Spatio-temporal analysis of the extremes of precipitation and temperature in the capital cities of India

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Abstract

This study presents an analysis of extreme temperature and precipitation events in the capital cities of India during 40-years study period (1982-2022). Daily maximum temperature, minimum temperature, and rainfall from NASA-POWER were used to compute climate extreme indices, recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) and Expert Team on Sector-Specific Climate Indices (ET-SCI). This is the first study analyzing the trend of extreme indices, with a focus only on its capital cities, and not for the country as a whole. Findings indicate that capital cities situated in the western ghat, islands, and Himalayan range, especially the north-eastern part of the country recorded increasing extremes of both temperature and precipitation in the last 40 years. The cities have experienced overall night-time warming and day-time cooling during the study period. A maximum decrease of -2.16°C was observed in Aizawl for the mean maximum temperature (TXm), whereas, an increase of +1°C was found in Kavaratti. There was a significant decrease in the summer days (SU25; 72 days in Aizawl), whereas, the tropical nights were observed to have significantly increased (TR20; 40 days in Shillong). In terms of precipitation extreme indices, cities located in the eastern and north-eastern parts of the country were exposed to the risks of higher amount and intensity of rainfall. Cities such as Patna and Lucknow however, witnessed significant reduction in the rainfall, and thus increased consecutive dry days. Overall, our study recommends the urgent need of planning considering the trend of these indices and taking appropriate action.

Keywords: climatic extremes, Trend analysis, capital cities, ETCCDI, ET-SCI, India

1. Introduction

Worldwide, the frequency of extreme weather events and associated hazards have been reported to rise in the recent decades. Although weather extremes resulting from temperature and precipitation is common throughout the world, the type, intensity, and magnitude of these extremes varies. Tropics have been witnessing increased precipitation in some areas, whereas, a decrease in the others. Record-breaking surface-air temperature has become a common feature (Morice et al., 2021) resulting in retreating glaciers in the high mountains and polar regions (Thompson et al., 2021), land degradation and desertification in the tropics (Huang et al. 2020; Talukder et al. 2021), and resulting widespread water shortages. Asia and Pacific is the most disaster prone region (UNFPA) witnessing 45% of the natural disasters arising globally. In the past few decades, Indian subcontinent has witnessed an increase in the duration, frequency, and intensity of the extreme weather events.

Rising temperatures, glacier melting, methane emissions they all connect and form a positive climatic feedback system, a system that accelerates further rise in temperature. The socio-economic consequences of such climatic changes along with the changed precipitation patterns are often destruction of infrastructures (caused by natural hazards such as landslides, cloud bursts, flash floods), water shortage for domestic and industrial usage, and reduced efficiency of manpower and natural resources. Changing climate has changed the biodiversity, productivity and species composition of temperate ecosystems (Maren and Sharma, 2021), distribution of major forest tree species (Chakraborty et al. 2016); soil organic carbon storage (Martin et al. 2010), soil microbial biomass carbon (Singh et al. 2021); shift of temperate tree species along the altitudinal transect (Dubey et al. 2003; Yadava et al. 2017; Singh et al. 2018), and has resulted in thermophilization of understorey plant communities (Govaert et al. 2021). It has also become a common phenomenon to experience different kinds of hydrometeorological hazards in different months of the year: river and inland flooding after a torrential rainfall; water shortage in the aquifers and reservoirs after a rainfall deficit in the region; severe heatwaves in summer months accompanied by forest fires; and a similar severe cold waves in the winter months resulting in mortality of annual crops by frost. The frequency of cyclones and related disasters have also shown a marked rise in the Arabian sea (Murakami et al. 2017), and over the Bay of Bengal (Wu et al. 2024) during past decade. The spatial distribution of the rainfall during monsoon months has also been reported to vary significantly. These results pertain to the recent assessment report of IPCC AR6.

In view of this, Extreme temperature and precipitation indices, as recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) have been intensively studied over India (Panda et al. 2016; Ramkrishna et al. 2022; Rehana et al. 2022). Most of these studies were involved in investigating the variation of the indices – either of the temperature or precipitation or both - in different space and time: over the country as a whole (Rehana et al. 2022; Thankamani and Rao, 2023); over Indian river basins (Singh et al. 2015; Singh, 2020; Chaubey et al. 2022); over North-east India (Luwangleima and Srivastava, 2019; Kalita et al. 2021). Some researchers also attempted to study the future projection of these indices under current and future global warming levels in India (Yaduvanshi et al. 2021) and across the globe (Reboita et al. 2022).

To the best of our knowledge, a study investigating the effect of climate change (in terms of ETCCDI and ET-SCI) focusing only on the capital cities of India is still lacking. Capital cities are the economic centers of any nation. They play an important role in shaping the political, economic, social, and cultural identity of a nation (Mayer et al. 2017). It is because of this reason, that these cites have faced unprecedented urbanization, and related environmental problems. Capital cities are particularly more vulnerable, because they shape their own microclimate. They hold high density of people in small areas, have high resource utilization, have more built-up lands and infrastructure. All these work together and often result in amplification of climatic extremes. In a study conducted by Tian et al. (2022), it was found that urban areas in the global north tend to be less sustainable than their surrounding rural areas. In terms of air quality and energy efficiency (EE), however, global north was found more sustainable than the global south. Poor air quality and lower EE, a marked feature in the developing nations, further aggravate the problem of climate change by a feedback in GHG emission. So, for a developing country like India, it is important to know the state of climate of our capital cities, and its trend after the digital and industrial revolution has taken place, which helped the nation to be self-sustainable in most of the sectors.

The present study, therefore, aims to study the variation in the frequency and intensity of climate extremes in capital cities of India using 30 indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) and Expert Team on Sector-Specific Climate Indices (ET-SCI). The results can be used as a guide to develop recommendations and prepare individual unique adaptation plan for the cities taking into account the climatic constraints and opportunities. Also, these trends were studied at the monthly and seasonal level for the temperature and rainfall respectively.

2. Data and Methodology

2.1 Study area

India is geographically located between latitudes 8°4′N to 37°6′N and longitude 68°7′E to 97°25′E – with almost 30 degree longitudinal and latitudinal stretch (Fig. 1). The country has a unique geography: bordered on the south by the Indian ocean; on the north by the great Himalayas; in the east by Bay of Bengal; and in the west by Arabian sea, and thus experience tropical, sub-tropical as well as temperate type of climate in its extreme corners. Mean maximum temperature varies a lot throughout the country (Fig. 2), depending on the time of day, season, latitude, and altitude. India, because of its unique geographic location, receives rain throughout the year, except during the summer months. South-west monsoon (June-Sept) is the main rain bearing season in a greater part of the country, supplemented by post-monsoon (Oct-Dec) in the southern peninsula, and winter rainfall in the North-western Himalaya and adjoining plains (Fig. 3). This bequeaths the country with a diverse and enormous set of flora and fauna, which includes but not limited to the coniferous trees in dry temperate forest (e.g., Deodar) in Himalayas to tropical evergreen forests in the Andaman & Nicobar Islands; subtropical humid broad-leaved forest in Cherrapunji, Meghalaya to dry tropical forest in north-western plains of Rajasthan. The frequency of light to moderate rainfall constituted about half and even more in the capital cities located in north-eastern states and on the western ghat (Fig. 4).

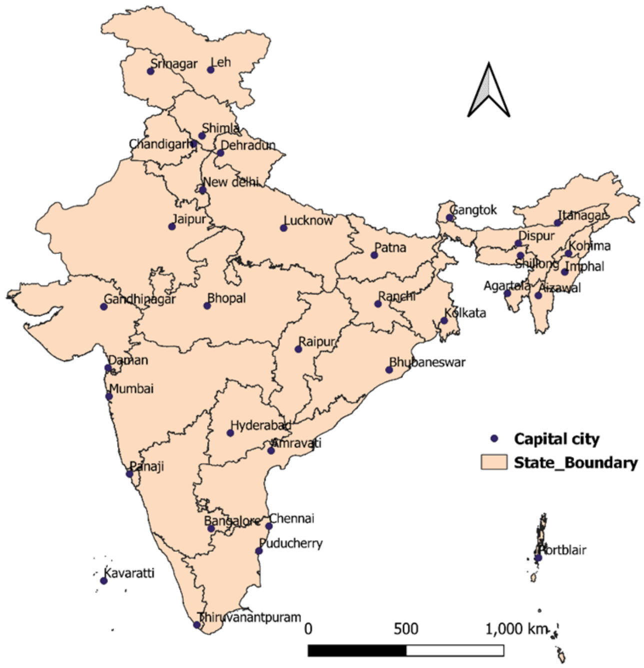

Figure 1. Location map of the study area indicating capital cities of India

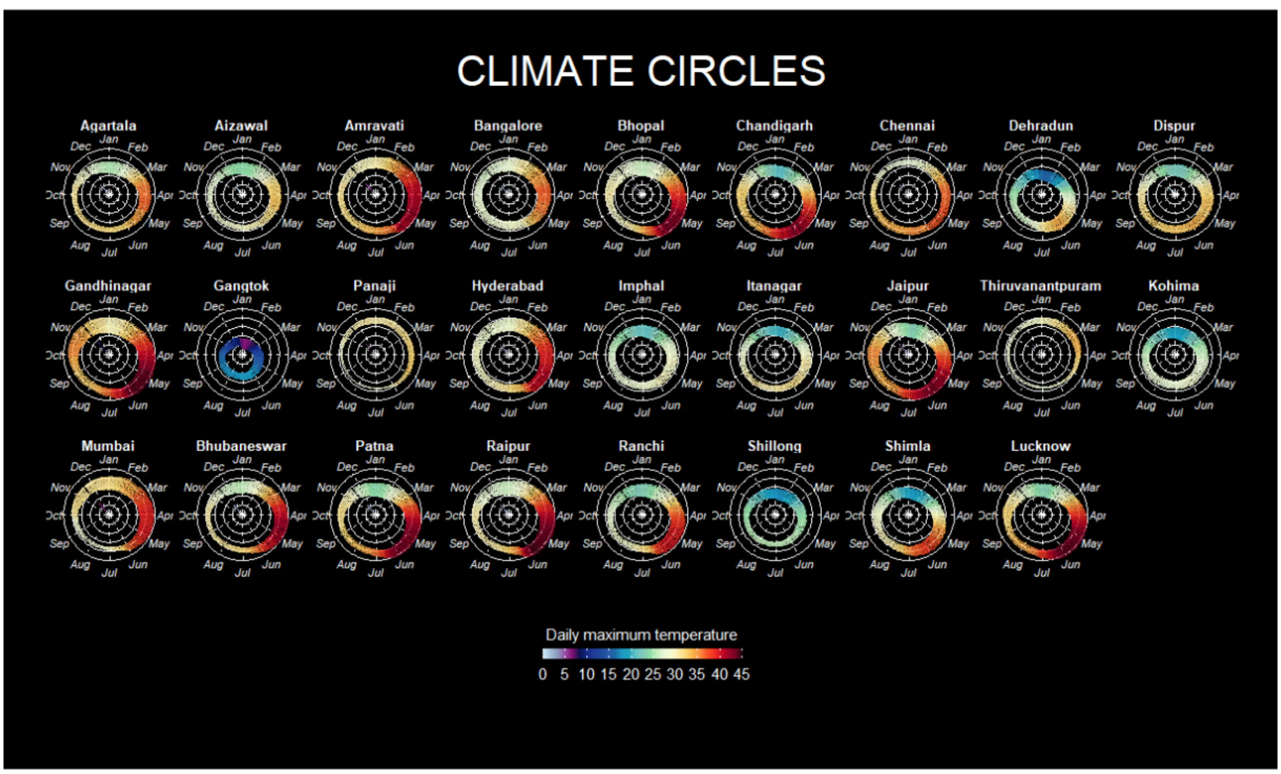

Figure 2. Climate circle presenting mean maximum temperature in the capital cities of Indian states

2.2 Data collection

For this study, point station daily data of weather parameters for the capital cities of India were collected from NASA POWER (Prediction of Worldwide Energy Resources) Project running under the Earth Science Research Program of NASA (https://power.larc.nasa.gov/data-access-viewer/). NASA POWER provides solar and meteorological data on a global grid of 0.5° x 0.5° spatial resolution, since 1981 onwards, and has been reported to perform well under different geographic conditions of India (Setiya et al. 2024). The dataset included maximum temperature, minimum temperature, and rainfall for 38 stations for the period spanning from 1982 to 2022. Authors have avoided using gridded data in order to see the results (i.e., the effect of climate change) only in the capital cities, and not across the country. Additionally, daily data were transformed into three temporal scales: monthly, seasonal and annual. Weather variables at different time scales were computed to ascertain the effect of climate change in different capital cities of the country.

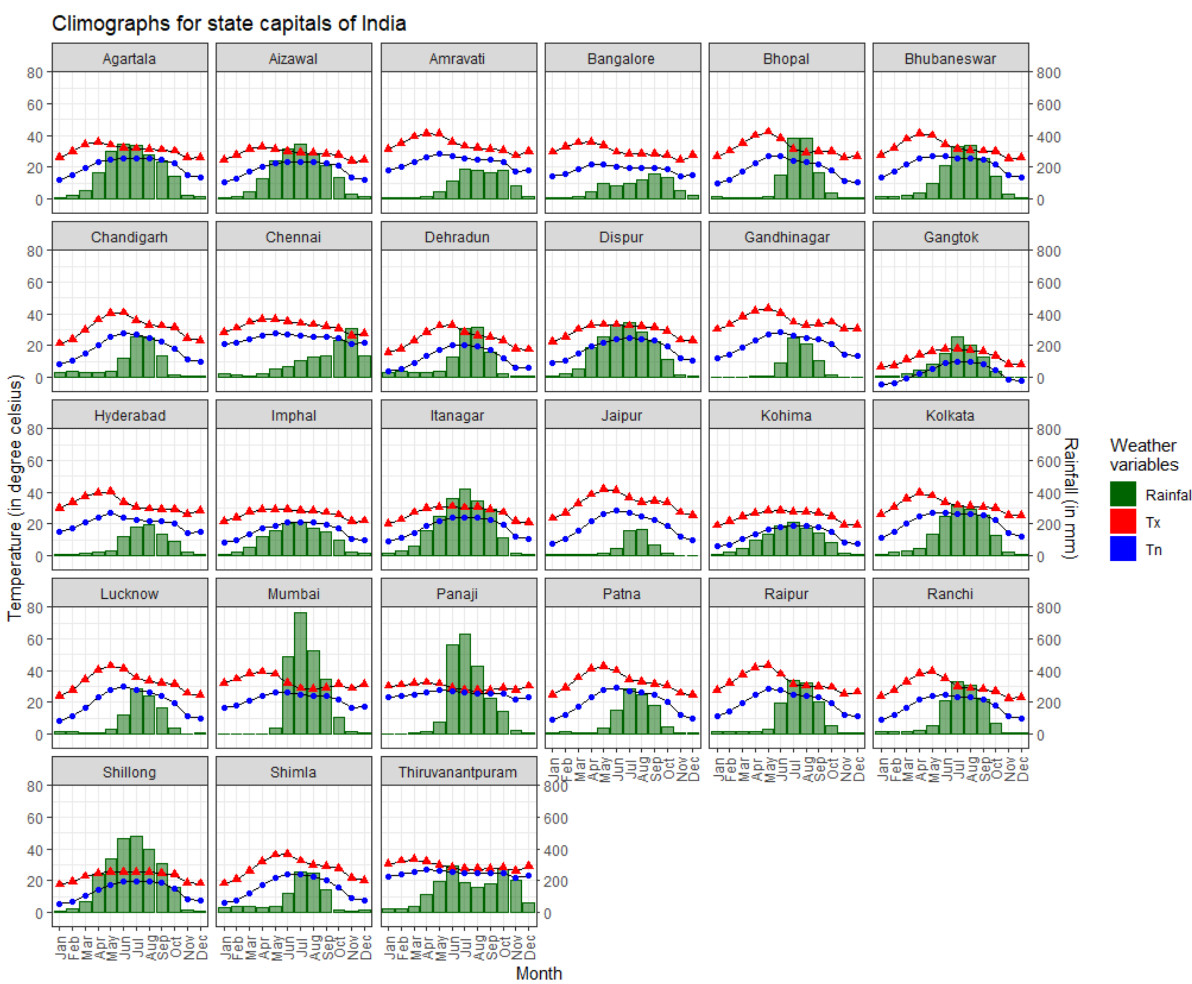

Figure 3. Climograph presenting the monthly variation of maximum temperature, minimum temperature, and rainfall in the capital cities of India

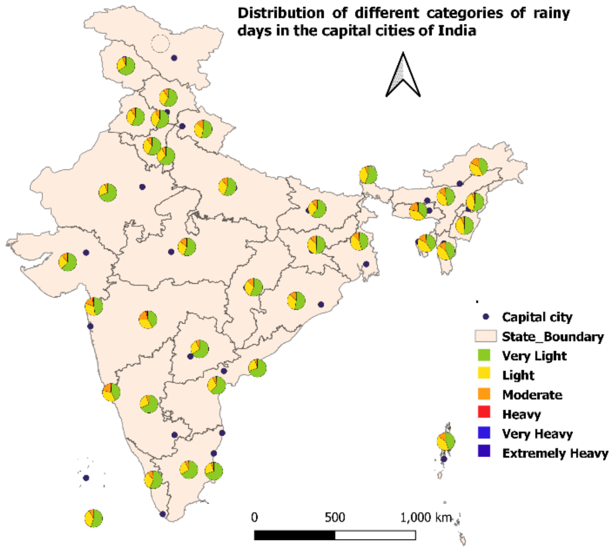

Figure 4. Frequency of different categories of rainy days in the capital cities of India

2.3 Extreme climate indices

This study examines the trend of temperature and precipitation extremes using 30 indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) and Expert Team on Sector-Specific Climate Indices (ET-SCI) (Table 1). These indices were calculated using the Climpact v2 using daily temperature (minimum and maximum) and precipitation dataset. Before calculating these extreme indices, dataset were first checked for the quality control. Detailed documentation for using Climpact using either single station file or multiple station can be found at https://github.com/ARCCSS-extremes/climpact/blob/master/www/user_guide/Climpact_user_guide.md#toc. There are four categories of extreme climate indices: intensity indices; duration indices; absolute threshold indices; and relative threshold indices, as indicated in Table 1.

Table 1. Extreme temperature and rainfall indices recommended by ETCCDI and ET-SCI

Index	Name	Description	ET	Unit
CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1mm	ETCCDI	days
CSDI	Cold spell duration index	Annual count of days with at least 6 consecutive days when TN < 10^{th} percentile	ET-SCI	days
CWD	Consecutive wet days	Maximum length of wet spell, maximum number of consecutive days with RR ≥ 1mm	ETCCDI	days
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	ETCCDI	°C
PRCPTOT	Total precipitation in wet days	Annual total precipitation in wet days	ETCCDI	mm
R10mm	Heavy precipitation days	Annual count of days when PRCP≥ 10mm	ETCCDI	days
R20mm	Very heavy precipitation days	Annual count of days when PRCP≥ 20mm	ETCCDI	days
R30mm	Extreme precipitation days	Annual count of days when PRCP≥ 30mm	ETCCDI	days
R95pTOT	Contribution from very wet days	Annual total PRCP when RR > 95p	ET-SCI	%
R99pTOT	Contribution from extremely wet days	Annual total PRCP when RR > 99p	ET-SCI	%
Rx1day	Max 1-day precipitation	Monthly maximum 1-day precipitation	ETCCDI	mm

Rx3day	Max 3-day precipitation	Monthly maximum consecutive 3-day precipitation	ETCCDI	mm
Rx5day	Max 5-day precipitation	Monthly maximum consecutive 5-day precipitation	ETCCDI	mm
SDII	Simple daily intensity index	Simple precipitation intensity index	ETCCDI	mm
SU25	Summer days	Annual count of days when TX (daily maximum temperature) > 25^{o}C	ETCCDI	days
TMm	Mean TM	Mean daily mean temperature	ET-SCI	°C
TN10p	Cold nights	Percentage of days when TN < 10th percentile	ETCCDI	% days
TN90p	Warm nights	Percentage of days when TN > 90th percentile	ETCCDI	% days
TNm	Mean TN	Mean daily minimum temperature (°C)	ET-SCI	°C
TNn	Min TN	Monthly minimum value of daily minimum temperature	ETCCDI	°C
TNx	Max TN	Monthly maximum value of daily minimum temperature	ETCCDI	°C
TR20	Tropical nights	Annual count of days when TN (daily minimum temperature) > 20^{o}C	ETCCDI	days
TX10p	Cold days	Percentage of days when TX < 10th percentile	ETCCDI	% days
TX90p	Warm days	Percentage of days when TX > 90th percentile	ETCCDI	% days
TXge30	TX of at least 30 °C	Annual number of days with TX of at least 30 °C	ET-SCI	days
TXge35	TX of at least 35 °C	Annual number of days with TX of at least 35 °C	ET-SCI	days
TXm	Mean TX	Mean daily maximum temperature (°C)	ET-SCI	°C
TXn	Min TX	Monthly minimum value of daily maximum temperature	ETCCDI	°C
TXx	Max TX	Monthly maximum value of daily maximum temperature	ETCCDI	°C
WSDI	Warm spell duration index	Annual count of days with at least 6 consecutive days when TX > 90th percentile	ET-SCI	days

Reference: https://climpact-sci.org/indices

Trend analysis was also done using Sen's slope estimator (Sen, 1968) at 5% significance level, for all the indices derived in this study. For effective visualization, the values corresponding to each data point is presented as a polygon – representing the boundary of the state or union territory - to make a clear distinction between the color values for a given index in different capital cities. Therefore, each polygon represent the observed climatic trend in the capital cities of respective Indian state.

3. Results

3.1 Mean temperature

Fig. 5 shows the trends in mean annual maximum temperature, minimum temperature, daily temperatures, and diurnal temperature range (DTR) during the 40-year study period (1982-2022). In majority of the capital cities of India, a decrease in mean annual maximum temperature (TXm; Fig. 5(a)) was observed during the study period. The decrease was up to -2.16 ^{o}C in Aizwal followed by -1.96 ^{o}C in Agartala. Increase in TXm, however, was observed only in 4 capital cities. The maximum increase was observed in island capital cities Kavaratti and Portblair (i.e., 1^{o}C and 0.76^{o}C respectively), followed by relatively lower increase on the Indian landmass: 0.5^{o}C increase in Panaji and 0.26^{o}C in Raipur. Unlike TXm, an increasing trend was observed in the case of mean annual minimum temperature (TNm; Fig. 5(b)), in all capital cities over the last 40 years. The magnitude of increase was especially high (>1^{o}C) in the capital cities situated in and near Himalayan range of mountains (Dehradun, Dispur, Gangtok, Itanagar, Kohima, Shillong, and Shimla). Decreasing TXm with increasing TNm resulted in narrowing of DTR across the country (Fig. 5(d)). The DTR trend, therefore, was significantly negative, with its magnitude exceeding -1°C throughout the country, except some of the coastal cities.

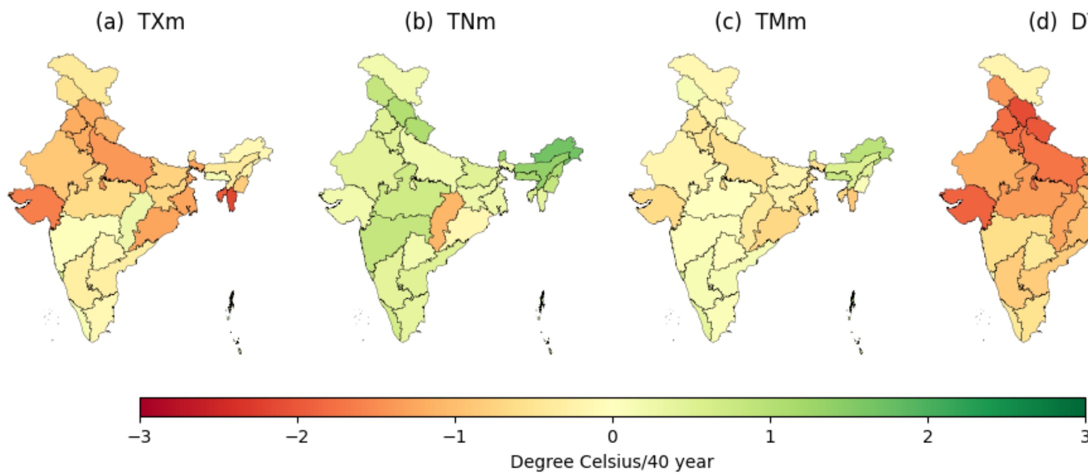

Figure 5. Spatial variation in the trend of mean annual (a) maximum (TXm) temperature, (b) minimum (TNm) temperature, (c) mean (TMm) temperature, and (d) diurnal temperature range (DTR) in the capital cities of India

The mean daily temperature, which is defined as the average of daily maximum and daily minimum temperature, showed an increasing trend (i.e., warming) across the country, especially in north-eastern and southern parts, reaching a maximum of 1°C in Kavaratti. For remaining parts of the country, negative trend was observed (-0.04 to -0.88°C; Fig. 5(c)) over the study period. Overall, significant warming trends were obtained in the north-eastern and southern peninsula of the country. The stronger trend in TNm as compared to the TXm resulted in a significant positive trend in the TMm in these cities (Fig. 5(c)). The cities where DTR exhibits significantly negative trend (-2 to -3°C) are the cities where either (1) TXm dropped significantly from the long-period average (LPA), or (2) TNm increased from the LPA, or, (3) a slight and opposite changes were found in case of both these indices.

In addition, we also computed the trend of mean maximum and mean minimum temperature at monthly scale (Supplementary Table 1). The mean monthly maximum temperature is significantly increasing throughout the year in Kavaratti and Port Blair. In the metro cities of the country, the mean monthly maximum temperature is decreasing in most of the months, with an increase in few others. The decrease was much greater in magnitude than the corresponding increase in few other months. The magnitude and direction of the trend varies between cities. For example, Shimla is consistently warming throughout the year (except in January), Dispur is warming only during 2nd half of the year (Aug-Dec), cities such as Aizawl and Itanagar are becoming warmer during Sept to March, whereas, Gandhinagar, Jaipur, Gangtok, Daman, Srinagar, and Delhi are warming mainly during the summer months and relatively cooling in other months. In majority of the capital cities, a decreasing trend was found in most of the months. The monthly trend for all cities can be visualized in detail in Supplementary Table 1. In the case of mean monthly minimum temperature, the increase was significant during most of the months in many capital cities across the country. This indicates that the energy demand in these cities would have also increased during the last 40-years period. Magnitude and direction of trend can be visualized for each city in the Supplementary Table 2.

3.2. Temperature thresholds

Although India can be regarded as climatically tropical, it experiences extraordinarily variety of climatic regions, ranging from tropical in the south, subtropical in north and north-east to temperate and alpine in the Himalayan north. Therefore, summer days (SU25) and tropical nights (TR20) are important indices for showing the changes in temperature extremes in different climatic regions (Fig. 6a and 6b). Summer days decreased significantly in several capital cities of the country, with a decrease of greater magnitude in the north, in the east, and two cities of north-eastern states, reaching lowest magnitude of 72 days (Aizawl) during the 40 years study period (1982-2022; Fig. 6a). In contrast, tropical nights increased significantly throughout the country during the same period, with a maximum increase of 40 days in Shillong followed by 38 days in Imphal (Fig. 6b). Capital cities such as Amravati, Bangalore, Itanagar, and Mumbai have witnessed an increased TR20 of magnitude greater than 20 days.

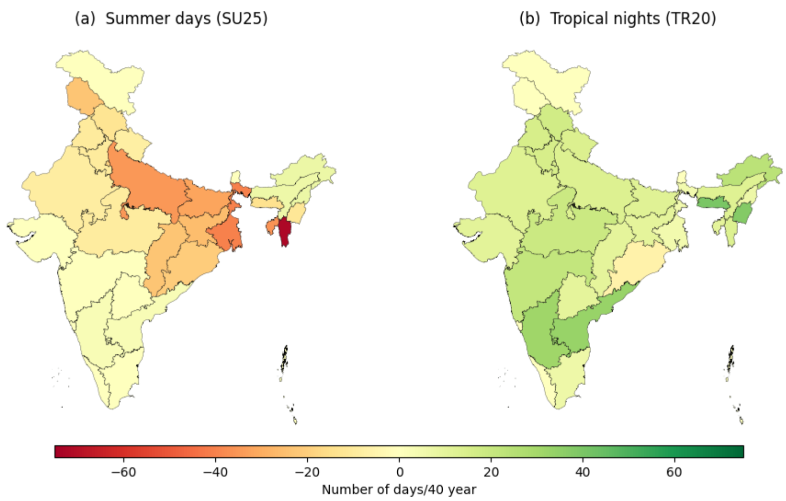

Figure 6. Spatial variation in the trends of (a) summer days (SU25) and (b) tropical nights (TR20).

3.3. Percentile-based annual temperature indices

Fig. 7(a-d) depicts the trends in cold days/nights and warm days/nights in different capital cities of India during the 40-year period (1982-2022). TX90p (warm days) and TN90p (warm nights) indices appeared to have opposite trends throughout the country, except Port Blair, Kavaratti, Panaji and Shillong (Fig. 7(a) and (b) respectively). A dramatic increase was observed in these cities for both warming days and warming nights. Index TX90p exhibited pronounced decreasing trend (0 to -19% days), with a maximum decrease in Aizawl followed by Agartala (Fig. 7(a)). TN90p exhibited pronounced increasing trend (values ranging from 0 to 23% days), with a magnitude greater than 20% days in Port Blair and Kavaratti (Fig. 7(b)).

Trend of cold days (TX10p; Fig. 7(c)), however, showed significant increase (decrease) in the majority (few) of the capital cities, particularly located in the north, east and north-west (south) India. The magnitude of increase (decrease) ranged from 0.6-14% (-1 to -24%), with a maximum increase (decrease) in Aizawl followed by Agartala (Kavaratti followed by Port Blair).

On the other hand, TN10p (cold nights) exhibited a significant downward trend throughout the country during this period, with a magnitude ranging from -2 to -22%, the maximum decrease observed in Port Blair followed by Kavaratti (Fig. 7(d)).

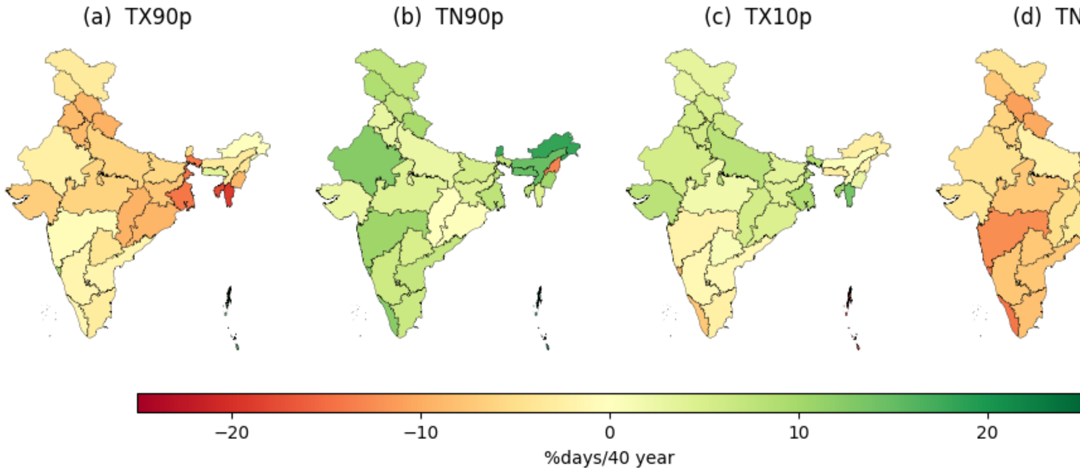

Figure 7. Trends in annual (a) warm days (TX90p), (b) Warm nights (TN90p), (c) cold days (TX10p) and (d) cold nights (TN10p) during the period 1982–2022 in the capital cities of India

3.4. Absolute annual temperature indices

Fig. 8 presents the trend of absolute temperature during hottest day/night (TXx, TNx) and coldest day/night (TXn, TNn). Index TXx (hottest day) showed a significant decrease in all capital cities, except Bhopal, Panaji, Thiruvananthapuram and islands, with a maximum decrease in Agartala (-3.2^{o}C) followed by Srinagar (-2.8 ^{o}C) and Chennai (-2.3 ^{o}C) (Fig. 8(a)). This means that absolute temperature on a hottest day in Agartala dropped up to 3.2 ^{o}C below the normal, whereas in Bhopal it rose to 0.6 ^{o}C above the normal during past 40 years (1982-2022). The trend for TNx (hottest night) varies between the cities, showing an increasing trend in the cities located in east, north-east, and western ghats, and a decreasing trend elsewhere. The maximum increase in the temperature of a hottest night was observed in Gangtok, where it was 1.2^{o}C above the normal. A concurrent drop of TNx was observed in other cities, with a maximum decrease of -1.1^{o}C below the normal in Jaipur (Fig. 8(b)).

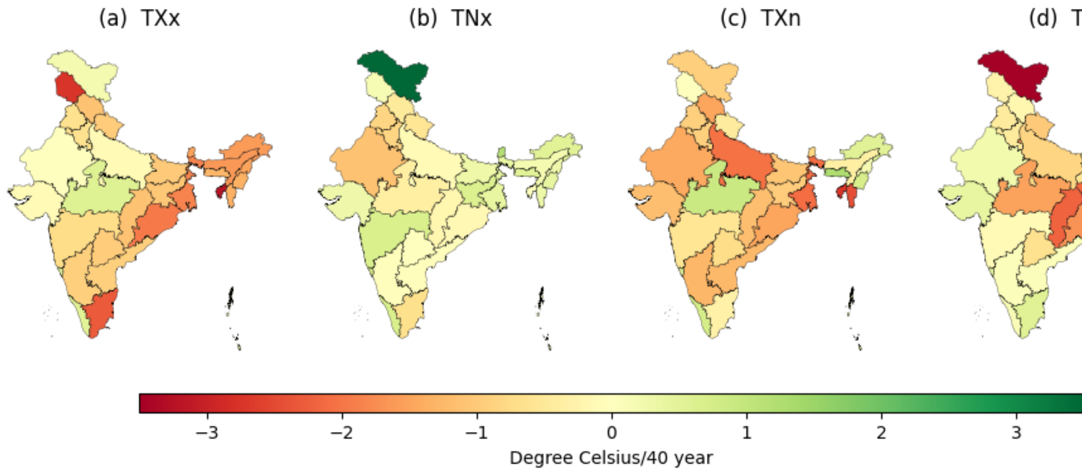

Figure 8. Trends in annual (a) maximum of maximum (TXx), (b) maximum of minimum (TNx), (c) minimum of maximum (TXn) and (d) minimum of minimum (TNn) temperatures during the period 1982–2022 in the capital cities of India

Analogous to TXx, trend of absolute temperature during the coldest days (TXn) was found to decrease significantly in several cities, except a few cities (Shillong, Kavaratti, Bhopal, Port Blair, Thiruvananthapuram, Imphal, Panaji, Itanagar, and Kohima) where an increase rather than decrease was observed. The absolute temperature on a coldest day rose to 1.3 ^{o}C above the normal in Shillong, whereas it dropped up to 2.8 ^{o}C in Agartala. The trend of absolute temperature for coldest night (TNn) was again highly variable. The temperature of the coldest night climbed up to 2^{o}C in Itanagar and adjoining cities of north-east, whereas the same dropped by -2.2 ^{o}C from the normal in Raipur and Ranchi.

The capital cities located in the north-eastern, western and southern parts of India have experienced a dramatic decrease (increase) in the absolute temperature on a hottest day (coldest night; Fig. 8(a) and (d)). A similar increase in the temperature on a warmest night was observed in cities situated in east and north-east India, western ghats and Jammu& Kashmir. The variation in the trend of hottest day/night and coldest day/night for different capital cities of India, has been presented in Fig. 8(a-d).

3.5 Warm and cold spells

The spatial trend of WSDI (warmer days for at least 6 days) and CSDI (colder days for at least 6 days) were shown in Fig. 9. During the last 40 years, both indices showed decreasing trend throughout the country, except Port Blair where an increasing trend was found in the case of WSDI. WSDI had a downward trend ranging between 3-22 days, with a maximum of 22 days observed in Agartala. Similarly, CSDI also showed a decreasing trend ranging between 4-17 days in different cities, with the highest decrease of 17 days in Port Blair.

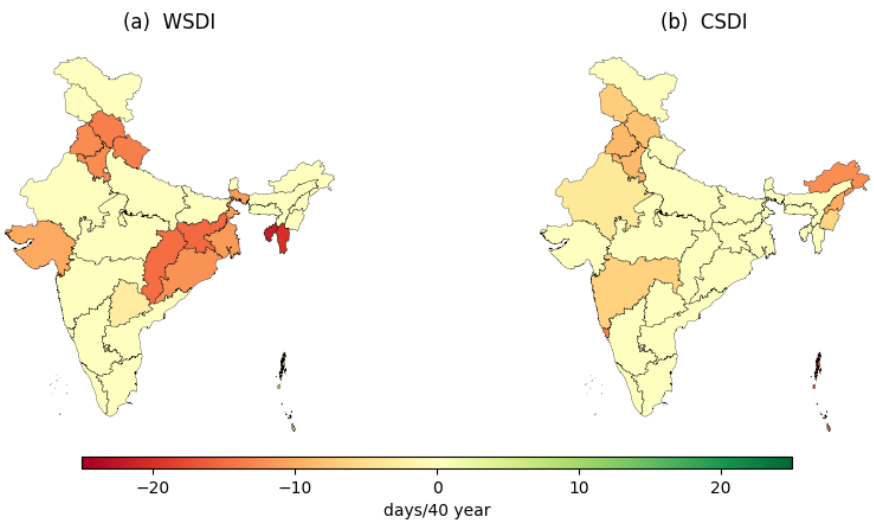

Figure 9. Trends of (a) warm (WSDI) and (b) cold (CSDI) spells

3.6 Extreme rainfall characteristics at different time scales

This section presents the spatial trends of extreme rainfall indices observed in capital cities of India during 1982-2022. Fig. 10 shows the trends of annual maximum (a) precipitation from 1-day, (b) precipitation from consecutive 3-days, (c) precipitation from consecutive 5-days, and wet days when precipitation is (d) ≥10 mm (e) ≥20 mm and (f) ≥30 mm. The trends in maximum 1-day rainfall (Rx1day), 3-day rainfall (Rx3day), and 5-day rainfall (Rx5day) indicated that rainfall has increased in majority of the capital cities of India. Trend of 1-day rainfall maximum showed an increase of about 20-40mm in the cities of eastern part of India. Rx1day index shows both increasing as well as decreasing trend, but Rx3day and Rx5day showed mostly upward trend, with a few exceptions. This suggests that capital cities with positive trend of Rx3-day and Rx5day would have experienced an increase in the consecutive heavy rainy days, and thus the urban flooding events, as observed in the past decade.

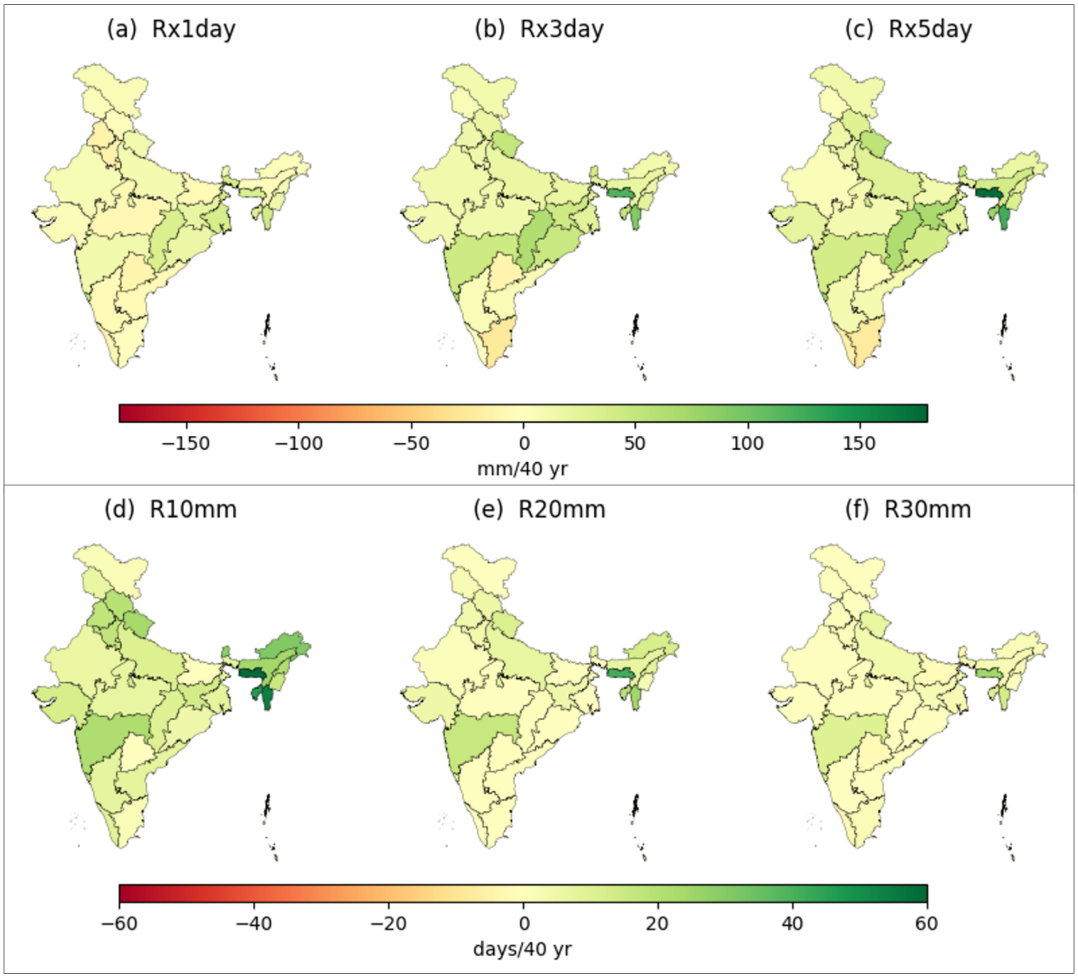

Figure 10. Spatial variation in the trend of annual maximum (a) rainfall from 1-day, (b) rainfall from consecutive 3-days, (c) rainfall from consecutive 5-days, and wet days when daily rainfall was (d) ≥10 mm (e) ≥20 mm and (f) ≥30 mm during 1982-2022 in the capital cities of India

Comparing the rainfall extremes in cities throughout the country, cities located in the eastern part witnessed greater increase in rainfall. The maximum increase of Rx1day, Rx3day and Rx5day were 48 mm (Panaji), 118 mm (Shillong), and 175 mm (Shillong) respectively. However, in some cities, these three indices showed decreasing trend (Fig. 10 (a-c)). The maximum reduction of Rx1day, Rx3day and Rx5day reported were 14mm (Chandigarh), 25mm (Chennai), and 23mm (Chennai).

3.7 Rainfall thresholds

The trend of annual number of days with rainfall ≥10mm (R10mm) was similar to the Rx3day and Rx5day trends in majority of the study area. Number of heavy rain days (R10mm) significantly increased in all capital cities throughout the country, except Patna and Hyderabad. Number of very heavy rain days (R20mm; with rainfall amount ≥20mm/day), however, showed an increase in the north, north-east and north-west, and a decrease in southern part of country. The index R30mm (rainfall amount ≥30mm/day) showed an increasing trend, again in the north-eastern capital cities, Mumbai, and Dehradun, whereas zero to negligible trend was observed in remaining capital cities.

Capital cities of north-eastern states, Mumbai, and Dehradun witnessed statistically significant increase in the trend of these three indices over last 40 years. The magnitude of increase was maximum in Shillong for all three levels of rain events: 59 days for R10mm; 42 days for R20mm; and 24 days for R30mm. Mumbai, the financial capital of India, has witnessed an increase of 22 days, 16 days, and 10 days for R10mm, R20mm, and R30mm respectively over the same period. On the other hand, decreasing trends in the case of very heavy rain days (R20mm) and extreme rain days (R30mm) were statistically significant, implying that these cities with negative trends may have had a considerable decrease in the wet days.

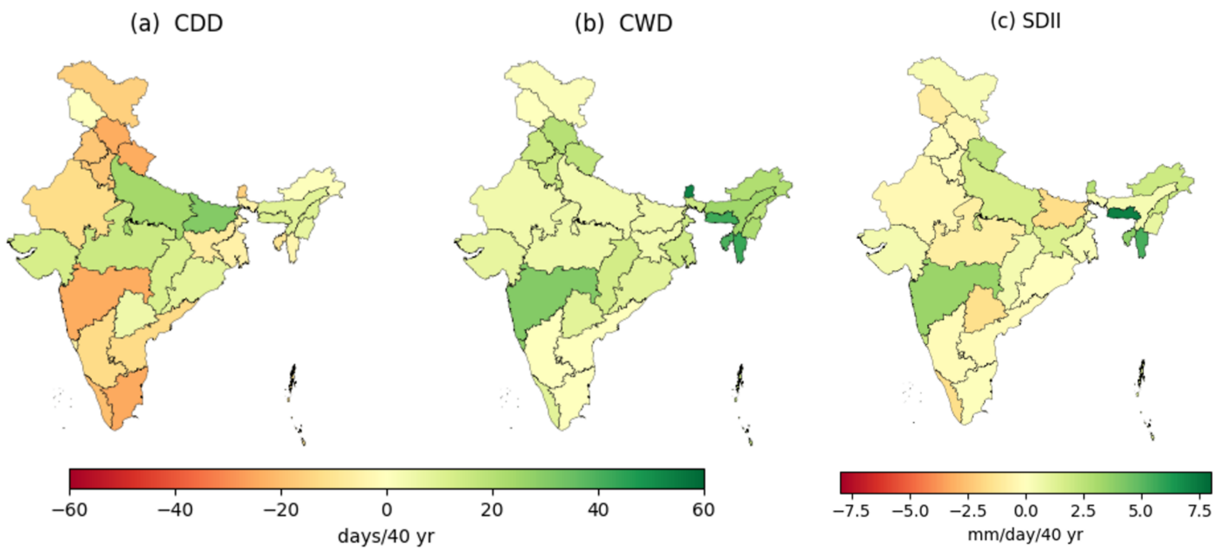

Figure 11. Trends in (a) consecutive dry days (CDD), (b) consecutive wet days (CWD) and (c) average daily precipitation intensity (SDII) in capital cities of India during the 40-year study period (1982-2022)

3.8 Dry and wet spells

Consecutive dry days (CDD) and consecutive wet days (CWD) are the two precipitation extreme indices that represents the length of dry and wet conditions, respectively. The spatial analysis of CDD during the study period (1982-2022) revealed mixture of trends (both positive and negative) in different cities (Fig. 11(a)). Although this index showed a downward trend in most of the cities, an increase of up to 25-30 days was observed in Patna and Lucknow. Cities located in southern peninsula and north-west India, however, experienced decrease in CDD. A decrease of 20-25 days was observed in Chennai, Dehradun, Mumbai, Shimla, and Thiruvananthapuram. The CWD increased significantly throughout the country (Fig. 11(b)), reaching a maximum of 53 days in Gangtok, and between 40-43 in Agartala, Aizawl, and Shillong over the last 40 years. It showed substantial increasing trends, particularly in Mumbai, Panaji, Kavaratti, and north-eastern part of the country, with an increase of 20 and more consecutive wet days. This is in agreement with the trends observed for three precipitation indices indicating annual number of days with a given threshold of rainfall (R10mm, R20mm, and R30mm).

It is interesting to also note here that although number of days with different thresholds of rainfall (trend of R10mm, R20mm, and R30mm) is increasing maximally in Shillong, number of consecutive wet days was observed to be higher in Gangtok. This necessitates computation of an additional index, simple daily intensity index (SDII), which shows the intensity of rainfall during wet days. This was computed as "annual total precipitation divided by the number of wet days (when total precipitation >= 1.0 mm;)". In the eastern and north-eastern part of the country, SDII demonstrated a significantly increasing tendency in majority of the studied area (Fig. 11(c)). The direction of SDII trend was governed by the relative magnitude of CDD and CWD, indicating that wet days increased, and consecutive dry days decreased when CWD is greater, for example, in Shillong and other cities in the north-east. The magnitude of increase was maximum in Shillong (7.2 mm/day) followed by Aizawl (5.4 mm/day), Agartala (3.8 mm/day), Mumbai (3.5 mm/day), Gangtok (2.64 mm/day), and Dehradun (2.36 mm/day) over the 40 years study period. A decrease in SDII however, was also observed in many cities, with a maximum in Patna (-1.68 mm/day).

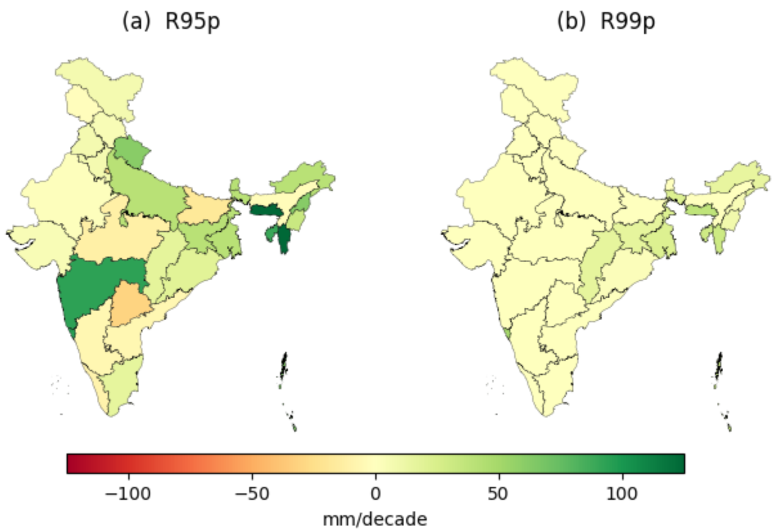

Figure 12. Trends in total annual precipitation from (a) very wet days and (R95p) and (b) extremely wet days (R99P) in capital cities of India during the 40-year study period (1982-2022)

3.9 Percentile-based rainfall indices

Trend of very wet days (R95p) and extremely wet days (R99p) varied significantly throughout the country (Fig. 12a and 12b). The two indices showed an opposite nature of trend in many cities, however, similar behavior were also reported. Similar to our earlier findings for other extreme precipitation indices, both R95p and R99p showed an increasing trend in the capital cities of eastern and north-eastern states. Overall, this implies that rainfall (intensity as well as the number of days) has increased in these cities. The R95p shows substantial increase in majority of the study area, with a maximum increase of 149 mm/decade in Shillong. However, a decrease was also observed in several other cities, recording maximum decrease of 30 mm/decade in Hyderabad. The R99p index, unlike R95p, showed no notable trend except in the country's eastern and north-eastern capital cities, Panaji, and both islands. The magnitude of increase of extremely wet days (R99p) was maximum in Panaji (49 mm/decade) followed by Shillong (37 mm/decade).

Fig. 13 shows the trend of annual rainfall (PRCPTOT) as well as the contribution of *very wet days* (R95PTOT) and *extremely wet days* (R99PTOT) to the total rainfall. A significant increase in total rainfall was observed in all capital cities, except Patna (Fig. 13(a)). The stronger upward trend of PRCPTOT was the result of increasing R10mm across the country (Fig. 10(d)), R20mm in north, north-east, and north-western part of the country (Fig. 10(e)), and R30mm mainly in the east, north, and north-east corner (Fig. 10(f)). The magnitude of increase of total annual rainfall per decade was highest in Shillong (458 mm) followed by Aizawl (362 mm) and Agartala (305 mm). For remaining capital cities, increase was ≤ 250 mm/decade. Downward trend of PRCPTOT was recorded only in Patna, having the magnitude of -15 mm/decade during the same time period.

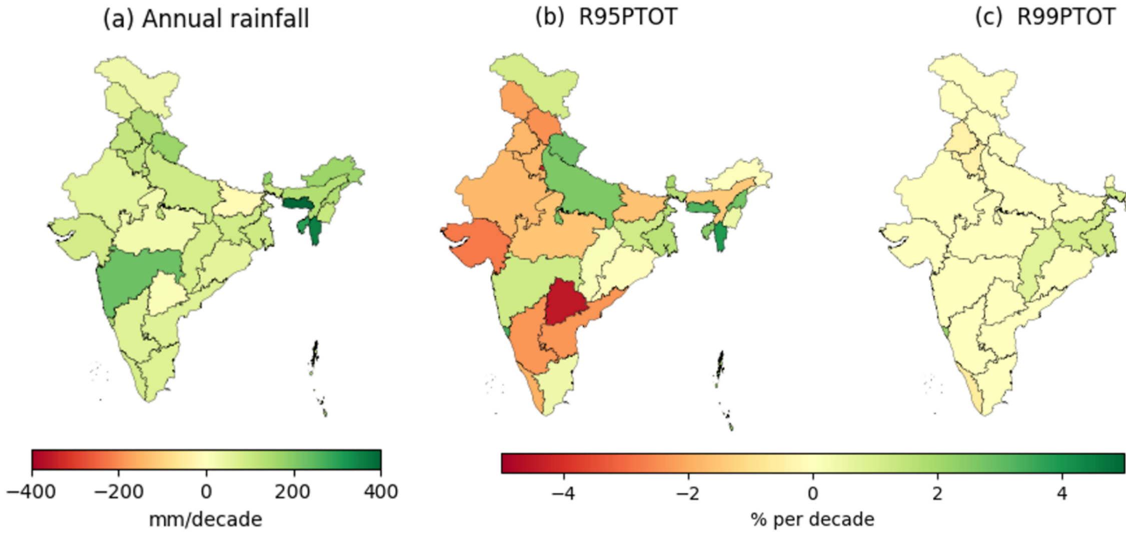

Figure 13. Spatial variation in the trend of (a) annual rainfall (PRCPTOT), (b) contribution of very wet days (R95PTOT) and (c) contribution of extremely wet days (R99PTOT) to total rainfall in different capital cities of India during the 40-year study period (1982-2022)

The contribution of *very wet days* to total rainfall (R95PTOT; Fig. 13(b)) however, showed both upward and downward trend: upward trend in the north, north-east, east, islands and western ghat (Mumbai and Panaji); and a downward trend elsewhere. Analogous to R99p, the trend of contribution of *extremely wet days* to total rainfall (R99PTOT; Fig. 13(c)) was small and negligible across the country, except few cities in the east and north-eastern corner of country.

Additionally, the trend of average seasonal rainfall, and that of the mean annual rainy days were also computed (Supplementary Table 3). Seasonal rainfall (except during summer season) were reported to increase significantly in the capital cities of north-eastern and Himalayan states. It is important to note here that the monsoon rainfall is significantly increasing in most of the capital cities, except Patna and Thiruvananthapuram, where decreasing trend was observed. The pre-monsoon rainfall is also showing a significant increase in about half of the study area, with a non-significant increase in others. During the post-monsoon and winter season, mixture of trends (positive and negative, significant and non-significant) were observed (Supplementary Table 3). The number of rainy days also showed significant increase throughout the country, with the maximum increase in Aizawl (1.83 days/year) followed by Gangtok (1.78 days/year).

4. Discussion

Present study investigated the trend of extreme climate indices during the 40-years (1982-2022) study period, in the capital cities of states and union territories of India. The results indicate a general increase in extreme temperature as well as extreme precipitation events in the capital cities of India, especially in the islands and north-eastern corner. This is in agreement with several studies demonstrating the rise of temperature and rainfall extremes across the globe (Fall et al. 2021; Sieck et al. 2021; Diba et al. 2022), including India (Sharma et al. 2017; Rehana et al. 2022; Maurya et al. 2023; Falga et al. 2022; Vieira et al. 2023) and its neighboring countries (Sheikh et al. 2015; Shrestha et al. 2017; Hong and Ying, 2018; Abdullah et al. 2022; Manalo et al. 2022). Yao et al. 2006 reported a consistent warming trends for the Himalayan region, including the Tibetan Plateau, during the past 100 years.

During the 40-years study period (1982-2022), magnitude of change (sen's slope) of extreme climate indices varied greatly across the country. Trend analysis of temperature indicates that the effect of global warming is conspicuous in most of the capital cities. The mean annual maximum temperature (TXm) showed a cooling (negative) trend during this period, whereas the mean annual minimum temperature (TNm) showed warming (positive) trend throughout the country's capital cities, except for a few capital cities. The unexpected downward trend of TXm contrary to what is expected due to global warming and the expected upward trend of TNm has resulted in decrease of DTR across the country. Unusual behavior of TXm and TNm can be explained as the effects of global warming as observed worldwide: urbanization and the resulting urban heat island effect; increasing concentration of dust and particulate matter (PM) in the atmosphere, generated by different kinds of developmental activities in and near capital cities; and thus trapping of more of the thermal radiation in the atmosphere. It has been well established that anthropogenically generated particulate matter cause direct scattering of short-wave radiation, increasing the planetary albedo, and thereby causing cooling effect (Charlson et al. 1992; Haywood and Boucher, 2000). However, very coarse dust particles (diameter $\geq 5\mu m$) have been confirmed to cause significant warming of the atmosphere (Kok et al. 2017). So, the two – dust and PM – depending on their size, structure and composition of individual fine particles, have very different radiative properties, and thus their effect on the local weather. The rise of TNm, specifically during September to November, and again during February to April has become a major cause of concern and will potentially increase the threat for energy self-sufficiency in these capital cities.

Although TNm is increasing, the overall warming or cooling of a city is equally governed by the magnitude of increase or decrease of TXm. Each city has a unique narrative. Notably, daily minimum temperatures are increasing, but their rate of increase is superseded by the rate of decrease of mean maximum temperature in the cities of northern part of India. This resulted in an overall cooling of these cities. Contrarily, in the case of capital cities located in north-eastern part of India, daily minimum temperatures are increasing at a rate faster than the rate of decrease of daily maximum temperatures, and thus resulted in overall significant increase of the mean annual daily temperature (TMm). TMm - the average of TXm and TNm - showed an increasing trend in the capital cities of peninsular India and north-eastern states, and a decreasing trend elsewhere. This was one of the key findings of the study.

Absolute temperature indices also indicate a similar trend, with a maximum decrease of -0.8 °C/decade for TXx (absolute temperature on a hottest day) in Agartala, and an increase of up to 0.42°C/decade for TNx (absolute temperature on a warmest night) in Leh during the same period. Temperature threshold indices such as summer days (SU25) and tropical nights (TR20) also substantiate the findings of daytime cooling and night-time warming in most of the capital cities of India. These trends can be attributed to the prevalence of Atmospheric Brown Clouds (ABC; haze) – a wide polluted layer - during the winter and pre-monsoon seasons (November – April; Bonasoni et al. 2010). This thick, grey-brown haze blanket extending from Indian ocean to the Himalayas, interacts substantially with the incoming solar radiation and modify radiation budget in the region. They result in cooling of the earth's surface by intercepting the incoming short-wave radiation, and warming of the atmosphere by trapping the outgoing longwave radiation (for details about its impact on radiation budget, refer Cotton et al. 2011). Ramanathan and Ramana, 2003 indicated that the persistence of the haze during the long dry season in Asia (November - May) has significant implications for the regional water budget, agriculture and human health owing to its black carbon content, the negative effect on the radiative energy budget of the region, and impact on the monsoon rainfall distribution.

It is worth noting that this study detected and ascertained more pronounced daytime cooling and night time warming compared to the earlier studies in many capital cities. For example, Kalita et al. (2020) observed an increasing trend of both maximum and minimum temperature in different regions of Meghalaya, having a magnitude varying from 0.6-0.7°C and 0.4-0.7°C respectively, over a period of 100 years (1901-2002). However, in last 40 years (1982-2022), the rate of increase of TXm was observed to be smaller (0.16°C) and that of TNm was found to be much higher (1.2°C) in Shillong compared to the previous study. At the monthly time scale, the trend of TXm was found to be decreasing throughout the year (except February and March), and in the case of TNm, it was increasing uniformly in all months (Supplementary Table 2).

Sharma (2017) examined a 1951-2013 dataset over Punjab and Himachal Pradesh and found upward trend for the absolute temperature on a hottest day (TXx), absolute temperature on a coldest night (TNn), summer days (SU25) and tropical nights (TR20) whereas, a downward trend was observed for absolute temperature on a warmest night (TNx), absolute temperature on a coldest day (TXn) and the resulting diurnal temperature range (DTR). The author concluded with the findings that there has been an overall warming of the region particularly the cold arid and semi-arid climatic region of Himachal Pradesh. Computation of these extreme temperature indices for Shimla, Chandigarh and Dehradun using the recent (1982-2022) dataset in present study however, indicate an increasing trend of mean minimum temperature (TNm), (TR20), warm nights (TN90p), and cold day (TX10p), whereas a decreasing trend was observed for mean maximum temperature (TXm), DTR, warmest days (TX90p), coldest nights (TN10p), and absolute annual temperature indices (TXx, TNx, TXn, TNn).

Findings of the present study also suggests that the capital cities throughout the country are not only experiencing increasing number of days with daytime cooling and night time warming, but also an increase in the extremes of *minimum temperature* in majority of the capital cities and that of *maximum temperature* in a few cities. Nights have become visibly warmer in almost all capital cities in the recent decade. Increasing trend of TXn and TNn, as observed in Panaji, Thiruvananthapuram and in the capitals of north-eastern states shows that the duration of winter season has shortened. Similar result was observed by Purnadurga et al. (2018). The decreasing trend of TXm and increasing trend of TNm is inconsistent with the results observed in other neighbouring countries. A predominantly increasing trend of TXx and minor positive trend of TNx were detected in China (Yin et al. 2017) and Zambia (Chisanga et al. 2017). Rising minimum temperature accompanied with rising levels of particulate matter (Hassan et al. 2023) and the prevalence of atmospheric brown clouds (ABC) are often attributed as few of the reasons for recent retreat of Himalayan glaciers to higher altitudes, permafrost thawing (Gruber et al. 2017; Gao et al. 2021), and enhanced methane emissions (Du et al. 2022). Also, owing to the temperature dependence of mineral solubility in water, rising temperature is becoming a matter of concern in terms of physical threats. In hilly to mountainous areas, permafrost degradation is destabilising the mountain slopes (Fort, 2015) and causing more frequent landslides and debris flow as observed in several capital cities in the past decade, directly threatening the infrastructure and nearby settlements.

Overall, comparison of percentile-based annual temperature indices for the capital cities located in different climatic regions suggest that north-eastern and southern part of the country has experienced significant increase in warm nights with a significant decrease of warm days. In addition, Fig. 7 (c) and (d) indicates an increase in the cold days and decrease in the cold nights. This supports our earlier findings - significant decrease of DTR- with maximum decrease in this part of the country. Variation in the trend of cold days/nights and warm days/nights for different capital cities can be visualized in Fig. 7 (a-d). It is worth noting that temperature related climatic extremes are on the rise in all capital cities of India. Increasing (decreasing) warm nights and cold days (warm days and cold nights) has direct consequence on the energy requirements, and food storage facility of the cities, which is a matter of concern.A decreasing trend observed for WSDI as well as CSDI indicates moderation of extreme climatic parameters in the entire region. The capital cities were affected by increasing number of warm extremes based on nights time indices rather than the cold extremes based on day time indices during the 40-years study period 1982-2022.

Increased scarcity of potable water in many Indian cities during the last decade motivated author to analyze rainfall extremes observed in the capital cities, which hold a great share of country's population. Rapidly increasing population, changing landuse, and increased human activities in and around cities has shaped a very different urban microclimate. The spatial analysis of CDD and CWD indicates decreasing number of consecutive dry days and increasing number of consecutive wet days in most of the cities. The expected opposite behavior of CDD and CWD was observed in Mumbai, Chandigarh, Shimla, Thiruvananthapuram, Jaipur, Gangtok, Dehradun. However, several other cities exhibited increasing trends of both CDD and CWD. The unexpected similar behavior of CDD and CWD was also reported in earlier studies conducted in Bangladesh (Khan et al. 2019; Abdullah et al. 2020), and Brazil (Oliveira et al. 2016; Costa et al. 2020). This can be explained by the behavior of R10mm, Rx3day and Rx5day in respective cities where these indices showed strong increasing trend. This is another very important finding of this study which suggests that seasonality is intensifying in these cities i.e., with dry seasons becoming more drier and wet seasons becoming more wetter.

An increasing extremes of temperature accompanied by increased CDD indicates that capital cities are going to be inhabitable in the near future for resource-poor. There will be an increased energy load, more failure of infrastructure, and reduced efficiency of the physical as well as the biological resources. Other megacities are already under the grip of extreme weather events. In agriculturally important states (such as Andhra Pradesh, Bihar, Madhya Pradesh, Odisha, UP, Gujarat) the significant increase of CDD accompanied by minimal increase of CWD and simultaneous decrease of SDII can have a long-term effect on per-capita water availability.

It is important to note the cities where R95PTOT and R99PTOT are showing increasing trend. Upward trend of these two indices implies that (1) extreme rainfall events have increased in these cities; (2) a greater fraction of the rainfall received are being lost in different forms; (3) reduced infiltration and percolation, and (4) increased risk of landslides and soil erosion. There is a need of special attention in the form of preparedness to minimize the impact of any kind of hazard associated with these extreme events. Several capital cities in the eastern and north-eastern part of India showed significant positive trends in "*very wet days*" and "*extremely wet days*". These cities demonstrated significantly increasing tendency in *consecutive wet days* and the intensity of rainfall during wet days. The magnitude of increase was also high in these capital cities. This suggests that larger proportion of the total rainfall in a year in these cities are received as heavy rainfall. During such rainfall events, since the water infiltrates into the soil at the maximum soil infiltration capacity initially and gradually slows down (Tarboton, 2003), the excess water contributes as the surface runoff, resulting in flooding in low-lying areas, landslides, and increased soil erosion. This demands an urgent need to formulate appropriate adaptation strategy specific for each city considering their edaphic, topography and available infrastructures.

5. Conclusion

In light of the above discussion, it appears that the region exhibited overall night-time warming and day-time cooling. Summer days decreased significantly in most parts of the country, with a decrease of greater magnitude in the north, in the east, and two cities of north-eastern parts. The tropical nights however, increased significantly throughout the country during the study period, with a maximum increase of 40 days in Shillong followed by 38 days in Imphal. These have direct consequence on the energy requirements, food storage facility, and other related sectors of the cities, which is a matter of concern. During the study period, cities were also exposed to increasing rainfall amount, with greater intensity, and more rainy days, especially in the eastern and north-eastern states. Capital cities such as Patna and Lucknow, however, witnessed rise in the length of dry spell (CDD) up to 25-30 days, indicating the possibility of lowering down of the groundwater table, and water shortage during the summer months. Thus, it becomes necessary to analyse these issues for each city, as how and up to what extent these trends are going to impact the day-to-day activities of inhabitants living there, and what actions can be taken to mitigate their negative effects. Such an attempt would help the local administrative bodies to plan accordingly and take appropriate action.

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Supplementary Table 1: Trend of monthly maximum temperature (per year) in the capital cities of India

Name of Capital city	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec
Dispur	-0.012	-0.010	-0.030	-0.049*	-0.035*	-0.024*	-0.010	0.000	0.008*	0.013	0.019*	0.017
Raipur	-0.068*	-0.040	-0.031	-0.023	-0.018	-0.037	-0.007	0.000	-0.005	-0.009	-0.018	-0.054*
Itanagar	0.004	0.006	0.000	-0.034*	-0.044*	-0.032*	0.000	0.000	0.017*	0.030*	0.016	0.015
Telangana	-0.015	-0.025	-0.017	-0.021	-0.051	-0.028	-0.004	-0.011	-0.024	-0.001	0.004	-0.020
Patna	-0.051*	-0.008	-0.019	-0.010	-0.041*	-0.016	-0.005	0.006	0.013	-0.012	-0.047	-0.052*
Gandhinagar	-0.034*	0.015	0.009	0.022	0.001	-0.060*	-0.048*	-0.023	-0.067*	-0.089*	-0.055*	-0.051*
Shimla	-0.004	0.011	0.021*	0.026*	0.013	0.008	0.012*	0.019*	0.016*	0.011	0.012	0.001
Ranchi	-0.016	-0.001	0.012	-0.001	-0.038	-0.050*	-0.061*	-0.039*	-0.051*	-0.042	-0.029*	-0.004
Bangalore	-0.038*	-0.007	-0.021	-0.010	-0.016	-0.008	-0.007	-0.002	-0.002	-0.002	-0.009	-0.043*
Thiruvananthapuram	0.007	-0.022	-0.025	-0.025	-0.046*	0.012	0.018	0.006	0.001	0.000	-0.010	-0.010
Bhopal	-0.025	-0.002	0.001	0.001	-0.004	0.021*	0.022*	0.017*	0.010	0.007	0.000	-0.016
Mumbai	-0.023	0.005	-0.005	0.007	-0.002	-0.051	-0.037*	0.002	-0.007	0.001	0.000	-0.031
Imphal	-0.024	0.002	0.009	0.023*	0.012	-0.008	-0.003	0.015*	0.007	0.003	0.008	-0.024
Shillong	-0.017	0.010	0.007	-0.015	-0.039*	-0.037*	-0.013	-0.018	-0.001	-0.010	-0.023	-0.023
Aizawl	0.019	0.024*	0.009	-0.020	-0.020*	-0.026*	-0.003	-0.001	0.012*	0.011*	0.027*	0.026*
Kohima	-0.084*	-0.050*	-0.022	-0.039	-0.056*	-0.048*	-0.016*	-0.021*	-0.009	-0.029*	-0.070*	-0.097*
Bhubaneswar	-0.012	-0.002	-0.008	-0.020	-0.026*	-0.028*	-0.012	-0.009	0.009	0.015	0.017	0.001
Chandigarh	-0.081*	-0.051*	-0.053*	-0.032	-0.037	-0.018	0.008	0.007	0.004	0.001	-0.005	-0.050*
Jaipur	-0.027	-0.008	0.016	0.009	-0.032	-0.043	-0.059*	-0.038*	-0.057*	-0.044*	-0.044*	-0.012
Gangtok	-0.026	0.019	0.017	0.023	-0.003	-0.044*	-0.034	-0.036	-0.061	-0.031	-0.028	-0.012
Chennai	-0.008	0.020	-0.029	-0.028	-0.041*	-0.034*	-0.017	-0.007	-0.003	0.000	0.026*	0.017
Hyderabad	0.010	-0.018	-0.010	-0.017	-0.036*	0.007	0.011	-0.017	-0.012	-0.002	0.005	0.013
Agartala	-0.019	-0.034*	-0.031*	-0.024	-0.038	-0.009	0.025	0.013	0.000	-0.007	0.003	-0.018
Lucknow	-0.066*	-0.043*	-0.039*	-0.065*	-0.058*	-0.041*	-0.018	-0.013	0.005	-0.008	-0.052*	-0.063*
Dehradun	-0.045*	-0.018	-0.018	-0.006	-0.031	-0.026	-0.083*	-0.036	-0.005	-0.047	-0.062*	-0.058*
Kolkata	-0.020	0.001	0.005	-0.009	-0.045	-0.050	-0.048*	-0.017	-0.010	-0.027*	-0.030*	-0.009
Panaji	-0.089*	-0.051*	-0.060*	-0.028	-0.023	-0.009	0.006	0.002	0.003	-0.005	-0.032*	-0.070*
Port Blair	0.020*	0.019*	0.018*	0.011	0.013*	0.007	0.017*	0.014*	0.017*	0.025*	0.032*	0.022*
Daman	-0.015	0.021	0.019	0.025*	0.002	-0.035	-0.016	0.008	-0.018	-0.050*	-0.051	-0.024
Delhi	-0.047*	-0.002	0.015	0.008	-0.032	-0.042	-0.055	-0.021	-0.019	-0.031	-0.034	-0.032
Srinagar	-0.017	0.006	0.013	0.004	-0.032	-0.060*	-0.031	-0.025	-0.012	0.002	-0.025	0.007
Leh	-0.033	-0.006	0.005	0.001	-0.018	-0.027	-0.008	-0.024*	-0.003	0.019	-0.011	-0.033
Kavaratti	0.022*	0.024*	0.028*	0.027*	0.020*	0.016*	0.022*	0.018*	0.020*	0.023*	0.025*	0.025*
Puducherry	0.009	-0.012	-0.012	-0.013	-0.016*	0.007	0.010	-0.008	-0.003	0.002	0.007	0.013*

Supplementary Table 2: Trend of mean monthly minimum temperature (per year) in the capital cities of India

Name of Capital city	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec
Dispur	0.056*	0.059*	0.046*	0.018	0.014*	0.009	0.011*	0.013*	0.025*	0.041*	0.052*	0.068*
Raipur	-0.029	-0.002	0.014	-0.002	0.015	-0.008	0.004	0.004	0.015*	0.017	0.016	0.006
Itanagar	0.062*	0.071*	0.070*	0.041*	0.017*	0.005	0.019*	0.021*	0.035*	0.043*	0.048*	0.065*
Telangana	-0.005	-0.018	0.006	0.005	-0.008	-0.013	0.005	0.009	0.002	0.017	0.028	0.010
Patna	-0.014	0.017	0.024	0.028*	0.014	0.007	0.003	0.011	0.022*	0.029	0.021	-0.002
Gandhinagar	-0.016	0.025	0.025	0.038*	0.025*	-0.003	-0.008	0.006	0.002	0.004	0.015	-0.009
Shimla	0.000	0.019*	0.032*	0.027*	0.020*	0.011*	0.012*	0.016*	0.025*	0.019*	0.017	0.010
Ranchi	0.019	0.040*	0.036	0.046*	0.031	0.008	-0.012	-0.001	0.021*	0.045*	0.035*	0.014
Bangalore	-0.030	0.008	0.015	0.016	0.013	0.010	0.005	0.003	0.017*	0.020*	0.009	-0.012
Thiruvananthapuram	0.016	-0.012	0.000	0.000	-0.001	0.011	0.019*	0.020*	0.012*	0.014	0.020	0.023
Bhopal	0.008	0.001	0.013	0.012*	0.014*	0.018*	0.018*	0.017*	0.016*	0.017*	0.018*	0.017
Mumbai	-0.012	0.025	0.028	0.031*	0.025*	-0.006	0.001	0.004	0.026*	0.036*	0.030	0.000
Imphal	-0.009	0.025*	0.031*	0.027*	0.021*	0.008	0.009*	0.012*	0.028*	0.025*	0.029	0.018
Shillong	0.030*	0.028	0.025*	0.011	0.013	0.006	0.011*	0.009*	0.021*	0.025*	0.020	0.034*
Aizawl	0.032*	0.037*	0.038*	0.029*	0.019*	0.014*	0.012*	0.016*	0.025*	0.033*	0.039*	0.052*
Kohima	-0.002	-0.003	0.015	0.006	0.012	-0.003	0.004	0.006	0.017*	0.026*	0.007	0.015
Bhubaneswar	0.037*	0.046*	0.036*	0.016*	0.016*	0.011*	0.016*	0.015*	0.026*	0.025*	0.027*	0.041*
Chandigarh	-0.047*	-0.048*	-0.010	-0.004	0.008	0.004	0.006	0.007*	0.011*	0.019	0.018	-0.001
Jaipur	-0.006	0.026	0.030	0.040*	0.018	-0.001	-0.021	-0.006	0.008	0.037*	0.019	-0.009
Gangtok	0.003	0.009	0.028	0.036*	0.031	-0.011	-0.018	-0.014	0.008	0.018	0.021	-0.001
Chennai	0.018	0.050*	0.020	0.034*	0.025*	0.022*	0.021*	0.026*	0.025*	0.035*	0.050*	0.050*
Hyderabad	0.011	-0.006	0.014	0.007	-0.006	0.009	0.012	0.011*	0.002	0.010*	0.017	0.021*
Agartala	-0.012	-0.016	-0.013	-0.001	-0.005	0.004	0.015*	0.017*	0.011*	0.014	0.024	0.005
Lucknow	0.008	-0.002	0.014	0.004	0.015*	0.007	0.006*	0.011*	0.020*	0.023*	0.014	0.030*
Dehradun	-0.018	0.031	0.005	0.022	0.018	0.000	-0.026*	-0.007	0.021*	0.037*	0.010	-0.014
Kolkata	0.020	0.035	0.027	0.035*	0.028	0.011	0.003	0.011*	0.033*	0.041*	0.040*	0.013
Panaji	-0.024	-0.033*	-0.009	0.005	0.016*	0.008	0.011*	0.010*	0.014*	0.036*	0.025	0.012
Port Blair	0.027*	0.017*	0.018*	0.013*	0.015*	0.006	0.015*	0.013*	0.014*	0.024*	0.036*	0.027*
Daman	-0.003	0.037*	0.032*	0.024*	0.019*	0.003	0.006	0.008	0.025*	0.006	0.006	0.002
Delhi	-0.019	0.021	0.022	0.043*	0.029	0.002	-0.024	-0.013	0.019	0.032*	0.018	-0.016
Srinagar	-0.017	0.023	0.037	0.048*	0.026	0.018	0.025*	0.015	0.041*	0.037*	0.012	-0.015
Leh	-0.102*	-0.057	-0.015	0.037	0.030*	0.022	0.038*	0.014	0.029*	0.030*	0.010	-0.050
Kavaratti	0.020*	0.023*	0.028*	0.026*	0.018*	0.014*	0.022*	0.018*	0.021*	0.020*	0.023*	0.023*
Puducherry	0.012	-0.002	0.009*	0.010	-0.002	0.007	0.017*	0.011*	0.007*	0.015*	0.016*	0.016*

Supplementary Table 3: Trend of annual and seasonal rainfall and rainy day per year

Name of the Capital city	Annual rf	Pre-monsoon	Monsoon	Post-monsoon	Winter	Rainy day
Dispur	15.19*	6.25*	7.37*	1.16	0.07	1.06*
Raipur	8.01*	0.22	7.52*	0.41	-0.12	0.54*
Itanagar	16.15*	7.25*	8.92*	0.74	-0.03	0.75*
Telangana	5.80	1.63*	6.65*	0.07	-0.09	0.69*
Patna	0.23	1.35*	-2.21	0.12	0.00	0.29
Gandhinagar	7.03*	0.00	9.52*	0.00	0.00	0.62*
Shimla	14.11*	1.81*	9.73*	0.64*	1.31*	1.39*
Ranchi	9.70*	1.10	6.98*	0.84	-0.10	0.50*
Bangalore	4.70	2.08*	1.27	1.97	0.02	0.88*
Thiruvananthapuram	6.96	2.82	-0.67	5.91*	0.45*	1.00*
Bhopal	1.00	0.02	2.54	-0.16	-0.17	0.47*
Mumbai	24.92*	0.09	20.61*	1.92	0.01	0.70*
Imphal	9.40*	2.32	7.04*	1.91	-0.18	1.07*
Shillong	44.65*	14.06*	30.04*	4.10*	0.41	1.58*
Aizawl	35.40*	7.16*	24.77*	4.45*	0.26	1.83*
Kohima	11.59*	3.15*	9.40*	1.55	-0.10	1.16*
Bhubaneswar	5.46	2.38*	1.84	1.86	-0.27	0.60*
Chandigarh	12.24*	1.18	8.98*	0.54*	1.04	1.22*
Jaipur	5.05*	0.49	5.42*	0.09	-0.05	0.53*
Gangtok	15.73*	4.89*	11.86*	0.89*	0.27	1.78*
Chennai	6.21	1.54*	3.65*	2.93	0.07	0.69*
Hyderabad	-0.19	0.65	1.36	-0.26	0.00	0.49*
Agartala	33.08*	8.84*	17.45*	4.13*	0.53	1.64*
Lucknow	10.63*	1.07*	7.61*	-0.29	0.22	0.44*
Dehradun	17.90*	1.65	14.01*	0.69*	1.06*	1.12*
Kolkata	11.39*	1.00	4.55	1.50	0.08	0.75*
Panaji	12.63*	0.88	10.66*	1.42	0.00	0.36*
Port Blair	12.17*	3.90*	7.22*	3.63	0.65	0.53*
Daman	25.65*	0.12	23.94*	1.29	0.00	0.89*
Delhi	1.35	0.71	0.97	0.12	-0.01	0.30
Srinagar	5.66	0.81	2.66*	0.58	2.43*	0.75*
Leh	3.79*	0.79	1.77*	0.35	0.90*	0.62*
Kavaratti	14.04*	3.03*	7.48*	3.95*	-0.04	1.11*
Puducherry	7.76*	1.85*	3.51*	3.81	0.05	0.78*

*Indicates trend is significant at 95% significance level

Columns contains the Sen's slope values of rainfall (mm/year) at different temporal scales. Last column corresponds to the trend of rainy days. Different color scales have been used for each column.