



Spatial patterns of long-term trends in thunderstorms in India

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Abstract

Long-term trends in the frequency of thunderstorm days are investigated using fifty years of data recorded by weather observatories throughout India. An attempt has been made to identify whether the trends are spatially cohesive and collocated with regions with maximum of thunderstorm days. This analysis of trends is significant, since most of the weather over India is of convective origin and has devastating impact on life and property. There are three thunderstorm maximum regions (a) northwest Indian Himalayas and adjoining Pakistan, (b) east India and (c) extreme southern parts of peninsular India. The results of the study revealed 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. The trend is more diffused for the thunderstorm maxima over north and south peninsular India. Comparison with rainfall trends from previous studies indicates that this decreasing trend of thunderstorm days is in phase with decreasing trends in rainfall activity over east central and northeast Indian regions. Detailed analysis indicates that frequency of thunderstorm days over these regions decreased during the latter half of the twentieth century followed by gradually increasing trend. This corresponds to a global warming hiatus and matches similar findings around the world. It seems likely that the decreasing moisture inflow from the surrounding oceans into the Indian subcontinent throughout the year due to weakening of the land-sea thermal gradient is causing a decreasing trend in the convection during this period. Over north and south peninsular India, where circum-global planetary waves play an important role in triggering convection, the strengthening of these waves offsets the effect of the generally decreasing moisture.

Keywords Thunderstorm · Trends · Extremes · Monsoon · India

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1 Introduction

The latest IPCC reports indicate that global mean temperatures will continue to rise through the twenty-first century if greenhouse gas emissions continue unabated (Collins et al. 2013). According to the Clausius–Clapeyron equation, the water-holding capacity of air increases by about 7% per 1 °C warming. Storms, whether individual thunderstorms, extratropical rain or snowstorms, or tropical cyclones, supplied with increased moisture, are likely to produce more intense precipitation events (Trenberth 2011).

Most studies examining long-term trends in extreme temperatures in India reveal substantial spatial variations in extreme temperatures, with predominantly positive trends concentrated over northern India and negative trends across the peninsular India (Pal and Al-Tabbaa 2010; Dash and Mamgain 2011; Revadekar et al. 2012; Kumar et al. 2017; Dimri 2018). The variable spatial patterns in the trends of extreme temperature indices were attributed to changes in land use land cover, aerosol levels, El Niño and anthropogenic processes in the above studies. Similarly, the trends in extreme precipitation also show substantial spatial variations, with most of India experiencing increasing trends in extreme precipitation indices (Sen Roy and Balling 2004; Goswami et al. 2006; Pattanaik and Rajeevan 2010; Sen Roy 2009). Globally, the monsoon flow is expected to weaken in a changing climate (Trenberth 2007). However, the trends and variations in extreme rainfall events, specifically over the Indian region, have been attributed to changes in sea surface temperatures and surface latent heat flux (Rajeevan et al. 2008), El Niño Southern Oscillation (ENSO) (Mondal and Mujumdar 2015) and Indian Ocean Dipole Mode (Ajaymohan and Rao 2008).

With rainfall over the Indian region being primarily of convective origin, frequency and intensity of occurrence of thunderstorms and lightning are good measures of convection over the region (Singh and Bhardwaj 2019 for example). WMO defines thunderstorms as one or more sudden electrical discharges, manifested by a flash of light (lightning) and a sharp or rumbling sound (thunder) (WMO 1988). However, the character of thunderstorms changes with season over the Indian region. While thunderstorms are more severe (in terms of wind speed and hail) during the period of March to June (Das et al. 2014), the rainfall realized from thunderstorms increases from April and is highest during the monsoon period (June to September) (Kandalgaonkar et al. 2005; Kulkarni et al. 2009; Manohar and Kesarkar 2004). Studies indicate that this is because the stratiform cloud fraction is higher during the monsoon season as compared to other seasons (Schumacher and Houze 2003; Sen Roy et al. 2015).

While the frequency of moist convection is likely to increase in a warming climate (Romps et al. 2014), its increasing severity in a warming climate is still a matter of some debate (Allen et al. 2018). Model simulations suggest that an increase in severity of thunderstorms in a warming climate may be spatially variable and dependent upon (a) the relative warming of the mid-troposphere relative to surface instability as well as (b) the effect of precipitation loading on the updraft velocity commensurate with higher concentration of hydrometeors within a storm (Trapp and Hoogewind 2016). Due to the mesoscale nature of non-monsoon convection over the Indian region, evaluating the trend in the severity of convection will be beyond the scope of this study with the current dataset. However, the trends of seasonal extreme precipitation over India using station-level data reveal similar spatial patterns during the dry pre-monsoon summer and monsoon seasons (although with less intensity), but different patterns during the winter season (Sen Roy 2009). There are few systematic studies examining the station-level long-term trends in frequency of convection,

excluding temperatures and precipitation, over India. A recent study with lightning data of 12 years indicates that there is a systematic increase in lightning activity over central India during the monsoon season, which is correlated with a simultaneous increase in Convective Available Potential Energy over the region (Pawar et al. 2012). Globally, the trends in station-level thunderstorm days are variable. The main similarity amongst the studies is the relatively high frequency of thunderstorm days in the 1950s and 1960s, followed by a downward trend during the latter half of the twentieth century (for example, Changnon and Changnon 2001 over the USA, Gorbatenko and Dulzon, 2001 over central Asia and Yu et al. 2016 over China). A recent study by Singh and Bhardwaj (2019) examining the monthly climatological frequency of thunderstorm days for four overlapping 30-year periods from 1951 to 2010 across 294 stations in India revealed significant decreasing trends in total number of thunderstorm days in all months as well as the annual scale during the each tri-decadal period.

In this regard, a relatively long-period dataset of daily thunderstorm days recorded at observatories of India Meteorological Department has made it possible to conduct long-term trend analysis of thunderstorm days throughout the year. The questions we seek answer are the following:

1. Is there a spatially cohesive increasing or decreasing trend in the frequency of thunderstorm days in India?
2. In a “dry-drier, wet-wetter” paradigm for precipitation trends due to climate change, are there similar trends in thunderstorms, collocated with the regions with the maximum average frequency of occurrence of thunderstorm days?
3. Are the trends, if any, linked to precipitation trends over the region?

2 Data and methods

The station-level reports of thunderstorms from class I observatories in India from 1967 to 2016 have been considered for this study. Weather information, including occurrence and duration of thunderstorms, and period and intensity of associated severe weather, is recorded by Class 1 observatories of India at 3-hourly intervals in the Monthly Meteorological Register (MMR) form. This format of reporting is as per WMO standards for surface observatories. Before archival at the National Data Centre of India, the data are quality-controlled in three stages (Jaswal et al. 2014). The digital MMR reports from the observatories for a day (starts at 0300 UTC of the previous day and ends at the same time of next day) are manually checked for all reported weather parameters by the supervising Meteorological Centres and thereafter re-checked at the Regional Meteorological Centres. This dual check corrects the data for large scale systematic errors such as negligence during night-time observations and non-reporting of mesoscale phenomena in the vicinity of the observatories as related with media reports. Before archival at the National Data Centre, and use thereafter in this study, the data are stringently quality-controlled as per WMO quality control criteria for surface observations (Abbott 1986). Figure 1 displays the location of the stations used in the study. While concerns of subjectivity due to the manual nature of recording thunderstorm occurrence may persist, comparing the climatology of these observations with the climatology of related variables (lightning climatology from TRMM LIS sensor data by Yadava et al. 2020 for example) on seasonal and annual scale

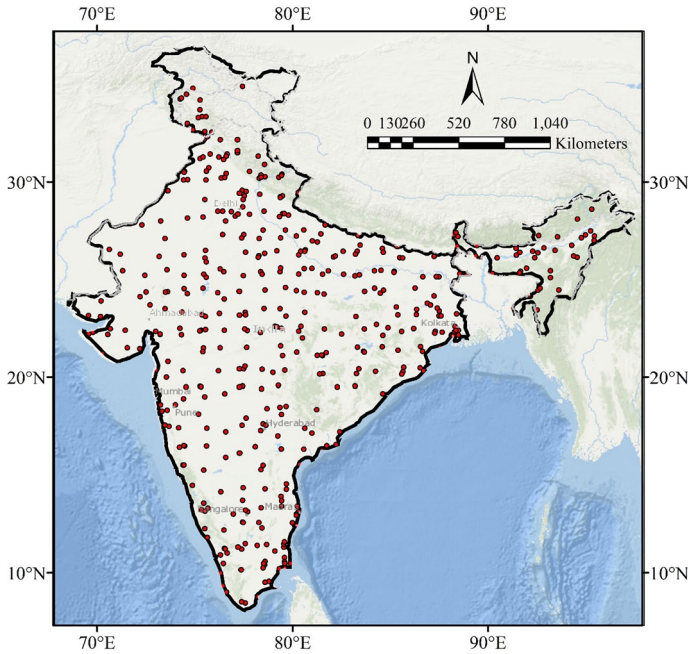


Fig. 1 Distribution of 24-h weather stations reporting thunderstorms over India 1967–2016

indicates that the present dataset is relatively stable and representative of the actual pattern of thunderstorms. Therefore, this dataset is suitable for the purposes of this study.

Long-term trends in thunderstorm frequency were calculated at the station level using the widely used Mann–Kendall (MK) trend test and Sen’s slope estimator (Mann 1945; Kendall 1975; Sen 1968). Specifically, we used ‘MAKESENS’ software to calculate the long-term trends, which includes the nonparametric MK test for trends as well as Sen’s method for the magnitude of the trend (Salmi et al. 2002). The World Meteorological Organization (WMO) due to its compatibility with non-normalized data as well as missing values recommends this nonparametric MK test. For the time series analysis, the Z test was used, and the Mann–Kendall test statistic S is calculated using the formula

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k), \tag{1}$$

where x_j and x_k are the annual values in years j and k , $j > k$, respectively, and

$$\text{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \tag{2}$$

The value of S designates the direction of the trend, with a positive value indicative of increasing trend and vice versa. The variance of S is computed by the following equation, which takes into account that there may several values in the time series that are tied:

$$\text{VAR}(S) \frac{1}{18} \left[n(n-1)(2n-5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right] \tag{3}$$

where q is the number of tied groups and t_p is the number of data values in the p th group. The values of S and $\text{VAR}(S)$ were used to compute the test statistic Z as given below:

$$z = \begin{cases} \frac{S-1}{\sqrt{\text{VAR}(s)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{VAR}(s)}} & \text{if } S < 0 \end{cases} \tag{4}$$

The trends were tested for significance levels at 0.001, 0.01, 0.05 and 0.1. In order to estimate the linear trend, the Sen’s nonparametric method was used to estimate the slope of an existing trend (change per year). Sen’s method chooses the median slope among all lines through pairs of two-dimensional sample points for robust linear regression (Sen 1968). The estimation of trend for N pairs of data was expressed as

$$Q_i = \frac{x_j - x_k}{j - k} \tag{5}$$

where $j > k$ and x_j and x_k are data values at times j and k , respectively. Further, information about the calculation is available in Salmi et al. (2002). This software has been widely used to detect long-term trends in meteorological and hydrological time series (Sarkar and Ali 2009; Ali et al. 2012; Rahman et al. 2016).

The station-level trends were next interpolated using empirical Bayesian kriging (EBK) technique. It is a stochastic spatial process that is represented locally as a stationary or non-stationary random field. The parameters of the locally defined random field are allowed to vary across space (Gribov and Krivoruchko 2020). This geostatistical interpolation technique automatically computes the different parameters of kriging through a method of subsetting and simulations. It is done by estimating, and then using, many semivariogram models, resulting in a spectrum of semivariograms. Each data subset uses models defined by nearby values, rather than being influenced by very distant factors. It also takes into consideration errors introduced by calculating the underlying semivariogram and thus not underestimating the standard errors of prediction. Specifically, to predict each location, a new semivariogram distribution is generated by a likelihood-based sampling of individual semivariograms from its spectrums in the specific location’s neighborhood (Krivoruchko 2012). It is particularly useful for reliable solution for both automatic and interactive data interpolation for large datasets. This method has been widely used in numerous research papers recently (Kutuzov et al. 2019; Nocco et al. 2019; Nogueira et al. 2019; Samsonova et al. 2017; Sen Roy 2019).

3 Results and discussion

Studies indicate that tropical regions, where India is located, are dominated by marginal conditional instability, dry midlevel air and weak shear of the horizontal wind (Barnes 2010). The oceans surrounding the peninsular India are the major source of moisture supply. Orography in the form of the Western Ghats along the west coast of India, the Himalayas to the north of India and its indentations over northeast India significantly control the

weather of this region. India also benefits from the gigantic land breeze–sea breeze intra-annual see-saw monsoon. The varying intensities of each of these forcing and their interaction with each other determine the variety of weather over this region. However, other than the monsoon season, mesoscale forcings have a major role in triggering convection. The resulting weather systems during non-monsoon seasons are mostly 10–100 km with a lifetime of one to five hours (Sen Roy et al. 2019).

Figure 2 a displays the spatial distribution of annual frequency of number of thunderstorm days (color fills with red color shades indicating increasing trends and blue color indicating negative annual trends) superposed with black contour lines indicating the annual average frequency. The annual frequency of thunderstorm days is highest over east India, with slightly lower values over extreme north India and south peninsular India. The frequency of thunderstorm days is least over the western and west central parts of India. These results are similar to findings from previous studies for the region, although the actual values of the maxima vary from study to study (please refer to Tyagi (2007) for a comparison of the value of maxima from various studies). On a monthly scale (Fig. 3a–l), the distribution of the average number of thunderstorm days indicates that there is a gradual increase in convection over the Indian subcontinent as it transits from winter to summer season. During the wintertime quiescence in January, there is on an average, less than one thunderstorm day every two years over many parts of the country. Weather transits to more active conditions in February through March as the landmass heats up. Three hot spots gradually emerge over the Indian region: (a) southern parts of West Bengal and adjoining Bangladesh and Assam region (as a result of moisture feeding into the region from the seasonal anticyclone over the north Bay of Bengal to the east of the North Indian dry line (Weston 1972; Akter and Tsuboki 2017)); (b) Northwest Indian Himalayas and adjoining Pakistan (due to the position of the orography in relation to the movement of westerly waves over the northwest Indian region); and (c) extreme southwest Indian peninsula, namely Kerala (on account of the movement of synoptic scale easterly waves over the region as well as the emergence of the north–south-oriented wind discontinuity

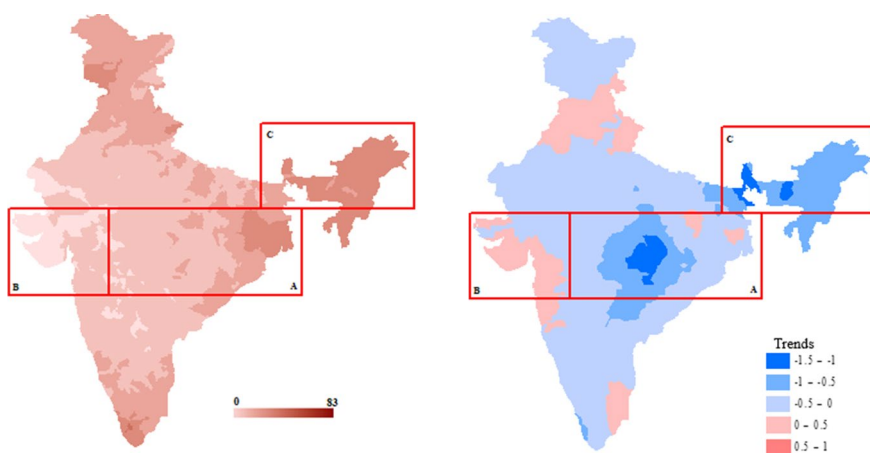


Fig. 2 a Spatial patterns of annual frequency of thunderstorm days during 1967–2016. **b** Spatial patterns of annual trends in thunderstorm events during 1967–2016. Boxes **A**, **B** demarcate the west central and east central Indian region, respectively, while the box **C** demarcates the northeast Indian region for detailed case studies

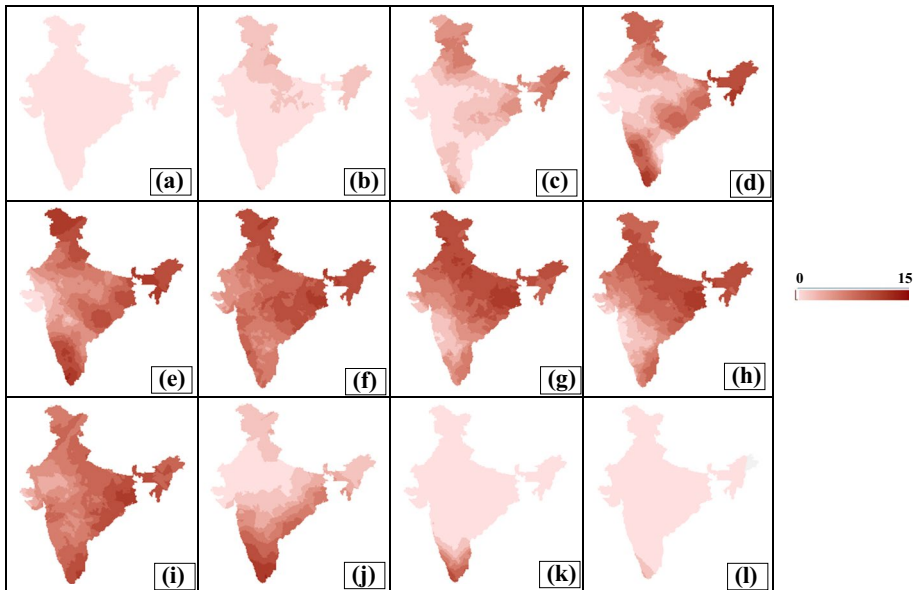


Fig. 3 Spatial patterns of average monthly number of thunderstorm days during 1967–2016 represented by shaded regions, (a) January; (b) February; (c) March; (d) April; (e) May; (f) June; (g) July; (h) August; (i) September; (j) October; (k) November; and (l) December

over peninsular India (Srinivasan et al. 1973)). By April and May, a north–south-oriented trough/wind discontinuity becomes more prominent along the eastern peninsula. A moisture discontinuity zone develops to the east of the trough, between the dry land winds and the moist winds from the periphery of the anticyclone over the Bay of Bengal, and becomes a favored zone for thunderstorm genesis (Rao and Ramamurti 1968). The frequency of thunderstorm days during these months is highest over a zone extending from northeast India and adjoining Bengal, southwestward to Kerala all along the east peninsular coast. There is a second maximum of thunderstorm days over Kerala. The thunderstorm maximum over northwest India persists because of movement of westerly troughs over the north Indian region. With the onset of the southwest monsoon season in June, the maximum frequency of thunderstorm days over the southwest peninsular India weakens. However, the overall thunderstorm frequency increases with the increasing moisture supply inland from the adjacent sea. Thereafter, in July and August, the monsoon pattern gradually sets in throughout the country, with enhanced frequency of thunderstorms and weakening of the localized maxima seen during the pre-monsoon dry season. The only exception is Gangetic West Bengal in eastern India. Most monsoon low-pressure systems originate in the head of the Bay of Bengal and move generally westward across this region. The huge mesoscale convective systems associated with these low-pressure systems bring a lot of thunderstorm activity over the Bengal–Bangladesh region. The thunderstorm activity is weakest over the West Indian region because of the dryness of the region. As the monsoon flow retreats from the Indian landmass, in September and October, the mid latitude westerly flow again strengthens over the northwest Indian region and the maximum re-appears here. Simultaneously, the easterly waves strengthen over the south Indian peninsula, and a new maximum of thunderstorm activity appears over southeast peninsular India in association with the onset of the northeast monsoon season. The maximum of thunderstorm

days over southwest peninsular India weakens simultaneously, while it persists over Bengal. In November, as the Indian landmass cools down and the wind flow becomes northerly to northwesterly over much of the Indian land mass, most of the thunderstorm activity is confined to the south peninsula associated with the movement of the easterly waves. By December, the atmosphere returns to its period of quiescence with minimum thunderstorm activity over the Indian region.

The trend in annual frequency of thunderstorm days (Fig. 2b) is predominantly weakly negative over most of the country except parts of north and west India. There is, however, strong negative trend over northeast and east central India. On comparing with Fig. 2a for the pattern of thunderstorm day maxima, it is noted that the regions with the most significant annual trend in thunderstorm days are not always collocated with regions with the highest frequency of thunderstorm. In view of the significant intra-annual variability of thunderstorm days, the month wise trends of thunderstorm activity for January to December are investigated and displayed in Fig. 4a–l.

On a monthly scale, the trend in frequency of thunderstorm days is weak throughout the Indian region throughout the year. During the months of January to March, the thunderstorm frequency has rising trend over most of the Indian region except the south peninsula, which has a declining trend. From April, as the Indian landmass heats up, the region of negative trends expands into the rest of peninsular and central Indian region. With the onset of Monsoon season in June, the negative trends in thunderstorm frequency are gradually confined to Central India and thereafter to east central India. Thereafter as the monsoon season withdraws and the Indian landmass cools down, positive trends gradually take over the north Indian region, while central India and peninsular India continue to have negative trends.

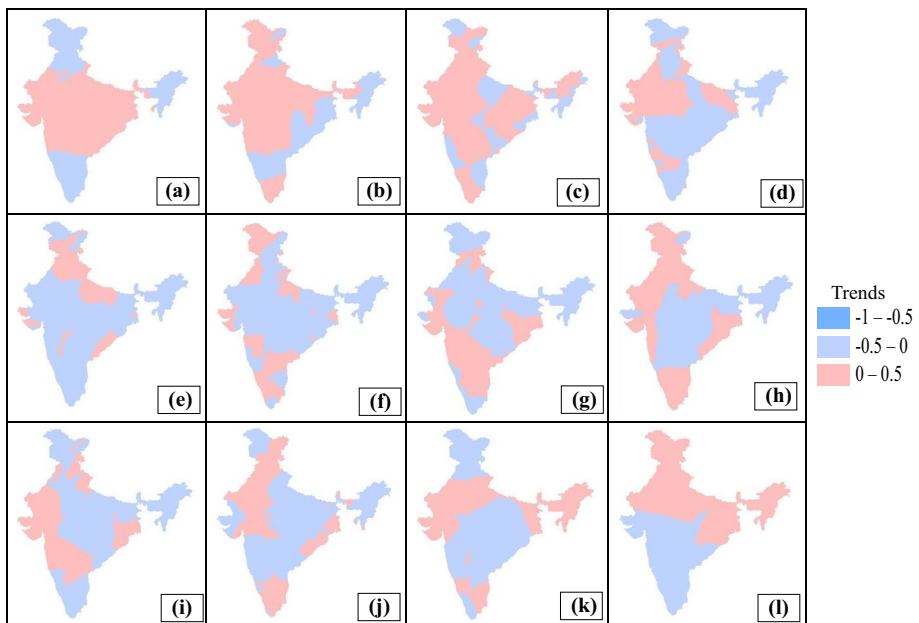


Fig. 4 Spatial patterns of trends of thunderstorm days during 1967–2016 represented by shaded regions. (a) January; (b) February; (c) March; (d) April; (e) May; (f) June; (g) July; (h) August; (i) September; (j) October; (k) November; and (l) December

From the discussion above, certain common features emerge: (a) The trends in monthly and annual frequency of thunderstorm days are weak over most of the Indian region. (b) During most months, over central, east and northeast India, where the frequency of thunderstorm days is high, there is an overall decreasing trend in frequency of thunderstorm days. There is a corresponding increasing trend in thunderstorm days over regions where the frequency of thunderstorm days is low. However, this does not hold true for south Indian peninsula and extreme north India, which have more mixed signals, with generally weak increasing trend of thunderstorm activity for the maxima.

It is noteworthy that the movement of the westerly and easterly troughs significantly controls the convection over the latter two regions over the Indian region, especially in the non-monsoon months. In a warming climate, along with the weakening of the monsoon flow, there is also likelihood of the strengthening of the circum-global planetary waves and the westerly flow in middle latitudes, which is likely to strengthen the North Atlantic Oscillation (NAO) (Trenberth 2007). Previous studies indicate that NAO significantly impacts the convection associated with the westerly troughs over the Indian region (Kar and Rana 2014; Chug et al. 2020) and monsoon precipitation (Sen Roy 2011). However, our analysis indicates weak response of convection over the subcontinent to this strengthening trend.

We next analyzed the trends over three specific regions: east central Indian region (outlined as “A” in Fig. 2a, b), west central Indian region (outlined as “B” in Fig. 2a, b) and northeast Indian region (outlined as “C” in Fig. 2a, b). The central Indian region is the monsoon core region (combination of “A” and “B” regions), which has been identified to be impacted significantly by climate change with increasing trend in extreme rainfall events during the monsoon season in a climate change scenario (Rajeevan et al. 2010; Goswami et al. 2006). Northeast India also has demonstrated significant decreasing trend in rainfall (Sen Roy 2009; Jain et al. 2013). Hence, the thunderstorm trend is investigated on a monthly scale over these two regions as well as on the annual scale. During most months (April to October), region “A” which has a high frequency of thunderstorm days has a negative trend in thunderstorm activity. Over the region “B”, with less frequency of thunderstorm days, there are increasing trends in most months except May and June. Over northeast India (region “C”), the pattern is more consistent, with decreasing trend throughout the region during most months. When the total number of thunderstorms is plotted for every year, region “B” has a weakly increasing trend in the number of thunderstorm days (Fig. 5). The “A” region over east central India has negative trend in annual frequency of thunderstorm days during 1970–1994 and sharply increases thereafter. The region “C” also has a decreasing trend in thunderstorm frequencies from 1982 to 1998, but increases more slowly thereafter. The overall trend in the annual frequency of thunderstorm days for both “A” and “C” regions for the entire period is negative. This dip in frequency of thunderstorm days is similar to observations over the USA (Changnon and Changnon 2001), as well as to parts of Russia and Kazakhstan (Gorbatenko and Dulzon 2001). Similar trends are reported for parts of China (Wei et al. 2011, Zhang and Pei 2011) and tropical Africa (Price and Asfur 2006). Williams et al. (2019) noted that the phase of globally decreasing trend in thunderstorm days over different regions is correlated with the periods of pronounced hiatus in global warming during the twentieth to twenty-first century. The widely cited explanation for these hiatus in global warming has been increased heat uptake by the ocean (Hansen et al. 2011; Trenberth et al. 2014). Also, it is noted that during these hiatus periods, there are stronger changes in oceanic temperature compared to the land temperature (Karl et al. 2015). Another study using multiple data from 1901 to 2012 has noted the significant reduction in rainfall during the monsoon season over the east central and northeast parts of the Indian subcontinent, which coincides with our findings

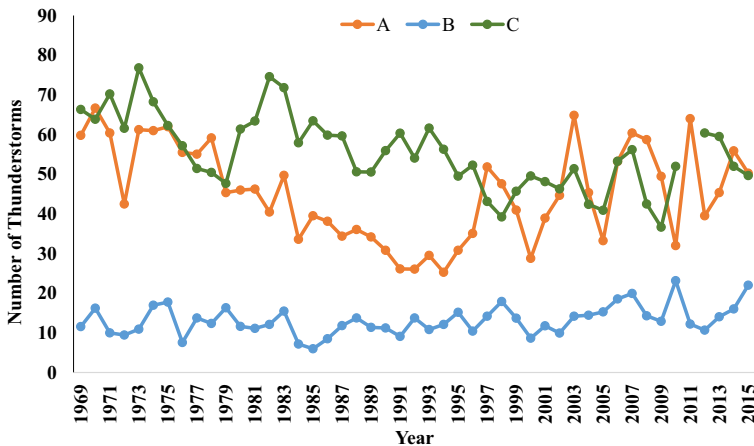


Fig. 5 Annual variation in frequency of thunderstorms for all stations inside each box demarcated in Fig. 2

of a decreasing trend (Roxy et al. 2015). Stronger oceanic heating due to rapid warming of the Indian Ocean and relatively subdued warming over the south Asian subcontinent during the period of hiatus is likely to decrease the land-sea thermal gradient over South Asia. The resulting weakening of the moisture flow inland is likely to inhibit convection over the subcontinent in all seasons. The fact that this affects only the eastern parts of the subcontinent indicates the convection over these regions, while generally being high, is particularly sensitive to the strength of the moisture flow. The increasing trend in frequency of thunderstorm days over the east central Indian region since the last decade of the twentieth century is supported by findings from previous studies. For instance, analysis of lightning data of 12 years (1998–2009) measured by TRMM satellite indicates an increasing trend in lightning activity during the monsoon season over central India (Pawar et al. 2012).

4 Conclusions

This study uses fifty years of station-level thunderstorm data in India to investigate if there are any spatially cohesive trends in the data correlated with thunderstorm frequency. This is significant in view of the large spatial and intra-annual variability of thunderstorms. Also, globally, it has been noted that on account of periodic hiatus in the trends, the frequency of thunderstorm days displays weak trends, especially in short datasets.

Our study notes that there are three maxima in frequency of thunderstorm days in India—east, northwest and extreme south peninsular India. At the monthly scale, there is slight migration of the thunderstorm maxima through the months. The maximum over north India is over extreme northwest Indian Himalayas and adjoining Pakistan during the non-monsoon months. It shifts southward to over Jammu and adjoining Himachal Pradesh, in the southern reaches of Northwest Indian Himalayas during the monsoon months. The thunderstorm maximum over east India is mostly confined to over Bengal throughout the year, except during April and May, when it has a northeast–southwest extension from northeast India, southwestward to the northeast peninsular coast of India. The maximum of thunderstorm activity over south India is over Kerala in the southwest peninsular India

during the first part of the year (up to June), before shifting to the southeast peninsular coast from July until the end of the year.

There is a decreasing trend in thunderstorm activity over the thunderstorm maximum region in east and northeast India in the monthly as well as annual scale, and a corresponding increasing trend over west central India, where thunderstorm frequency is less. Detailed analysis indicates that this decreasing trend in frequency of thunderstorm days is most pronounced, during the latter half of the twentieth century (1970 to 1994 for east central India and 1980 to 1998 for northeast India), and increase thereafter. This trend corresponds to similar global trends noted in multiple studies and overlaps with periods of global warming hiatus. During these periods of hiatus, the convection over the east central and northeast parts of the Indian subcontinent is found to be particularly sensitive to the decrease in the land–sea thermal gradient and shows a decreasing trend. Similar decreasing trend is also noted in the precipitation of these regions in other studies mentioned above. The monthly trend of thunderstorm activity is more diffused for the south peninsula and north India, where on annual scale there is a weak positive trend corresponding to the regions of thunderstorm maximum. The precipitation and convection over the northwest Indian region are associated with the movement of westerly troughs and easterly troughs over south peninsular India. Strengthening of the circum-global planetary waves is likely to partially counteract the decreasing moisture flow from the surrounding seas, resulting in weak increase in convective activity over these regions.

The occurrence of extreme and non-extreme weather or climate events affects the overall vulnerability to future extreme events by modifying resilience, coping capacity and adaptive capacity (IPCC 2012). Socio-economic losses from weather-related climate disasters have increased with substantial spatial variability, magnified particularly in developing economies in the tropics, including India, that are sensitive to the variability of extreme weather events. There has been substantial human cost (more than 2000 lives lost every year) and economic cost, which is increasing every year (NDMA 2020). These are associated with smaller-scale convective weather phenomena such as local severe thunderstorms. Hence, in view of the damaging potential of such thunderstorms, the results of our study will aid in better development of local-level policy.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Soma Sen Roy and Shouraseni Sen Roy. The manuscript was written by Soma Sen Roy and Shouraseni Sen Roy. All authors read and approved the final manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

References

- Abbott PF (1986) Guidelines on the quality control of surface climatological data. World Meteorological Organization, WCP-85, WMO/TD 111: pp 65
- Ajayamohan RS, Rao SA (2008) Indian Ocean dipole modulates the number of extreme rainfall events over India in a warming environment. *J Meteor Soc Japan Ser II* 86:245–252
- Akter N, Tsuboki K (2017) Climatology of the premonsoon Indian dryline. *Int J Climatol* 37:3991–3998

- Ali MH, Abustan I, Rahman MA, Haque AAM (2012) Sustainability of groundwater resources in the North-Eastern Region of Bangladesh. *Water Resour Manag* 26:623–641. <https://doi.org/10.1007/s11269-011-9936-5>
- Allen JT (2018) Climate change and severe thunderstorms. In: Brooks H (ed) *Oxford research encyclopedia of climate science*, pp 1–67. <https://doi.org/10.1093/acrefore/9780190228620.013>
- Barnes GM (2010) Meteorological hazards in the Tropics: severe convective storms and flash floods. In: *Tropical meteorology, encyclopedia of life support systems (EOLSS)*. UNESCO, Paris, France, pp 109
- Changnon SA, Changnon D (2001) Long-term fluctuations in thunderstorm activity in the United States. *Clim Change* 50(4):489–503
- Changnon SA (1985) Secular variations in thunder-day frequencies in the twentieth century. *J Geophys Res Atmos* 90:6181–6194
- Chug D, Pathak A, Indu J, Jain SK, Jain SK, Dimri AP, Niyogi D, Ghosh S (2020) Observed Evidence for steep rise in the extreme flow of Western Himalayan rivers. *Geophys Res Lett*. <https://doi.org/10.1029/2020GL087815>
- Collins M, Knutti R, Arblaster J, Dufresne J-L, Fifehert T, Friedlingstein P, Gao X, Gutowski WJ, Johns T, Krinner G, Shongwe M, Tebaldi C, Weaver AJ, Wehner M (2013) Long-term climate change: projections, commitments and irreversibility. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, New York, pp 1029–1136
- Das S, Sarkar A, Mohanty UC, Tyagi A, Sikka DR, Joseph PV, Rathore LS, Habib A, Baidya SK, Sonam K (2014) The SAARC STORM: a coordinated field experiment on severe thunderstorm observations and regional modeling over the South Asian Region. *Bull Am Meteorol Soc* 95:603–617
- Dash SK, Mangain A (2011) Changes in the frequency of different categories of temperature extremes in India. *J Clim Appl Meteorol* 50:1842–1858
- Dimri AP (2018) Comparison of regional and seasonal changes and trends in daily surface temperature extremes over India and its subregions. *Theor Appl Climatol*. <https://doi.org/10.1007/s00704-018-2486-5>
- Enno SE, Post P, Briede A, Stankunaite I (2014) Long-term changes in the frequency of thunder days in the Baltic countries. *Boreal Env Res* 19:452–466
- Gribov A, Krivoruchko K (2020) Empirical Bayesian kriging implementation and usage. *Sci Total Environ* 722:137290
- Gorbatenko V, Dulzon A (2001) Variations of thunderstorm. In: 5th Korea-Russia international symposium on science and technology. Proceedings. KORUS 2001 (Cat. No. 01EX478), 2, pp. 62–66. <https://doi.org/https://doi.org/10.1109/KORUS.2001.975178>
- Goswami BN, Venugopal V, Sengupta D, Madhusoodanan MS, Xavier Prince K (2006) Increasing trend of extreme rain events over India in a warming environment. *Science* 314:1442–1445
- Hansen J, Sato M, Kharecha P, von Schuckmann K (2011) Earth's energy imbalance and implications. *Atmos Chem Phys* 11:13421–13449
- IPCC (Intergovernmental Panel on Climate Change) (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. Aspecial report of working groups I and II of the intergovernmental panel on climate change, p 582
- Jain SK, Kumar V, Saharia M (2013) Analysis of rainfall and temperature trends in northeast India. *Int J Climatol* 33:968–978
- Jaiswal RS, Neela VS, Fredrick R, Rasheed M, Zaveri L, Sowmya V (2014) Identification of convective/stratiform dominance over surface rainfall. *Mausam* 65(2):219–232
- Kandalgaonkar SS, Tinmaker MIR, Nath A, Kulkarni MK, Trimbacke HK (2005) Study of thunderstorm and rainfall activity over the Indian region. *Atmosfera* 18:91–101
- Kar SC, Rana S (2014) Interannual variability of winter precipitation over northwest India and adjoining region: impact of global forcings. *Theor Appl Climatol* 116:609–623
- Karl TR, Arguez A, Huang B, Lawrimore JH, McMahon JR, Menne MJ, Peterson TC, Vose RS, Zhang HM (2015) Possible artifacts of data biases in the recent global surface warming hiatus. *Science* 348(6242):1469–1472
- Kendall M (1975) *Rank correlation methods*, 4th edn. Charles Griffin, San Francisco
- Krivoruchko K (2012) Empirical Bayesian Kriging: implemented in ArcGIS geostatistical analyst. Arc User. Fall 2012 <https://www.esri.com/news/arcuser/1012/files/ebk.pdf>
- Kulkarni MK, Tinmaker MIR, Manohar GK (2009) Characteristics of thunderstorm activity over India. *Int J Meteorol* 34:341–350
- Kumar N, Jaswal AK, Mohapatra M, Kore PA (2017) Spatial and temporal variation in daily temperature indices in summer and winter seasons over India (1969–2012). *Theor Appl Climatol* 129:1227–1239

- Kutuzov S, Lavrentiev I, Smirnov A, Nosenko G, Petrakov D (2019) Volume changes of Elbrus glaciers from 1997 to 2017. *Front Earth Sci* 7:153. <https://doi.org/10.3389/feart.2019.00153>
- Mann HB (1945) Nonparametric tests against trend. *Econometrica* 13:245–259
- Manohar GK, Kesarkar AP (2004) Climatology of thunderstorm activity over the Indian region: II. *Spat Distrib Mausam* 55:31–40
- Mondal A, Mujumdar PP (2015) Modeling non-stationarity in intensity, duration and frequency of extreme rainfall over India. *J Hydrol* 521:217–231
- NDMA (2020) Guidelines for Thunderstorm & Lightning/Squall/Dust/hailstorm and Strong wind. Accessed on September 22, 2020 <https://ndma.gov.in/images/pdf/Draft-Guidelines-thunderstorm.pdf>
- Nocco MA, Smail RA, Kucharik CJ (2019) Observation of irrigation-induced climate change in the mid-west United States. *Glob Chang Biol* 25:3472–3484. <https://doi.org/10.1111/gcb.14725>
- Nogueira ADA, Bragagnolo C, DaSilva MB, Carvalho LS, Benedetti AR, Pintoda-Rocha R (2019) Spatial variation in phylogenetic diversity of communities of Atlantic forest harvestmen (opiliones, arachnida). *Insect Conserv Divers* 12:414–426. <https://doi.org/10.1111/icad.12356>
- Pal I, Al-Tabbaa A (2010) Long-term changes and variability of monthly extreme temperatures in India. *Theor Appl Climatol* 100(1):45–56
- Pattanaik DR, Rajeevan M (2010) Variability of extreme rainfall events over India during southwest monsoon season. *Meteorol Appl J Forecast, Prac Appl Train Tech Model* 17:88–104
- Pawar SD, Lal DM, Murugavel P (2012) Lightning characteristics over central India during Indian summer monsoon. *Atmos Res* 106:44–49
- Price C (2009) Will a drier climate result in more lightning? *Atmos Res* 91:479–484
- Price C, Asfur M (2006) Inferred long term trends in lightning activity over Africa. *Earth Planets Space* 58:1197–1201
- Rahman AS, Kamruzzama M, Jahan CS, Mazumder QH (2016) Long-term trend analysis of water table using 'MAKESENS' model and sustainability of groundwater resources in drought prone Barind area, NW Bangladesh. *J Geol Soc India* 87:179–193
- Rajeevan M, Bhate J, Jaswal AK (2008) Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. *Geophys Res Lett* 35:L18707. <https://doi.org/10.1029/2008GL035143>
- Rajeevan M, Gadgil S, Bhate J (2010) Active and break spells of the Indian summer monsoon. *J Earth Sys Sc* 119:229–247
- Rao YP, Ramamurti KS (1968) Forecasting, manual, Pt. I. Climatology of India and neighbourhood India meteorological department 6–7
- Revadekar JV, Kothawale DR, Patwardhan SK, Pant GB, Rupa Kumar K (2012) About the observed and future changes in temperature extremes over India. *Nat Haz* 60:1133–1155
- Romps DM, Seeley JT, Vollaro D, Molinari J (2014) Projected increase in lightning strikes in the United States due to global warming. *Science* 346:851–854
- Roxy MK, Ritika K, Terray P, Murtugudde R, Ashok K, Goswami BN (2015) Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. *Nature Comm* 6:1–10
- Salmi T, Maatta A, Anttila P, Airola TR, Amnell T (2002) Detecting trends of annual values of atmospheric pollutants by the Mann-Kendal test and Sen's slope estimates - the Excel template application MAKESENS. User manual, Publication on air quality, Finnish Meteorological Institute, pp35
- Sarkar AA, Ali MH (2009) Water-table dynamics of Dhaka city and its long-term trend analysis using the "MAKESENS" model. *Water Int* 34:373–382
- Samsonova VP, Blagoveshchenskii YN, Meshalkina YL (2017) Use of empirical Bayesian kriging for revealing heterogeneities in the distribution of organic carbon on agricultural lands. *Eurasian Soil Sci* 50:305–311. <https://doi.org/10.1134/S1064229317030103>
- Schumacher C, Houze RA Jr (2003) Stratiform rain in the tropics as seen by the TRMM precipitation radar. *J Clim* 16:1739–1756
- Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. *J Amer Stat Assoc* 63:1379–1389
- Sen Roy S, Balling RC Jr (2004) Trends in extreme daily precipitation indices in India. *Int J Climatol* 24:457–466
- Sen Roy S, Saha SB, Roy Bhowmik SK, Kundu PK (2015) Analysis of monthly cloud climatology of the Indian subcontinent as observed by TRMM precipitation radar. *Int J Climatol* 35:2080–2091
- Sen Roy S (2009) A spatial analysis of extreme hourly precipitation patterns in India. *Int J Climatol* 29:345–355. <https://doi.org/10.1002/joc.1763>
- Sen Roy S (2011) The role of the North Atlantic oscillation in shaping regional scale peak seasonal precipitation across the Indian subcontinent. *Earth Interact.* <https://doi.org/10.1175/2010EI339.1>

- Sen Roy S (2019) Spatial patterns of trends in seasonal extreme temperatures in India during 1980–2010. *Wea Clim Extremes* 24:100203
- Singh O, Bhardwaj P (2019) Spatial and temporal variations in the frequency of thunderstorm days over India. *Weather* 74:138–144
- Siingh D, Buchunde PS, Singh RP, Nath A, Kumar S, Ghodpage RN (2014) Lightning and convective rain study in different parts of India. *Atmos Res* 137:35–48
- Srinivasan V, Ramamurthy K, Nene YR (1973) Summer—Nor'westers and Andhis and large scale convective activity over peninsula and central parts of the country. India Meteorological Department, Forecasting Manual, Part III
- Trapp RJ, Hoogewind KA (2016) The realization of extreme tornadic storm events under future anthropogenic climate change. *J Clim* 29:5251–5265
- Trenberth KE, Jones PD, Ambenje P, Bojariu R, Coauthors (2007) Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z and others (eds) *Climate Change 2007. The Physical Science Basis*. Intergovernmental Panel on Climate Change 4th assessment report. Cambridge University Press Cambridge, New York, pp 235–336.
- Trenberth KE (2011) Changes in precipitation with climate change. *Clim Res* 47:123–138
- Trenberth KE, Fasullo JT, Balmaseda MA (2014) Earth's energy imbalance. *J Clim* 27:3129–3144. <https://doi.org/10.1175/JCLI-D-13-00294.1>
- Tyagi A (2007) Thunderstorm climatology over Indian region. *Mausam* 58:189
- Wei J, Liu M, Zhang B, Yu J (2011) Analysis of the trends of thunderstorms in 1951–2007 in Jiangsu province. *J Trop Meteorol* 17:58–63
- Weston KJ (1972) The dry-line of Northern India and its role in cumulonimbus convection. *Q J Roy Meteor Soc* 98:519–531
- Williams E, Guha A, Boldi R, Christian H, Buechler D (2019) Global lightning activity and the hiatus in global warming. *J Atmos Solar Terr Phys* 189:27–34
- WMO (1988) General meteorological standards and recommended practices. Technical Regulations. I: Basic Documents No. 2, WMO Publication No.49
- Yadava PK, Soni M, Verma S, Kumar H, Sharma A, Payra S (2020) The major lightning regions and associated casualties over India. *Nat Hazards* 101(1):217–229
- Yu Y, Li JL, Xie J, Liu C (2016) Climatic characteristics of thunderstorm days and the influence of atmospheric environment in Northwestern China. *Nat Hazards* 80(2):823–838
- Zhang X, Pei H (2011) The characteristics and variation trends of temporal and spatial distribution of thunderstorms in the area of Linyi. In: International conference on information science and technology. IEEE, pp 652–656

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