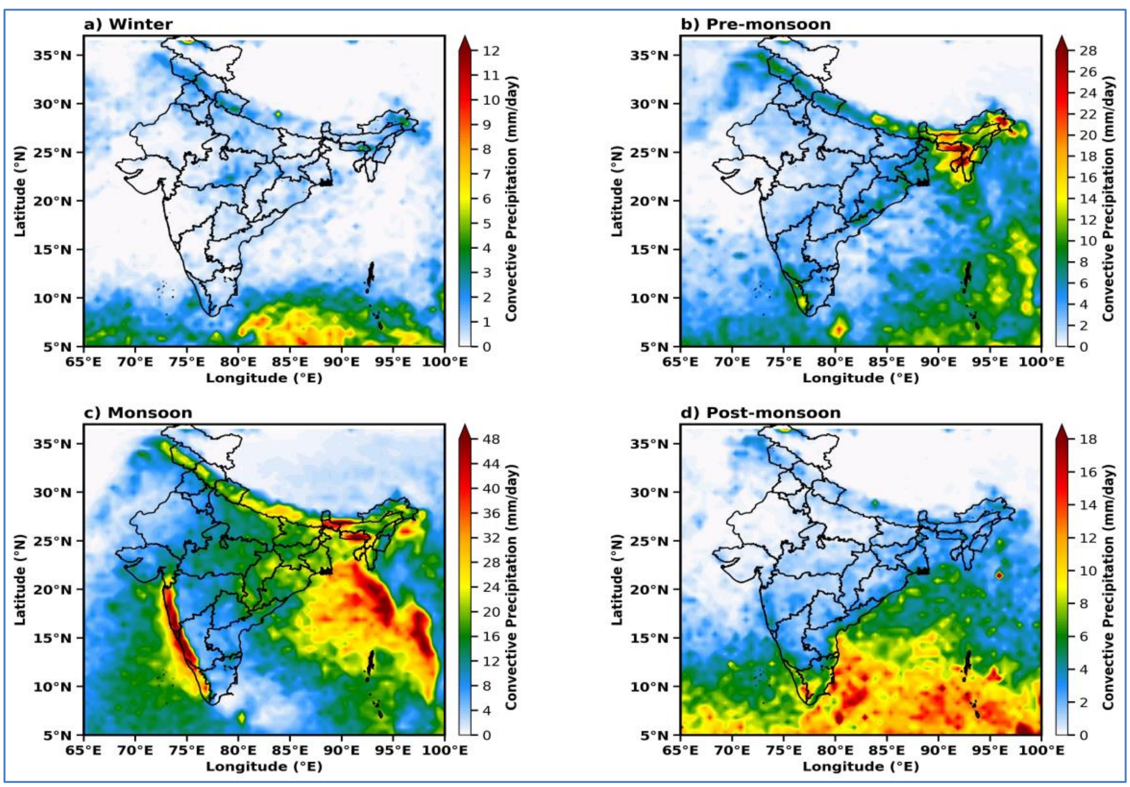

Fig. 3.1. Convective Rainfall. (a) Winter (Jan-Feb), (b) Pre-monsoon (Mar-May), (c) Monsoon (Jun-Sep) and (d) Post-monsoon (Oct-Dec) [source: TRMM data].

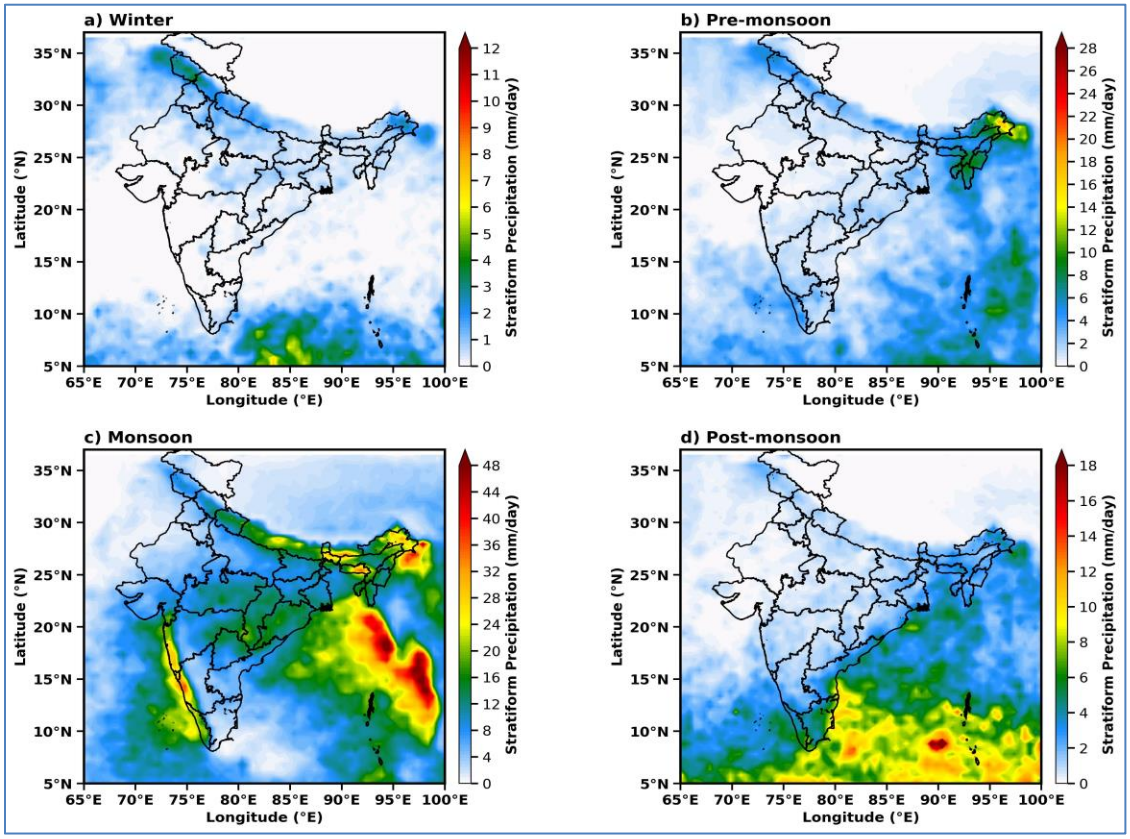

Fig. 3.2. Stratiform Rainfall. (a) Winter (Jan-Feb), (b) Pre-monsoon (Mar-May), (c) Monsoon (Jun-Sep) and (d) Post-monsoon (Oct-Dec) [source: TRMM data].

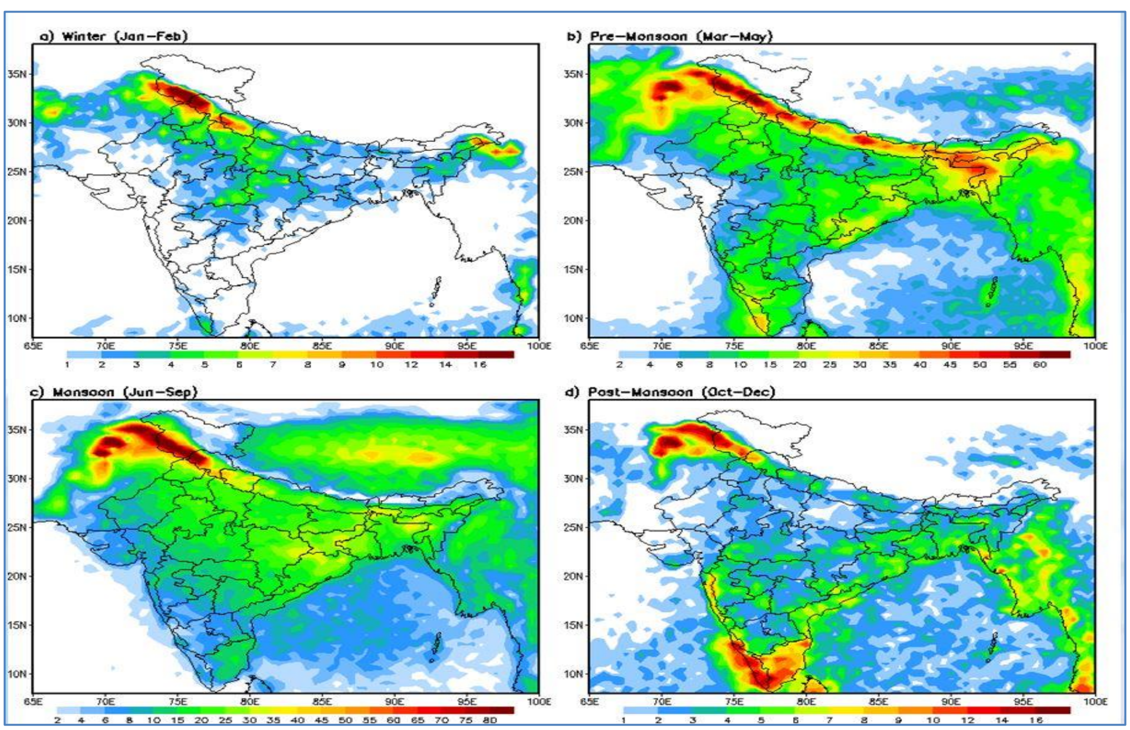

Fig. 4. Thunderstorm days based on no. of distinct days of lightning activity. (a) Winter (Jan-Feb), (b) Pre-monsoon (Mar-May), (c) Monsoon (Jun-Sep) and (d) Post-monsoon (Oct-Dec). [Source: TRMM rainfall /LIS data].

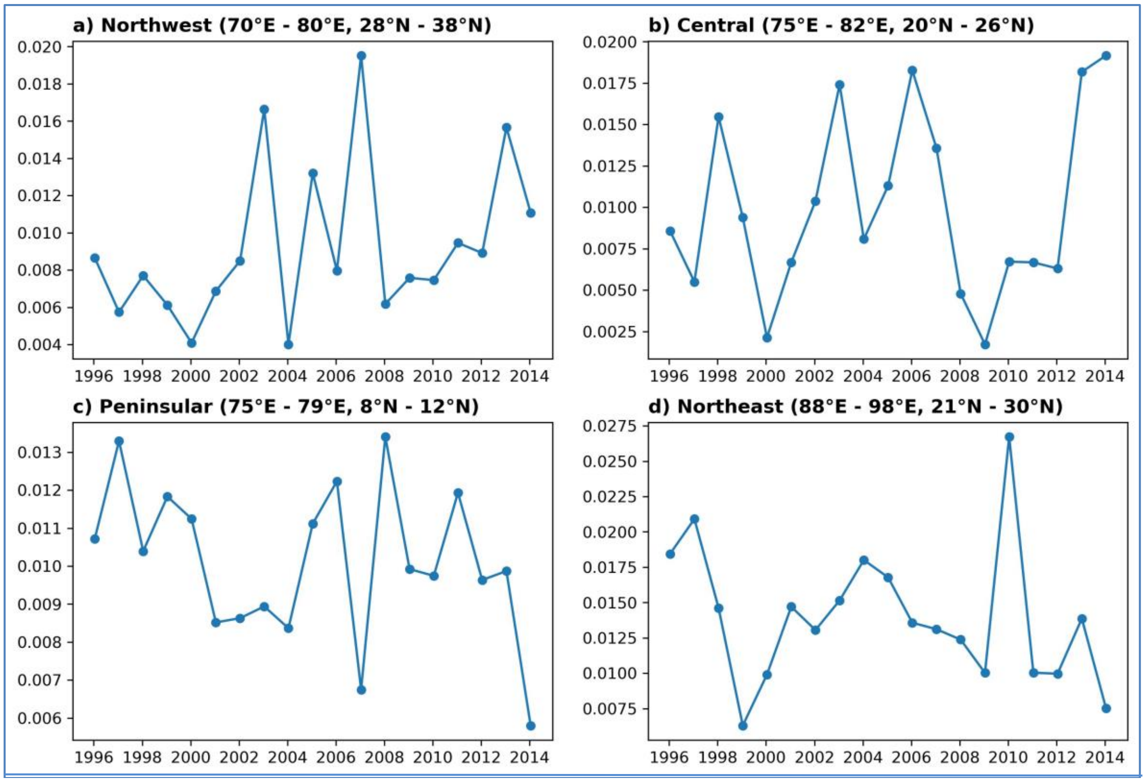

Fig. 5. Variation of low resolution monthly flash rate : winter season. (a) Northwest (70º-80º E ; 28º-38º N), (b) Central (75º-82º E ; 20º-26º N), (c) Peninsular (75º-79º E ; 8º-12º N) and (d) Northeast (88º-98º E ; 21º-30º N).

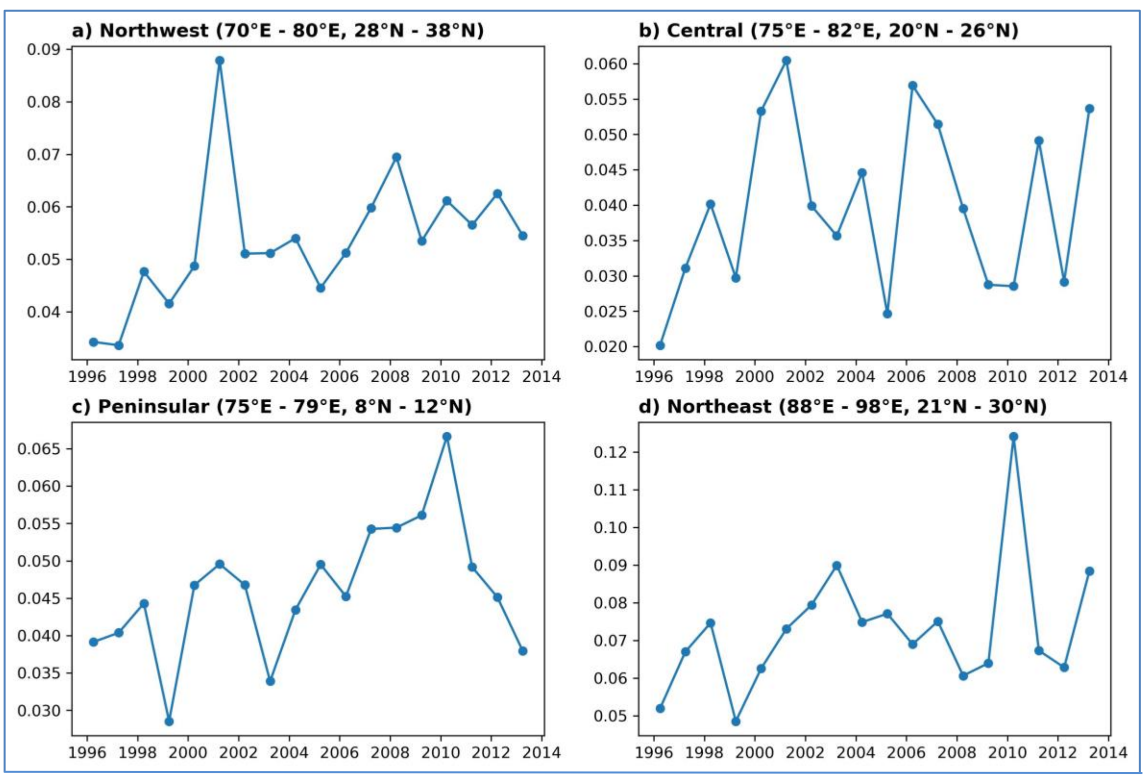

Fig. 6. Variation of low resolution monthly flash rate : Pre-monsoon season. (a) Northwest (70º-80º E ; 28º-38º N), (b) Central (75º-82º E ; 20º-26º N), (c) Peninsular (75º-79º E ; 8º-12º N) and (d) Northeast (88º-98º E ; 21º-30º N).

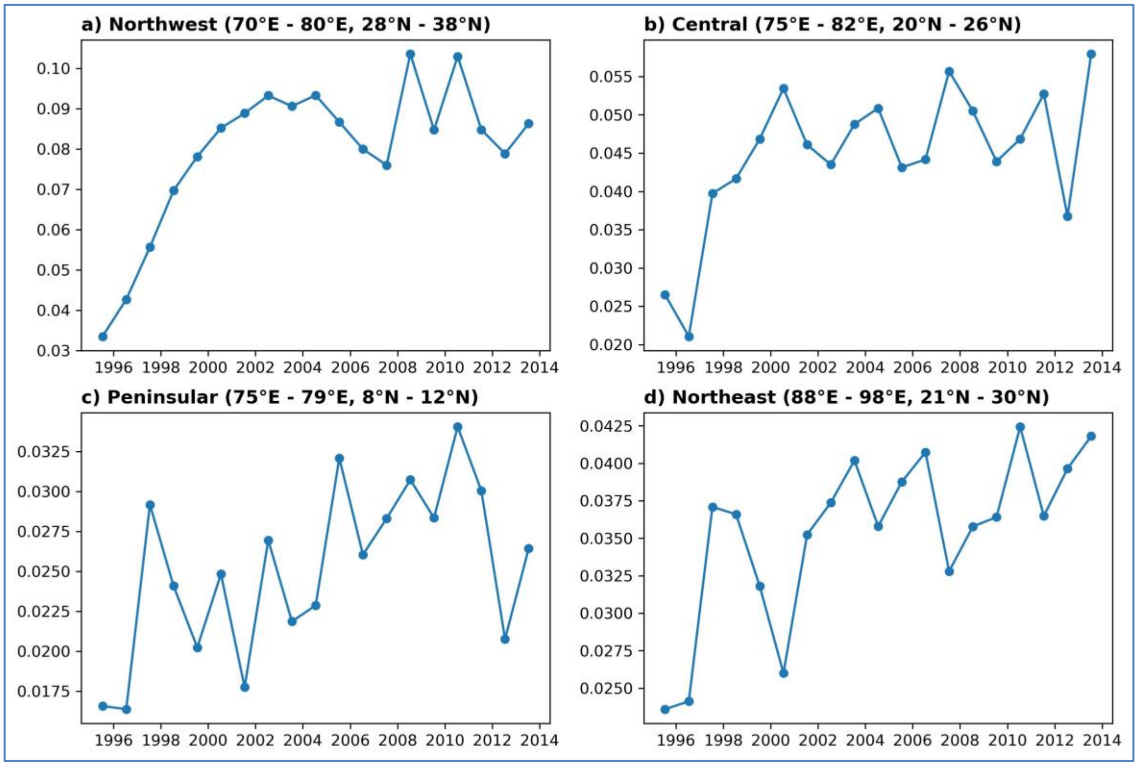

Fig. 7. Variation of low resolution monthly flash rate : Monsoon season. (a) Northwest (70º-80º E ; 28º-38º N), (b) Central (75º-82º E ; 20º-26º N), (c) Peninsular (75º-79º E ; 8º-12º N) and (d) Northeast (88º-98º E ; 21º-30º N).

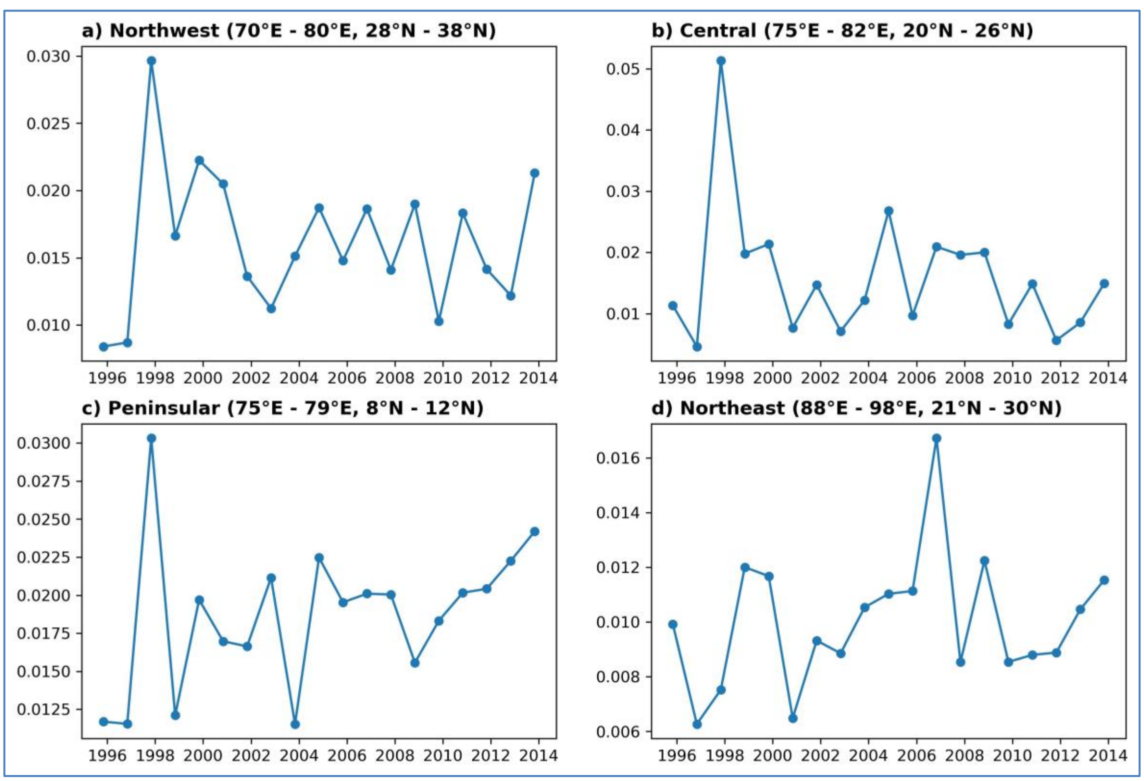

Fig. 8. Variation of low resolution monthly flash rate : Post-Monsoon season. (a) Northwest (70º-80º E ; 28º-38º N), (b) Central (75º-82º E ; 20º-26º N), (c) Peninsular (75º-79º E ; 8º-12º N) and (d) Northeast (88º-98º E ; 21º-30º N).

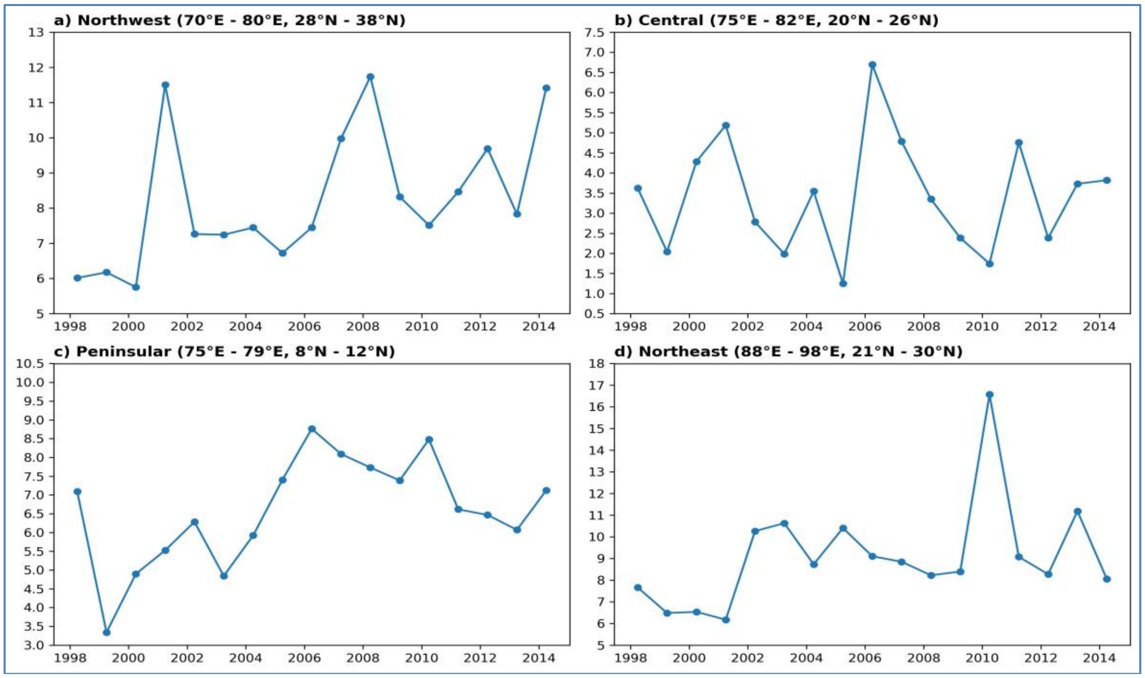

Fig. 9. Variation of Thunderstorm days : Pre-monsoon season. (a) Northwest (70º-80º E ; 28º-38º N), (b) Central (75º-82º E ; 20º-26º N), (c) Peninsular (75º-79º E ; 8º-12º N) and (d) Northeast (88º-98º E ; 21º-30º N).

The average behaviour of lightning for different season is clearly seen in Figs. 2(a, b, c & d) of high-resolution seasonal climatology. The zones of different seasons in lightning differ season to seasons start from NW to NE, Central, peninsular and South India. These figures have been generated from TRMM precipitation data sets. To get more insight of type of precipitation like convective /stratiform at different seasons (winter, pre-monsoon, monsoon & post monsoon) TRMM data sets analysed in details for the period (1996-2014) and presented in the Figs. (3.1 & 3.2). Fig. 4 represents the thunderstorm days based on number of distinct days of lightning activity at different seasons throughout the year over Indian domain. The information of lightning has been generated with the help of TRMM LIS data and then total number of days was evaluated.

We know that the future projections of the lightning activity and its impact over the specified region is difficult because the sub grid scale phenomena such as convective clouds or lightning are poorly resolved and taken into account by climate models.

The behaviour of lightning activity is different at different parts of Indian domain. Therefore, we have divided the Indian domain in IV regions for this study (*i*) Northwest (70º-80º E & 28º-38º N) (*ii*) Central (75º-82º E & 20º-26º N) (*iii*) Peninsular (75º-79º E & 08º-12º N) & (*iv*) Northeast (88º-98º E & 21º-30º N).

Figs. 5 to 8 shows year-wise variation of monthly flash rates generated from LIS data for the winter (Fig. 5), Pre-monsoon season (Fig. 6), monsoon (Fig. 7) and post monsoon season respectively. The trend of flashes is quite irregular in all Figs. (5 to 8) due to chaotic nature of the lightning activity in time and space. The seasonal variation of thunderstorm days of the above said IV domains has been shown in Fig. 9 and the trend of number of thunderstorm days is quite irregular. The moderate range of AOD values between 0.14 to 0.5 supports the lightning activities (Kucienska *et al*., 2013). The seasonal variations of all the IV selected regions are shown in Fig. 10.

Cloud electrification depends on the various mechanisms, the non-inductive ice-ice interaction and (Mansell *et al.*, 2005) positive or negative charge is as a function of the cloud temperature and liquid water content (LWC). The seasonal variation of ice water path at IV divisions of India derived from MODIS data has been shown in Fig. 11. The variation is quite irregular and may be due to complex interactions involved inside the clouds. Fig. 12 shows the seasonal variation of other contributing factor upper tropospheric water vapour in the IV selected regions. The figure shows the in upper troposphere the distribution of upper troposphere water is not uniform and have highly variable both in temporal and spatial scales.

The Liquid Water Path (LWP) is the measure of the weight of the liquid water droplets in the atmosphere

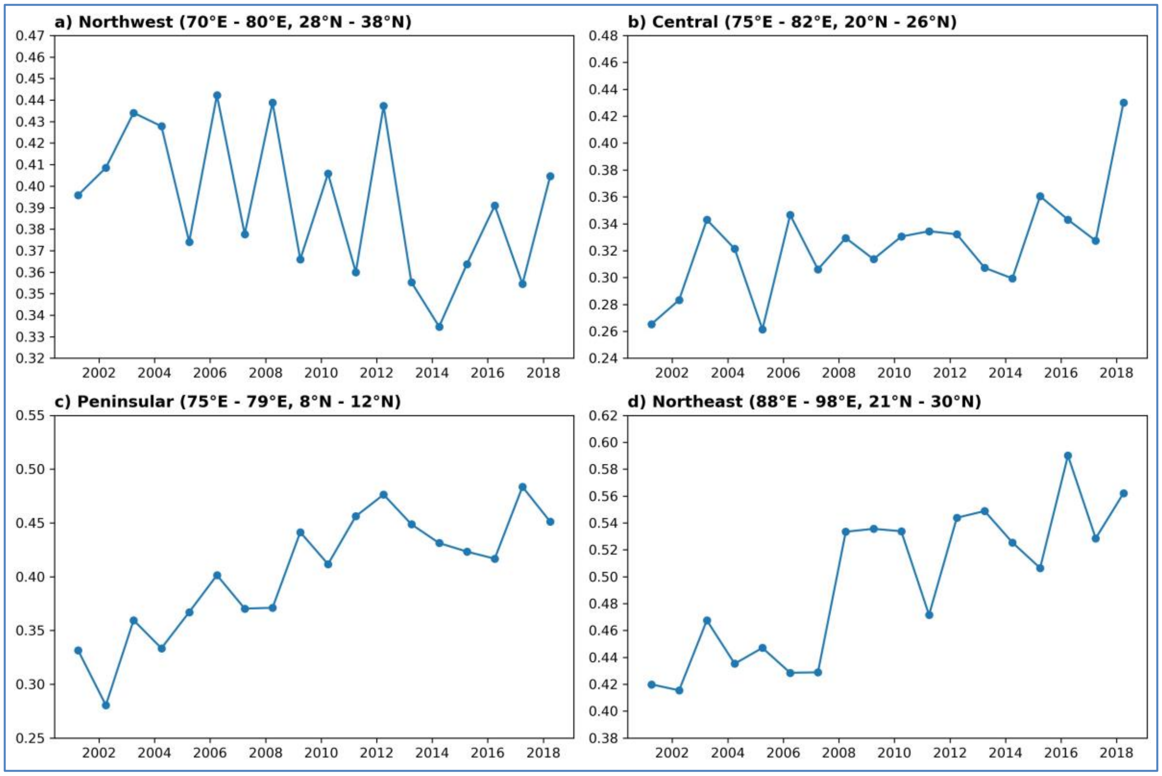

Fig. 10. Variation of AOD: Pre-monsoon season. (a) Northwest (70º-80º E ; 28º-38º N), (b) Central (75º-82º E ; 20º-26º N), (c) Peninsular (75º-79º E ; 8º-12º N) and (d) Northeast (88º-98º E ; 21º-30º N).

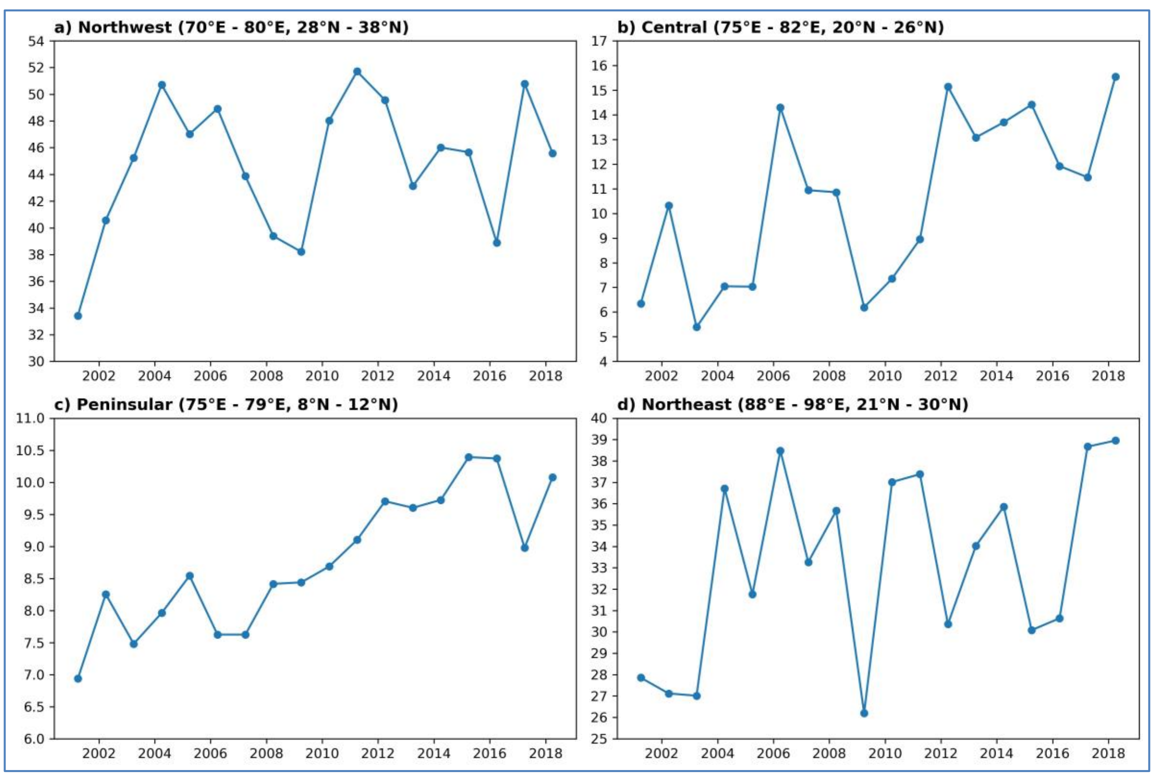

Fig. 11. Variation of Ice water path : Pre-monsoon season. (a) Northwest (70º-80º E ; 28º-38º N), (b) Central (75º-82º E ; 20º-26º N), (c) Peninsular (75º-79º E ; 8º-12º N) and (d) Northeast (88º-98º E ; 21º-30º N).

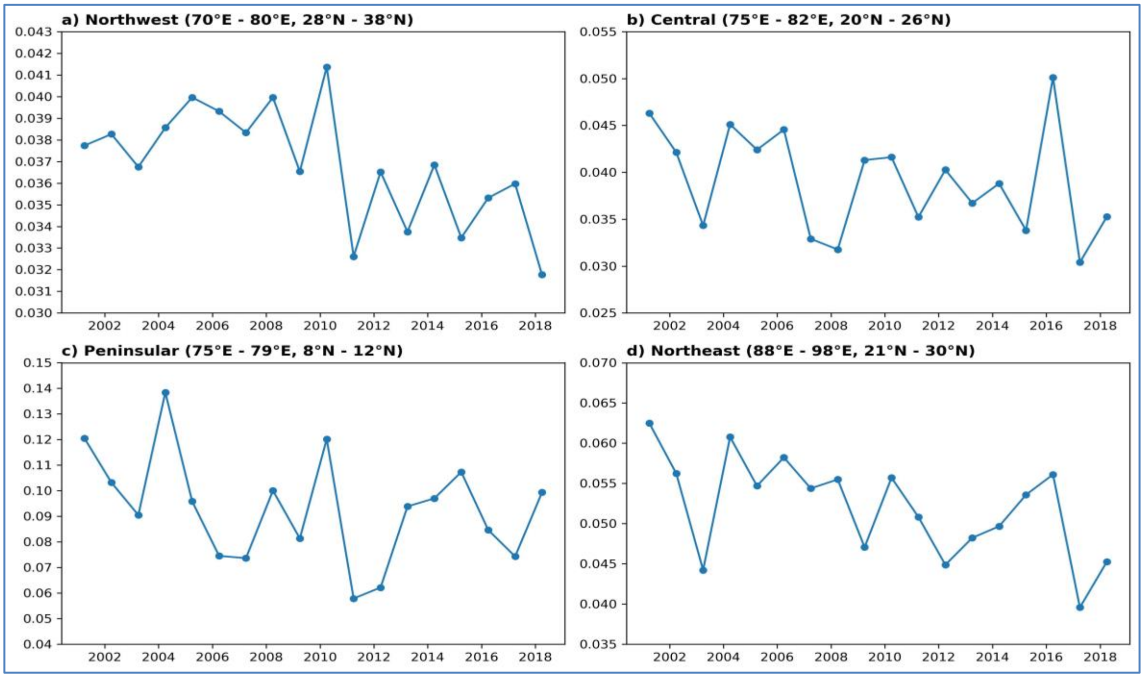

Fig. 12. Variation of upper tropospheric water vapour : Pre-monsoon season. (a) Northwest (70º-80º E ; 28º-38º N), (b) Central (75º-82º E ; 20º-26º N), (c) Peninsular (75º-79º E ; 8º-12º N) and (d) Northeast (88º-98º E ; 21º-30º N).

above a unit surface area of the earth. It can be estimated both through active and passive remote sensing. It is integration of the liquid water content (both ice and water) in the atmosphere; therefore, it is indicative of mixed phase of clouds. These clouds are generally associated with high vertical growth having both liquid and ice particles. These particles are continuously in up and down motion depending on the instability (conductivity) present in the atmosphere around the area. Therefore, its analysis in the context of lightning is very important and necessary. It is significantly related to lightning activity at 53% of all grid-point locations for one or more seasons throughout the year, noting that about 19% of the study region on average could be expected to have a significant correlation for at least one or more seasons at the 95% confidence level based on random chance. 50% of land locations and 54% of ocean locations have a significant correlation between lightning activity and NINO 3.4 for one or more seasons, noting that about two thirds of the study region is oceanic. For land regions, a significant positive correlation occurs for one or more seasons at 35% of locations and a significant negative correlation occurs at 18% of locations.

Lightning and it association with other predictors in seasonal and different geographical regions of India is demonstrated.

Forecast prediction of lightning is very challenging task as it is widespread, frequent and random activity. There are many factors /predictors are associated with lightning and their correlation varies with space and time. Therefore, we depend many types of observations like current weather, model generated information, actual lightning network data, remote sensing data on board on different type of satellite systems in space, climatology over the area, season & prominent weather systems, their occurrence, frequency, duration *etc*. Generally, the current observations provide a clue about the prevailing weather system like how much intense and old its height and temperature below freezing or not *etc*. Lightning flashes alone cannot make lightning prediction but by knowing the average lightning flashes can be useful to build up skill & generate/ demarcate the potential lightning activity zone at different regions of Indian domain.

Another possible linkage is intense convection which helps to building up instability in the atmosphere by supporting the rising of moist air in the development of cumulonimbus cloud, which often associated with hydrometeors such as graupel, hail, ice particles and liquid water droplets.

Figs. 13 to 17 shows the correlation of lightning activity with temperature, aerosol optical depth (AOD), ice water path, cloud optical thickness and upper troposphere water vapour. These correlations have both positive and negative values and quite random in nature. The association of these parameters with lightning activity is not as consistent as in pre-monsoon period. Therefore,

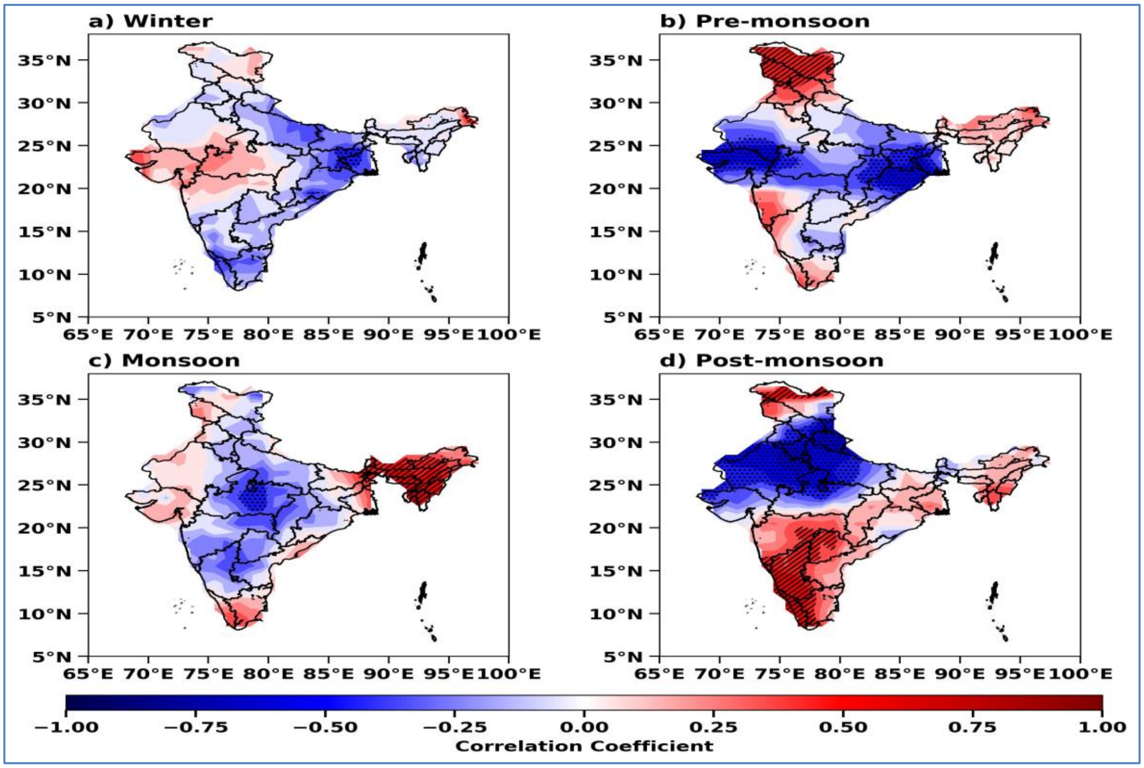

Fig. 13. Temperature correlation. (a) Winter (Jan-Feb), (b) Pre-monsoon (Mar-May), (c) Monsoon (Jun-Sep) and (d) Post-monsoon (Oct-Dec).

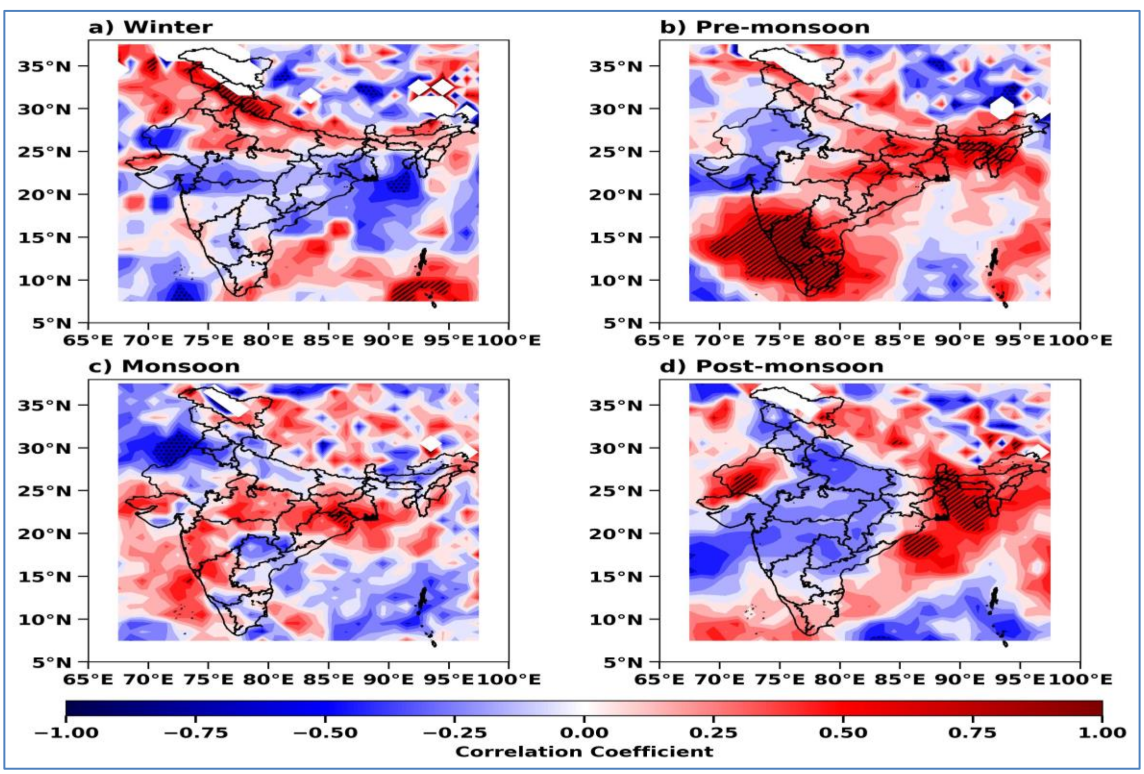

Fig. 14. Lightning and AOD correlation. (a) Winter (Jan-Feb), (b) Pre-monsoon (Mar-May), (c) Monsoon (Jun-Sep) and (d) Post-monsoon (Oct-Dec).

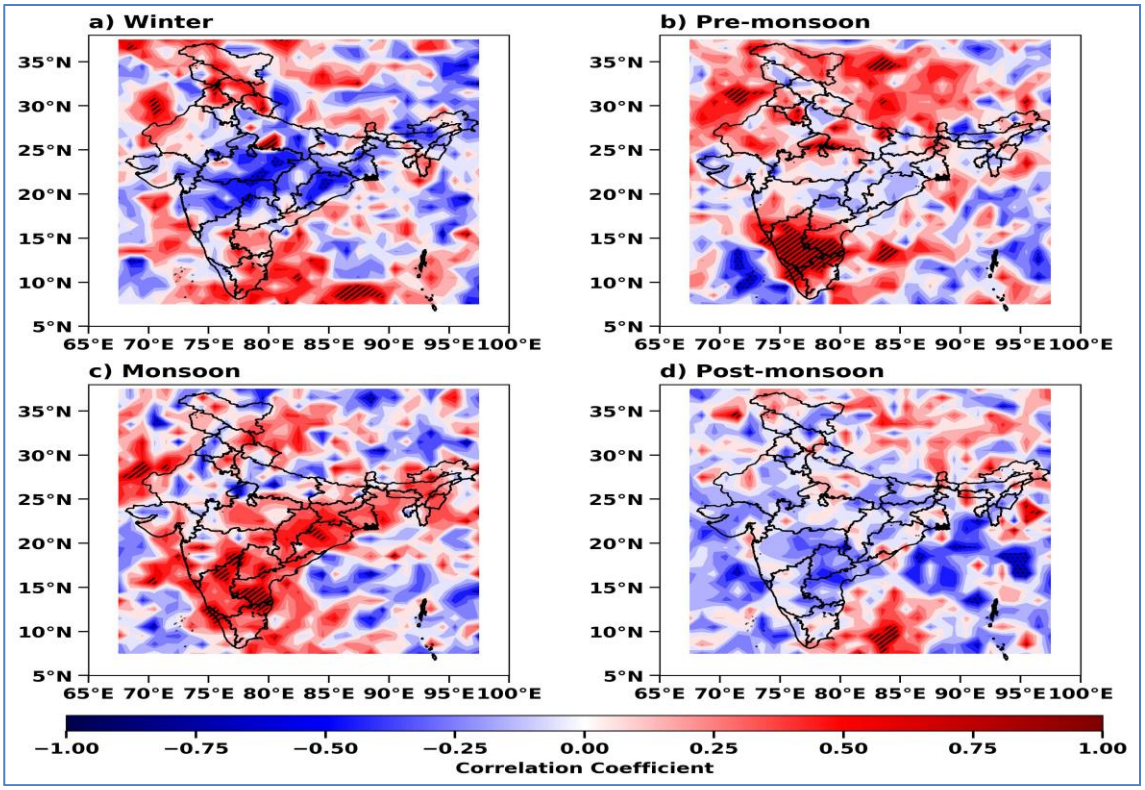

Fig. 15. Lightning and cloud ice water path correlation. (a) Winter (Jan-Feb), (b) Pre-monsoon (Mar-May),(c) Monsoon (Jun-Sep) and (d) Post-monsoon (Oct-Dec).

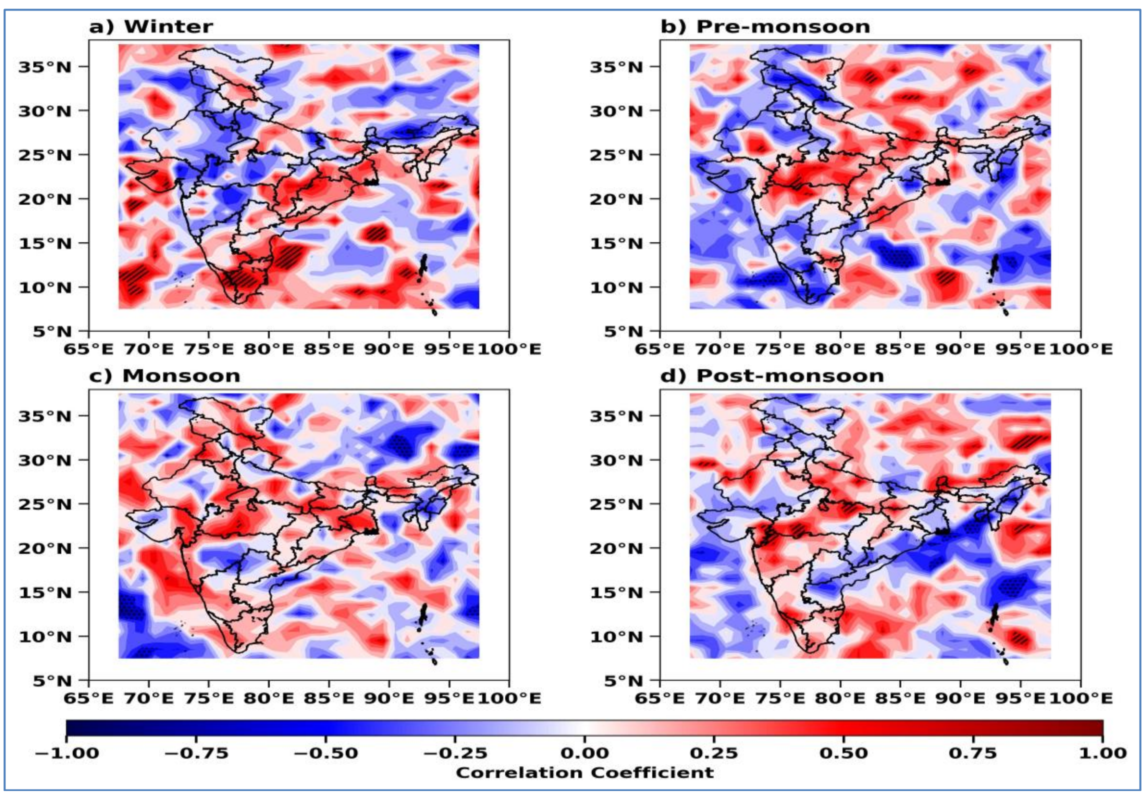

Fig. 16. Lightning and cloud optical thickness correlation. (a) Winter (Jan-Feb), (b) Pre-monsoon (Mar-May), (c) Monsoon (Jun-Sep) and (d) Post-monsoon (Oct-Dec).

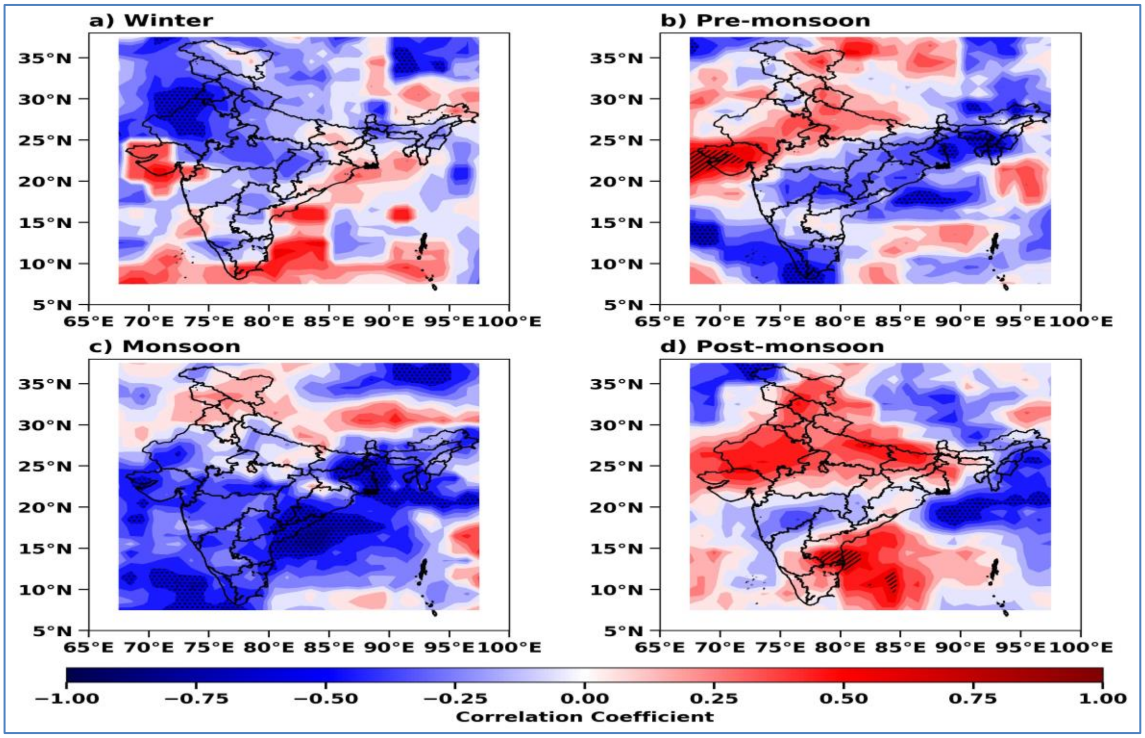

Fig. 17. lightning and upper tropospheric water vapour correlation. (a) Winter (Jan-Feb), (b) Pre-monsoon (Mar-May), (c) Monsoon (Jun-Sep) and (d) Post-monsoon (Oct-Dec).

in tropical regions the vertical development of clouds involves interaction of various microphysical processes of the atmosphere. In this process the estimated parameters (temperature, aerosol optical depth (AOD), ice water path, cloud optical thickness and upper troposphere water vapour) are mutually interrelated. Lightning activity association with individual parameters will not support strongly and have weak correlation as shown various figures generated with MODIS, TRMM or LIS data in this paper. However, their role in totality we cannot ignore and therefore timely execution and judicial utilization of such products will help to the forecaster in judging the impact of such chaotic activity in India.

4. Conclusions

In this paper lightning activity has been analysed with various atmospheric variables like surface temperature, upper tropospheric water vapour, cloud ice, Convective Available Potential Energy (CAPE) and aerosol optical depth (AOD). There correlations with the occurrences of the lightning flashes are having both positive and negative correlation. It is seen that these correlations are not very strong and therefore lightning occurrences & interactions involved are not yet clearly understood.

It is observed from the study that the increase of upper air temperature more than the surface temperature leads to stability at lower levels in the atmosphere and hence fewer thunderstorms activities or indirectly lightning instances. The convective transport of additional water vapour leads to absorb the infrared radiation emitted from the earth surface or increase the warming in the upper troposphere. The higher CAPE value is positively correlated within the convective development and hence it may enhance the lightning activity. Therefore, by analysing certain parameters like upper troposphere temperature, liquid water path, AOD & CAPE *etc.* can be found very useful to understand better the possible impact of lightning. It will further enhance the knowledge & forecasting skills of the forecasters both spatial and temporal domain. In future with the help of large data set of ground as well as multi-sensor data from space platform a suitable geospatial decision support system can be developed to issue the warning with sufficient lead time.

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