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RESEARCH REPORT

Assessing annual, seasonal and monthly variability of rainfall and temperature patterns in India

Prabodha Kumar Pradhan, Raghavendra Ashrit, Mohana S. Thota and V. S. Prasad

July 2024

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201 309, INDIA

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9	Abstract (brief)	This report aims to understand information on the regional climate in India. Indian region is the most important part of South Asia. India's geographical locations are unique, such as the juxtaposition of the Arabian Sea, the Bay of Bengal, and the Indian Ocean. Moreover, the Himalayan ranges spread across Pakistan and India, which function as a wall, dividing the climate of India and the South Asian region. The recent climate research unit (CRU) datasets, such as rainfall, temperature maximum and minimum (Tmax and Tmin), climatology, variability, and trends for annual, seasonal, and monthly scales, were analysed during 1951–2020. Regarding spatial and inter-annual variability, India has witnessed decreasing trends in annual rainfall during the last seven decades. However, rising rainfall also reveals in the pre-monsoon and post-monsoon seasons rather than the monsoon season. Subsequently, Tmax and Tmin have shown a significantly increasing trend above ~0.12 ^{o}C per decade annually and in seasonal time scales. A salient feature of this report is the introductory results based on CRU datasets. The climate information on extreme events can be improved using high-resolution daily multiple datasets, such as Indian Monsoon Data Assimilation and Analysis (IMDAA).
10	References	20

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सारांश

इस रिपोर्ट का उद्देश्य भारत में क्षेत्रीय जलवायु पर जानकारी को समझना है। भारतीय क्षेत्र दक्षिण एशिया का सबसे महत्वपूर्ण हिस्सा है। भारत की भौगोलिक स्थिति अद्वितीय है, जैसे अरब सागर, बंगाल की खाड़ी और हिंद महासागर का संगम। इसके अलावा, हिमालय पर्वतमाला पाकिस्तान और भारत में फैली हुई है, जो एक दीवार के रूप में कार्य करती है, जो भारत और दक्षिण एशियाई क्षेत्र की जलवायु को विभाजित करती है। हाल की जलवायु अनुसंधान इकाई (सीआरयू) के डेटासेट, जैसे कि वर्षा, अधिकतम और न्यूनतम तापमान (टीमैक्स और टीमिन), जलवायु विज्ञान, परिवर्तनशीलता, और वार्षिक, मौसमी और मासिक पैमानों के रुझान, का विश्लेषण 1951-2020 के दौरान किया गया था। स्थानिक और अंतर-वार्षिक परिवर्तनशीलता के संबंध में, भारत में पिछले सात दशकों के दौरान वार्षिक वर्षा में गिरावट देखी गई है। हालाँकि, बढ़ती वर्षा मानसून के मौसम के बजाय प्री-मानसून और मानसून के बाद के मौसम में भी सामने आती है। इसके बाद, टीमैक्स और टीमिन ने सालाना और मौसमी समय के पैमाने पर प्रति दशक ~0.12 ^{o}C से ऊपर की उल्लेखनीय वृद्धि देखी है। इस रिपोर्ट की एक प्रमुख विशेषता सीआरयू डेटासेट पर आधारित परिचयात्मक परिणाम हैं। इंडियन मॉनसून डेटा एसिमिलेशन एंड एनालिसिस (आईएमडीएए) जैसे उच्च-रिज़ॉल्यूशन वाले दैनिक एकाधिक डेटासेट का उपयोग करके चरम घटनाओं पर जलवायु जानकारी में सुधार किया जा सकता है।

Abstract

This report aims to understand information on the regional climate in India. Indian region is the most important part of South Asia. India's geographical locations are unique, such as the juxtaposition of the Arabian Sea, the Bay of Bengal, and the Indian Ocean. Moreover, the Himalayan ranges spread across Pakistan and India, which function as a wall, dividing the climate of India and the South Asian region. The recent climate research unit (CRU) datasets, such as rainfall, temperature maximum and minimum (Tmax and Tmin), climatology, variability, and trends for annual, seasonal, and monthly scales, were analysed during 1951–2020. Regarding spatial and inter-annual variability, India has witnessed decreasing trends in annual rainfall during the last seven decades. However, rising rainfall also reveals in the pre-monsoon and post-monsoon seasons rather than the monsoon season. Subsequently, Tmax and Tmin have shown a significantly increasing trend above ~0.12 ^{o}C per decade annually and in seasonal time scales. A salient feature of this report is the introductory results based on CRU datasets. The climate information on extreme events can be improved using high-resolution daily multiple datasets, such as Indian Monsoon Data Assimilation and Analysis (IMDAA).

1. Introduction

India is the seventh largest country in the world, and the second most populous, home to over 1.36 billion people. Approximately 43% of the population is dependent on agriculture as their main employment source. However, its contribution to gross domestic product (GDP) is declining, with the agriculture sector constituting 16% in 2019, as reported by the World Bank (https://climateknowledgeportal.worldbank.org/). The regional climate over the Indian subcontinent involves complex atmosphere-ocean–land–cryosphere system interactions on different space and time scales. The distinct topographical and geographical features of the Indian subcontinent endow the region with widely varying climatic zones ranging from the arid Thar desert in the north-west, Himalayan tundra in the north, humid areas in the southwest, central and northeastern parts, together with diverse microclimatic areas that spread across the vast subcontinent *(Krishnan et al 2020)*.

A dominant feature of the regional climate is the Indian Summer Monsoon (ISM), which is characterized by pronounced seasonal migrations of the tropical rain belts associated with the Inter-Tropical Convergence Zone (ITCZ), along with large-scale seasonal wind reversals *(Gadgil 2003)*. The Himalayas and the Hindu Kush mountains protect the Indian subcontinent from large-scale incursions of cold extra-tropical winds during winter. Additionally, the seasonal warming of the Himalayas and the Tibetan Plateau during the boreal summer set up a north-south thermal contrast relative to the tropical Indian Ocean, which is important for initiating large-scale summer monsoon circulation.

India is situated between 66^{o} E to 98^{o} E and 8^{o} N to 38^{o} N and experiences a range of physio-geographic features spread widely over its 28 States and 8 Union Territories. These are mainly classified into (i) mountainous terrain [Himalayan range, Western Ghats, and Eastern Ghats], (ii) northern plains, (iii) peninsular plateau, (iv) deserts, (v) coastal plains [east and west coast] and (vi) island groups [Andaman & Nicobar, Lakshadweep]. India extends out into the Indian Ocean and is surrounded by the Arabian Sea (AS) on the west and the Bay of Bengal (BoB) on the east. India is gifted with a variety of climatic conditions due to its distinct geography. The Himalayas act as a barrier to the frosty katabatic winds flowing down from Central Asia, keeping the bulk of the Indian subcontinent warmer than most locations at similar latitudes.

1.1 Topography of India

Fig. 1 shows the digital elevation of the study area produced from the NOAA 0.25° x 0.25° resolution dataset. The study area is undulating, with the lowest and highest elevations ranging from 25 m to 6000 m above mean sea level (MSL). Generally, the Himalayan range starts from Pakistan, India, Nepal, and Bhutan, and their elevations are more than 4000m above MSL. However, the Indo-Gangetic plains, nearly about 3000 km long, have an elevation < 50 m above MSL. The Western and Eastern Ghats elevation > 1000 m above MSL, whereas Northeast with isolated hills Kangchenjunga at 90° E. The study by *Queney (1948)* summarized that when airflows through the various mountains, they generate and control the kelvin, gravity, and Rossby waves with different spatial scales.

1.2 Overview of climatic features of India

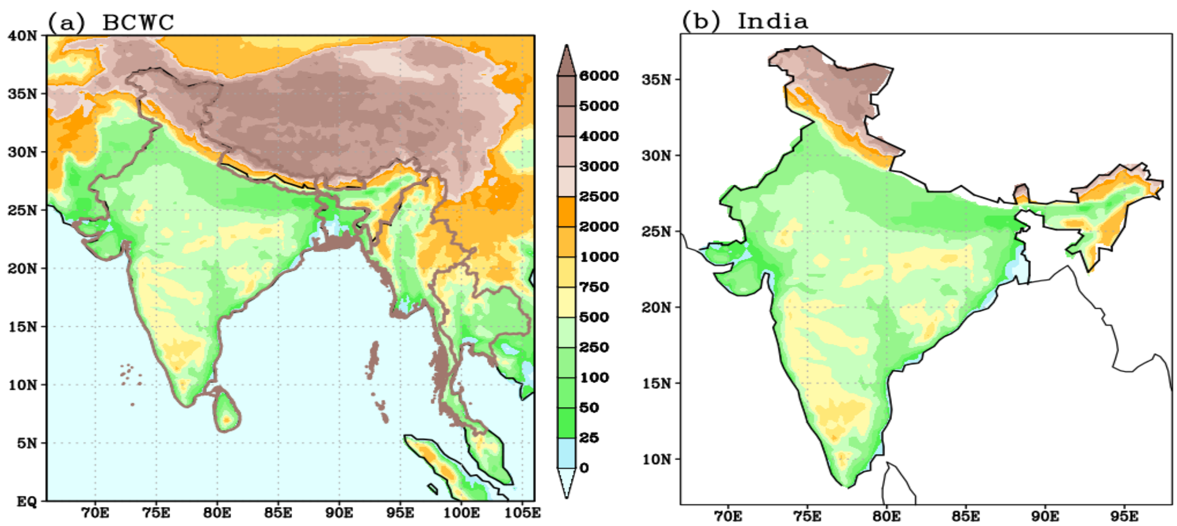

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Fig.1 Topography above MSL of (a) BCWC countries and (b) India (m) derived from NOAA at 0.25-degree resolutions.

As per IMD criteria, the calendar year is divided in four seasons. The climatological seasons in India are broadly classified as the winter (January–February), pre-monsoon (March–April–May), summer monsoon (June–July–August–September) and the post-monsoon (October–November-December) seasons respectively. The climate condition of Indian region is precisely dominated by the climate conditions of both summer and winter monsoon.

During the winter season, North West (NW) India, especially Jammu & Kashmir and Punjab, receives significant rainfall due to western disturbances. Also, the southeast peninsula receives rainfall, mainly due to easterly waves. Cold wave conditions manifest in various parts of the country, especially the northern and central regions. Also, widespread fog occurs over major parts of the country. Western disturbances often regulate the activity of these mesoscale systems during the winter season (JF) over northern India.

In pre-monsoon (MAM), the important synoptic scale system that causes damage during this season is the tropical cyclones, which, in most cases, originate in the latitude belt of 10ºN to 15ºN over the oceanic regions and often re-curve towards India, Bangladesh, Myanmar coast. Also, heat wave conditions develop over major parts of the country during the mid-season, which often persist until the monsoon advances over the Indian region. The rainfall during the pre-monsoon season is essentially due to the mesoscale systems like local convection, thunderstorms, hailstorms, etc. Also, dust storms mostly occur over NW India.

India receives the major part of its annual rainfall during the southwest monsoon (JJAS) season. The main components of the southwest monsoon over India are Mascarene high, Somali low-level jet, Heat low, Tibetan anticyclone, and Tropical easterly jet *(Rao 1976)*. The location and intensity of these components govern the strength and spatial distribution of rainfall over India. Also, the semi-permanent feature of the southwest monsoon, viz. monsoon trough with embedded vortices, controls the rainfall activity *(Krishnamurty 1976)*. The major weather systems contributing to the rainfall during the season are monsoon lows & depressions, off-shore troughs and vortices, and mid-tropospheric cyclonic circulations *(Rao 1976)*.

During the post-monsoon season (OND), cyclonic storms, forming over the Bay of Bengal as well as over the Arabian Sea, that move inland, and the easterly waves that pass westwards across the peninsula are the important rain-producing systems. In the earlier part of October, the storms originate in the latitude belt to the north of 15 º N, travel north or northeastwards, and cause widespread and heavy rainfall in West Bengal and Assam. Later during the season, they mostly form in the latitude belt 10º N to 15º N and strike Tamil Nadu and Andhra Pradesh coasts and produce heavy rainfall along their tracks. Tamil Nadu also receives rainfall during this season due to cyclonic wind shear in northeasterly winds *(Rajeevan et al. 2023)*. Severe weather an event (heat/cold waves, heavy rainfall episodes, flash floods, and cloud bursts) often occurs and have devastating impacts on “local/regional” populations and their normal businesses. Understandably, they are different in different geophysical environments *(Ashrit et al., 2023).*

The most important definitions of meteorological parameters, such as precipitation and maximum and minimum temperature (Tmax and Tmin), are discussed below. With an increasing population in the nation *(Mishra et al. 2017)*, these increased characteristics of heatwaves will have a huge impact both in terms of social and economic aspects *(Sharma et al. 2020)*. Thus, for appropriate adaptation strategies, the policy-makers and information about the vulnerability hot spots would need a reliable understanding and prediction of the Tmax and Tmin. However, information regarding the causation of such extreme events and changes in behavior toward global warming plays an important role *(Bellprat et al. 2019)*. These parameters have the potential to change the weather and climatic patterns over the globe. The odds of extreme weather and climate events are changed on the basis of precipitation or temperature *(Rohli and Vega, 2018)*. Currently, the devastating evidence that human activity impacts extreme heat and rain. This climatic analysis may play a key role in establishing public awareness of climate change in India.

(a) Precipitation: Precipitation is expressed as the depth of rain or snow to which it would cover a horizontal projection of the earth’s surface if there were no loss by evaporation, run– or infiltration and if any part of the precipitation falling as snow or ice were melted.

(b) Maximum Temperature**:** The highest temperature reached since the last setting of the maximum thermometer. The maximum thermometer is routinely set after the afternoon 12 UTC, which is referred to as Tmax observations.

(c) Minimum Temperature**:** The lowest temperature reached, since the time of last setting of the minimum thermometer. The minimum thermometer is routinely set after the morning 03 UTC considered as Tmin observations.

1.3. Motivation of this study

As a member country of the Bay of Bengal Initiative for Multi-Sectorial Technical and Economic Cooperation (BIMSTEC), India plays an important role in the collaborative efforts towards weather climate data products and capacity building. The BIMSTEC Centre for Weather and Climate (BCWC) has been instrumental in exploring and understanding the climatic conditions within member countries such as Nepal, Bhutan, Bangladesh, Myanmar, Srilanka, and

Thailand including India. The BCWC has the directive to study and analyze the climatic conditions in the BIMSTEC countries.

This involves monitoring and understanding meteorological patterns, extreme weather events, and their potential impact on various sectors such as transport, agriculture, industries, water resources, and disaster management. This research report aims to examine India's climatic features, which serve multiple purposes. Firstly, India is the second most populated country, and food, shelter, and sustainability depend on climate conditions. Therefore, to meet the demand in the aforementioned sectors, knowledge of the past and present climatic conditions in India is essential. The climatology, standard deviation, and trends (annual, season, and monthly) of precipitation, Tmax, and Tmin information are crucial for climate resilience *(Rohli and Vega, 2018)*. Also, it can provide insights into the challenges and opportunities arising from the climatic conditions in India; basic information is necessary for policymakers to take climate action plans in different government and non-government organizations and agencies within the country and BCWC region.

This document investigates detailed regional climate information over India, focusing on precipitation (mm), Tmax, and Tmin (^{o}C). The investigation into the climatic features of India's previously mentioned parameters under the assessment of the BCWC is a critical initiative. It supports the collaborative spirit of BIMSTEC, aiming to enhance regional resilience, sustainable development, and effective climate adaptation policies.

2. Data and Methodology

Climate Research Unit (CRU) time-series TS version of 4.07 (CRU TS v. 4.07), the current version of, using a revised interpolation function and superseding v4.06, v4.06.01 and v3.26. A gridded time-series dataset covers the period 1901-2023, and was released on 19 April 2023. The datasets cover all land areas (excluding Antarctica) at 0.5°-degree resolution. The available variables are precipitation, mean temperature, maximum temperature (Tmax), minimum temperature (Tmin), diurnal temperature, vapor pressure, cloud cover, wet, frost day frequency, and potential evapotranspiration respectively. The datasets are available for the period of 1901-2023, and details are discussed at https://crudata.uea.ac.uk/cru/data/hrg/index.htm#current. The particulars of the CRU datasets are documented in *Hariss et al. (2020).*

For the present study, the regional climate information over India using three important parameters such as monthly precipitation, maximum and minimum temperature (Tmax and Tmin) at 0.5 x 0.5-degree resolutions for the period of 70 years (1951–2020) are considered. The mean, standard deviation (SD) of rainfall, Tmax, and Tmin calculated for the annual, seasonal such as winter (JF), pre-monsoon (MAM), monsoon (JJAS), and post-monsoon (OND) periods followed by the Indian Meteorological Department (IMD) criteria. However, the monthly mean and SD for the aforementioned period are also analyzed and discussed. To understand the statistically monotonic upward or downward trend of rainfall, the Tmax and Tmin Mann-Kendall (MK) tests have been considered for annual, seasons, and monthly scales over the Indian region.

3. Result and discussion

3.1 Rainfall pattern over India during 1951-2020

The study of inter-annual variability of precipitation (hereafter rainfall) is essential for India as it manifests extreme events and excess/deficient rainfall that have caused drought and floods; it has significant impacts on the socio-economy of the country. The rainfall pattern in India is predominantly due to summer and winter monsoon systems *(Pant and Rupa Kumar, 1997; Yadav et al., 2012)*. The rainfall patterns, such as annual, winter, pre-monsoon, monsoon, and post-monsoon seasons, are discussed in Table 1. Moreover, the fluctuations of rainfall on a monthly scale were also deliberated.

3.1.1 Annual

The long-term mean annual climatology of rainfall in (mm) from 1951 to 2020 is presented in Fig. 2. The annual cycle of rainfall during the study period shows that rainfall is maximum over the Northeast and west coasts of the Indian region. Second maximum rainfall has been noticed over the east coast of India, Indo-Gangetic planes, part of Odisha, Chhattisgarh, West Bengal, Madhya Pradesh, and Bihar states, as shown in Fig. 2 (a). Fig. 2 (b) represents the annual SD in mm over India, where the maximum SD of rainfall is 140 mm over the west coast and northeast of the Indian region. The SD of rainfall has shown over the JK, Rajasthan, Punjab, and part of Tamil Nadu and Karnataka states lower than other parts of the country. The annual rainfall trends per decade depicted in Fig. 1 (c), shown positive and negative trends over the country as a whole. The negative trends shown in Indo-Gangetic plane and that extend towards northeast

Indian region. A notable negative trend was also noticed along the west coast of India, particularly the Karnataka coast. The remaining parts of India show positive trends of ~4 mm per decade. The time series shows the annual rainfall during seven decades (1951-2020) in Fig. 3. The trend had shown negative trends as a whole -0.1423 mm per decade which is not statistically significant. Similar results are agreeing with *Krishnan et al. (2020)*.

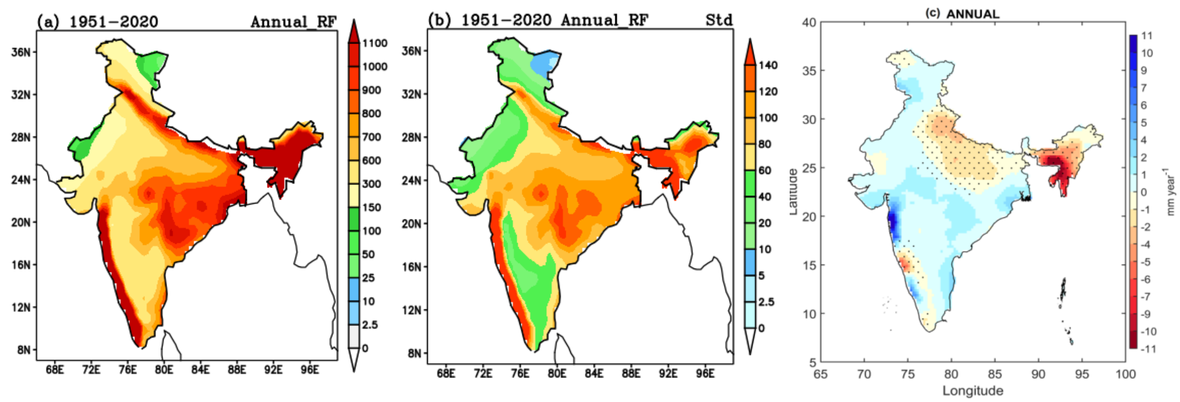

Fig. 2 Spatial distribution of annual rainfall (mm) over India (a) mean, (b) stand deviation, and (c) trends (mm/decades) during the period of 1951-2020 derived from CRU data at 0.5-degree resolution (grid boxes hatched where trends are significant 95% confidence).

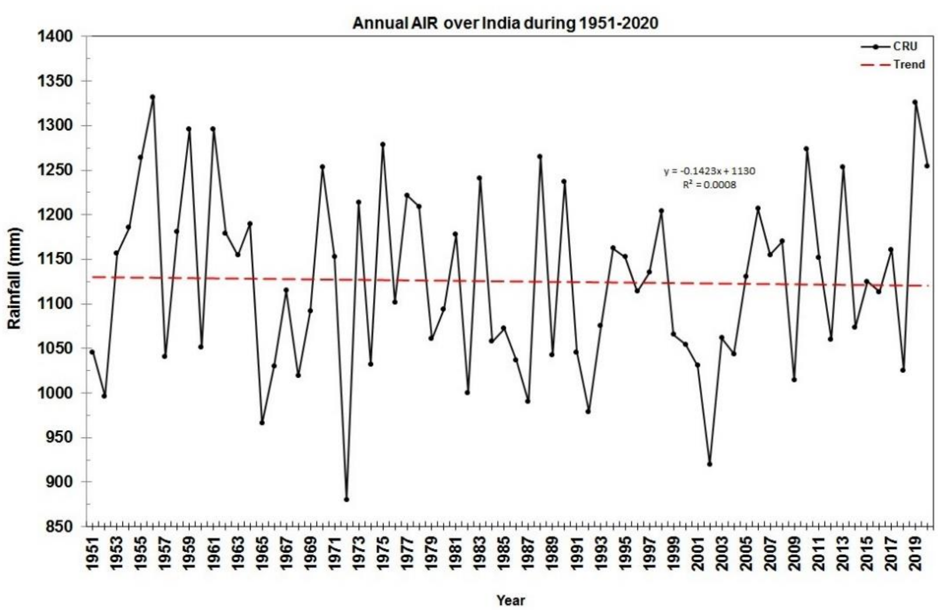

Fig. 3 The inter-annual variability of annual rainfall (mm) over India during 1951-2020 (red-line shows trends at the rate in mm/year).

3.2 Seasonal rainfall

(a) Winter (JF)

The mean and SD of rainfall (mm) during the winter season (JF) over India from 1951 to 2020 from CRU observation are shown in Fig. 4 (a-b). It is noted that, in general, all datasets show high rainfall zone over rainfall zones over northeast India, northern parts of Kashmir, and the rain shadow area of southeast India (Fig. 4a). However, low rainfall of less than 10 mm has shown over the northwest zone and peninsular India (PI) in Fig. 4 (a). The inconsistency in observations occurs mainly in northern parts of India. The maximum SD rainfall is represented over Jammu and Kashmir and adjoining regions, as depicted in Fig. 4 (b). During winter, parts of Odisha, west Bengal, and Bihar also showed significant amounts of rainfall. In addition, Tamil Nadu also showed above 15 mm SD of rainfall, as shown in Fig. 4 (b). The spatial distribution of rainfall trend during seven decades showed positive trends over Rajasthan, Gujarat, Odisha, and adjoin Chhattisgarh states (Fig. 5a). The time-series of long-term linear trend averaged over Indian landmass does not show any trend over the period 1951–2020 presented in Fig. 6(a).

(b) Pre-monsoon (MAM)

Fig. 4 (c-d) shows the rainfall pattern during pre-monsoon season (MAM). The pre-monsoon seasonal mean rainfall had shown a significant amount of > 100 mm along the entire east coast belt of India, PI, and part of Jammu and Kashmir. The maximum season has been noticed over northeast India (Fig. 4c). The SD of rainfall maximum has shown over part of northeast India and the Kerala coast (Fig. 4 d). The spatial distribution of rainfall trends during 1951-2020 showed slightly positive trends over Odisha, West Bengal, and Jammu region. The PI has shown a significantly negative trend of -3 mm per decade (Fig. 5 b). The time-series analysis of the linear trend from 1951 to 2020 showed a positive trend of 0.005 mm, which is not very statistically significant (Fig. 6 b).

(c) Monsoon (JJAS)

Figs. 4 (e-f) show 70 year’s average of spatial rainfall received during the monsoon (JJAS) season, SD and trends (mm) respectively. Most parts of northeast India, central India, north India, received more than 400 mm of rainfall per season. Parts of Arunachal Pradesh, Assam & Meghalaya, Sikkim, the entire west coast, received more than 850 mm of rainfall per season. However, Assam & Meghalaya and the west coast of India received maximum rainfall as compared to other parts of India.

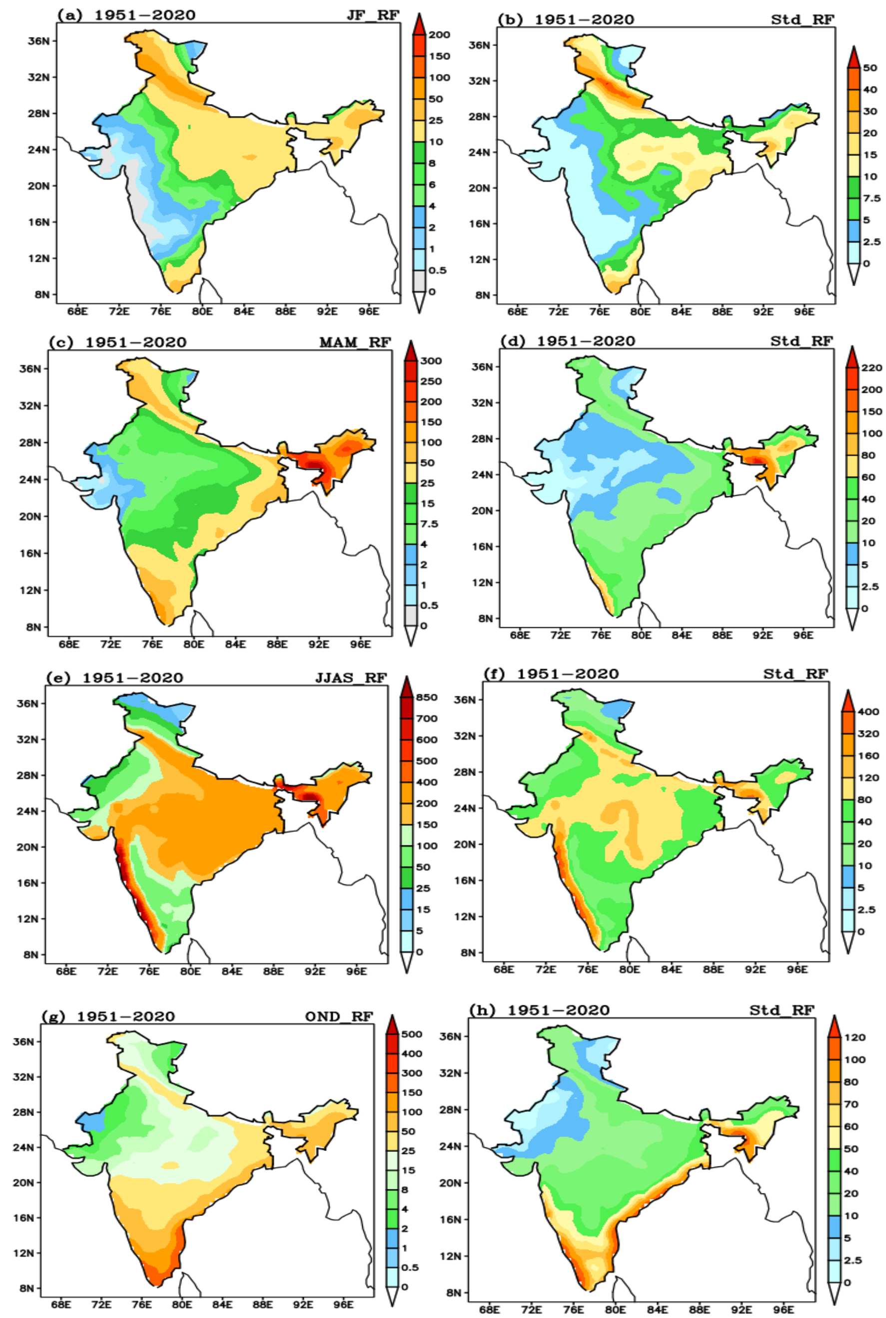

Fig. 4 Spatial distribution of seasonal mean rainfall (mm) for (left panel) (a) winter (January-February, JF), (c) pre-monsoon (March-May, MAM), (e) monsoon (June-September, JJAS), and (g) post-monsoon (October-December, OND) seasons during the period 1951-2020; Fig (b, d, f and h) same as (a, c, e and g), but for the standard deviation (mm) derived from CRU dataset at 0.5 degree resolutions.

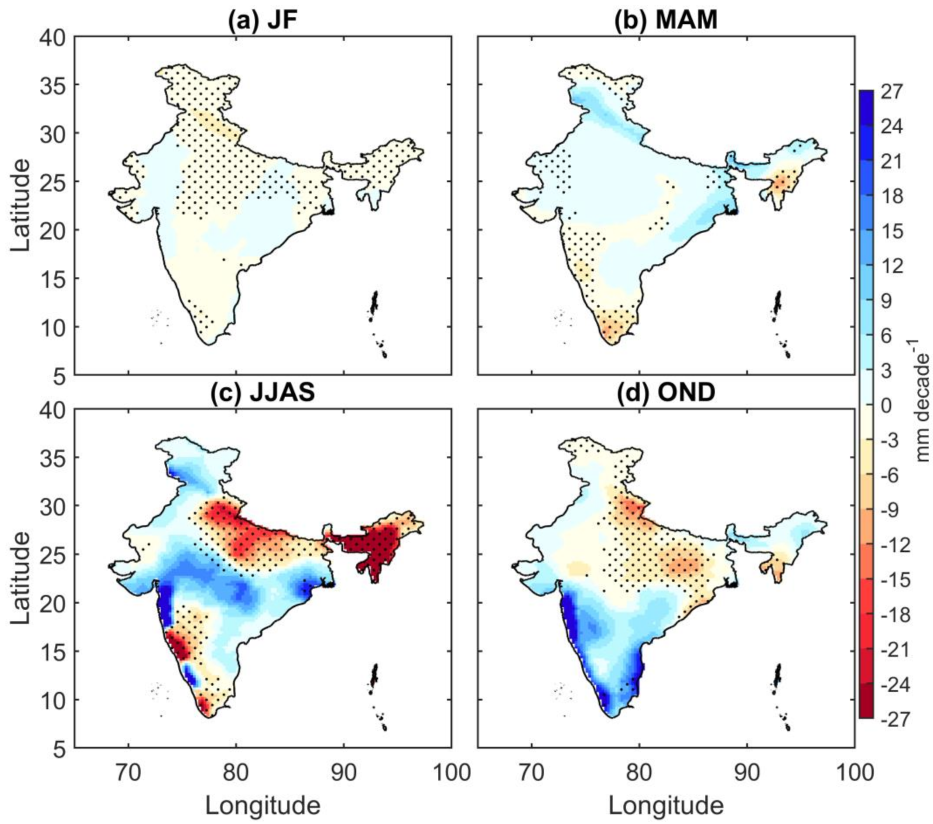

Fig. 5 Same as Fig. (3), but for seasonal trends in mm per decades (a) winter (JF), (b) pre-monsoon (MAM), (c) monsoon (JJAS), and (d) post-monsoon (OND) during the period of 1951-2020 derived from CRU data at 0.5-degree resolution (grid boxes hatched where the trend is significant 95% confidence).

SD of rainfall, more than 400 mm per season was observed along the west coast and northeast India. Apart from that, the second maximum SD of rainfall of 160 mm per season was observed monsoon zone and Telangana except in Tamil Nadu state (Fig. 4f). The magnitude of positive rainfall trends of 9 mm per decade was noticed over most of the homogeneous region except Indo-Gangetic Plains the negative trends has noticed northeast India and part of west coast region, which is 95% statistically significant has presented in Fig. 4 (d). The Fig. 5 (c) depicts the area-weighted average rainfall (mm), and its long-term trend over the country as a whole shows slightly negative trends of 0.002 mm per season. However, the positive trends more prominent during 1951-1989, whereas a negative trends appeared in between 1990 to 2009. Thus, the negative trends have shown during 1951-2020 as depicted in Fig. 6 (c).

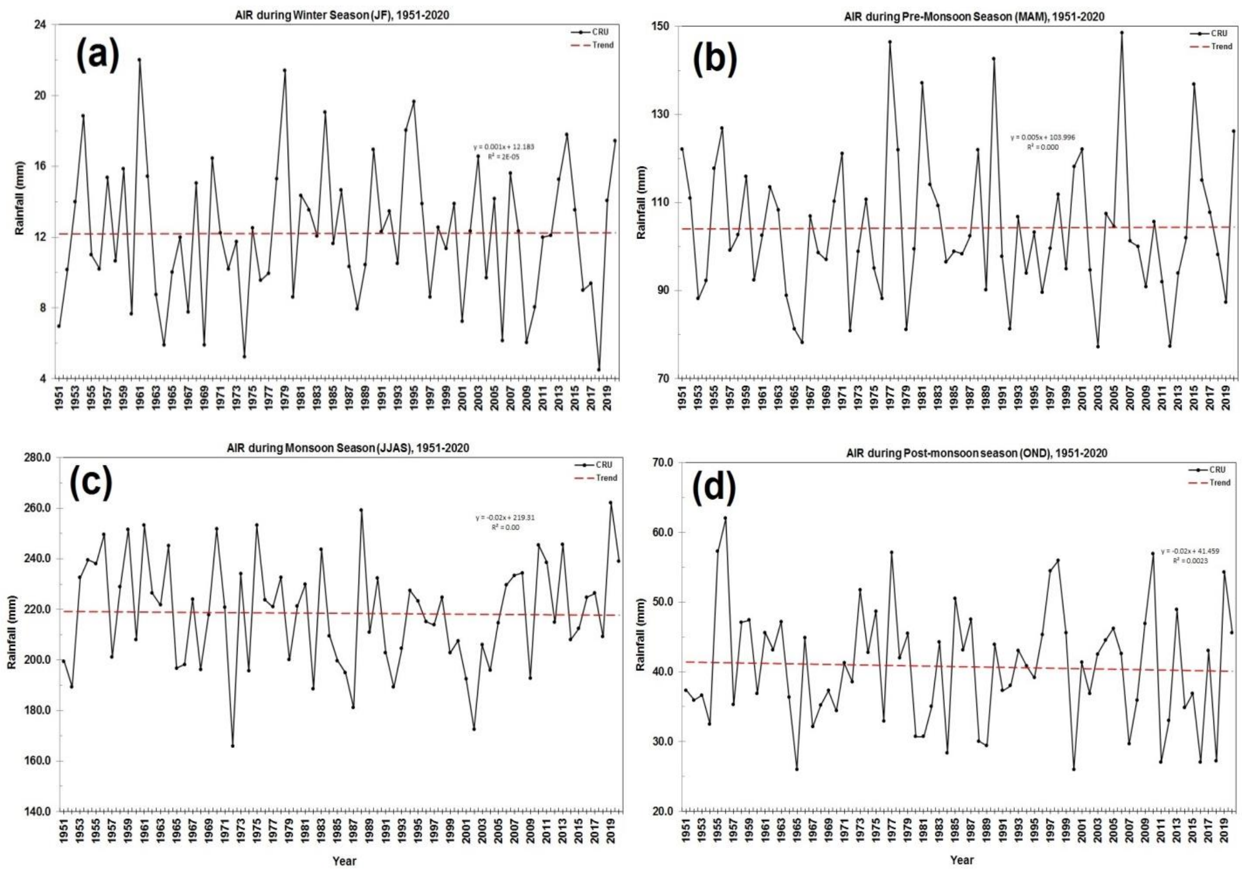

Fig. 6 The intra-annual variability of seasonal rainfall (mm) over India during 1951-2020 (a) winter (JF), (b) pre-monsoon (MAM), (c) monsoon (JJAS) and (d) post-monsoon (OND). The red-line shows trends in mm/year.

(d) Post-monsoon (OND)

The rainfall (mm) climatology and SD for the post-monsoon season (OND) for the period 1951-2020 is presented in Fig. 4 (g-h). It shows the peninsular India (PI) experiences the highest (>50 mm) amount of rainfall. Moreover, both the east and west-coast regions of PI experience reasonable amounts of rainfall as compared to the remaining part of India. Northeast India receives a very good amount of rainfall, whereas the northernmost subdivisions (Jammu and Kashmir, Himachal Pradesh Uttarakhand, Bihar, and Jharkhand) experienced < 25mm rainfall (Fig. 4 g). The remaining subdivisions, such as Gujarat, Rajasthan, and Haryana, experience less than 8mm of rainfall (Fig. 4 g). The Fig. 4 (h) is same as Fig. 4(g), but for standard deviation (SD) of rainfall. Major subdivisions of the PI show maximum SD as compared to the central and northern parts of India. However, lower SD has been shown over the Gujarat, Rajasthan, and adjoining regions (Fig. 3h). The horizontal distribution of rainfall trend per decade shown in Fig. 5 (d), a major area of PI has positive trends whereas weak negative trend depicted over Indo-Gangetic planes. The negative trends exist in Odisha, Chhattisgarh, Madhya Pradesh, and Uttar Pradesh regions. In addition, the positive trends are more pronounced over West Bengal and extreme northeastern parts of India (Fig. 5d). The time series shown the rainfall average over India and its trend during the post-monsoon season of (1951-2020) significantly shows (Fig. 6d) a negative trend as the value -0.021 mm/season, the value is not statically significant. The statistical details of AIR (mean, SD, and trends) during annual and four different seasons are illustrated in Table 1.

Table 1. All-India-Rainfall (AIR) details in statically during annual and seasonal in (mm) derived from CRU data

Parameter AIR (mm)	**Annual**	**Winter (JF)**	**Pre-monsoon (MAM)**	**Monsoon (JJAS)**	**Post-monsoon (OND)**
Mean	1128.6	12.34	104.3	219.1	41.1
Standard deviation	102.4	6.02	16.1	21.47	8.73
Trends /decade	-1.423	0.01	0.05	-0.2	-0.2

3.3 Monthly Rainfall

The spatial distributions of monthly rainfall average and SD during 1951-2020 are shown in Fig. (7) and Fig. (8). The lower amount of rainfall was observed from January to April, but some higher amounts of rainfall were noticed in April and May over northeast India and Kerala region Fig. 7 (d-e). Substantial enhancement rainfall was noticed in the month of June, and a very good amount of rainfall was recorded along the west coast and northeast India.

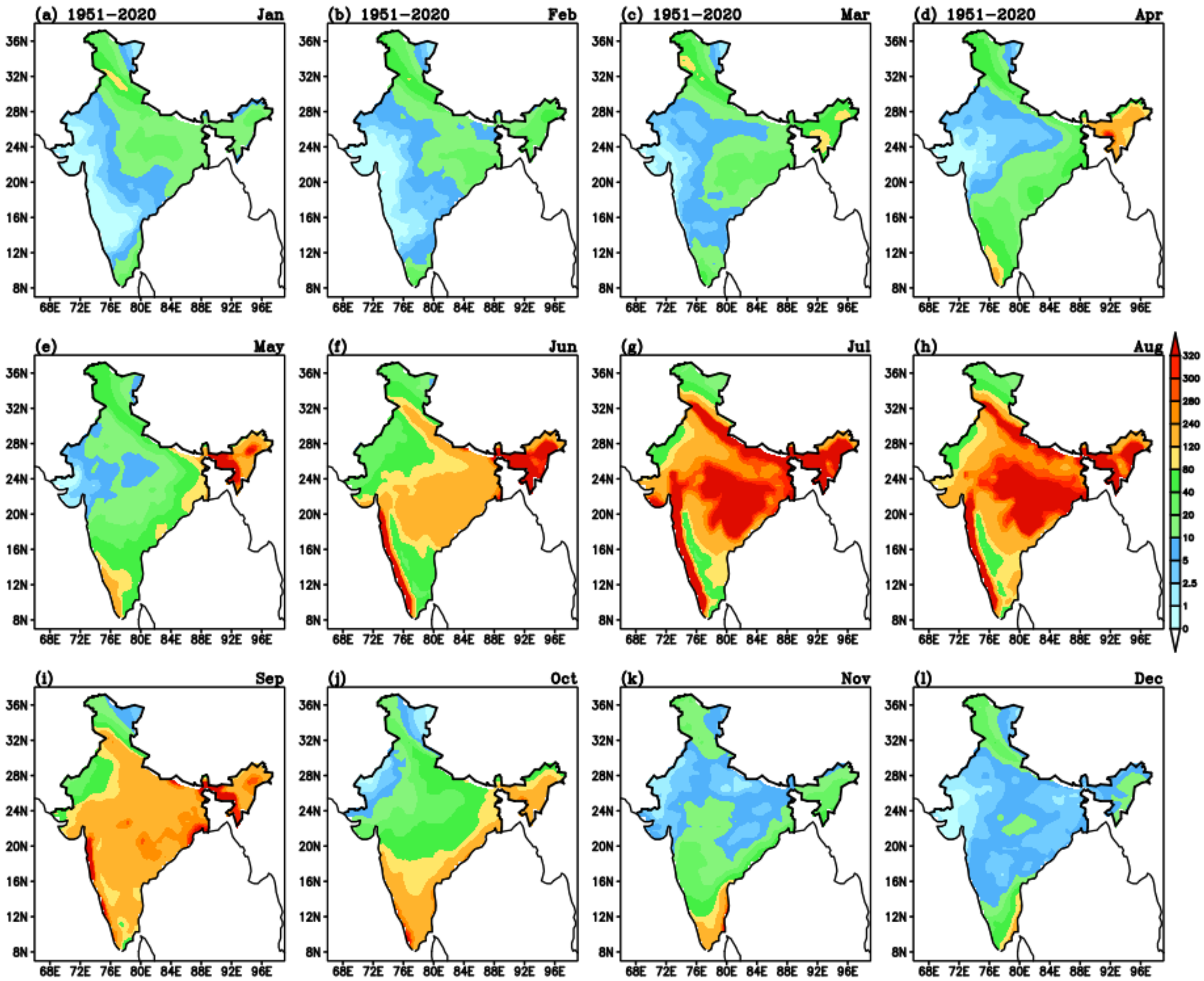

Fig. 7 Spatial distribution of monthly rainfall (mm) mean for (a-d) January to April (top) panel, (e-h) May-August (middle panel), (i-l) September-December (bottom panel) during 1951-2020 derived from CRU data at 0.5-degree resolutions.

Due to the progress of the southwest monsoon, the entire country received 220 mm of rainfall in June except for part of Gujarat, Rajasthan, Haryana, Jammu, and Kashmir states (Fig. 7f). Fig. 7 (f) and (g) shows the maximum rainfall has noticed during July and August over monsoon zone, Indo-Gangetic Plane, west coast and northeast India. The entire country received a very good amount of rainfall, and a maximum of 220 mm was recorded along the west coast and central India. The rainfalls are significantly associated with the monsoon rain-bearing systems during the southwest monsoon season. In the month of September, rainfall was similar to August but slightly reduced in intensity, as depicted in Fig. 7. (h), due to the withdrawal phase of the monsoon. In October and November, rainfall intensity was confined over the PI as well as east-coast and northeast India, as shown in Fig. 7 (j) and (k). In December month, the intensity of rainfall significantly reduced as the ITCZ moved towards the south Indian Oceanic region, and thus, the rain band shifted along with ITCZ.

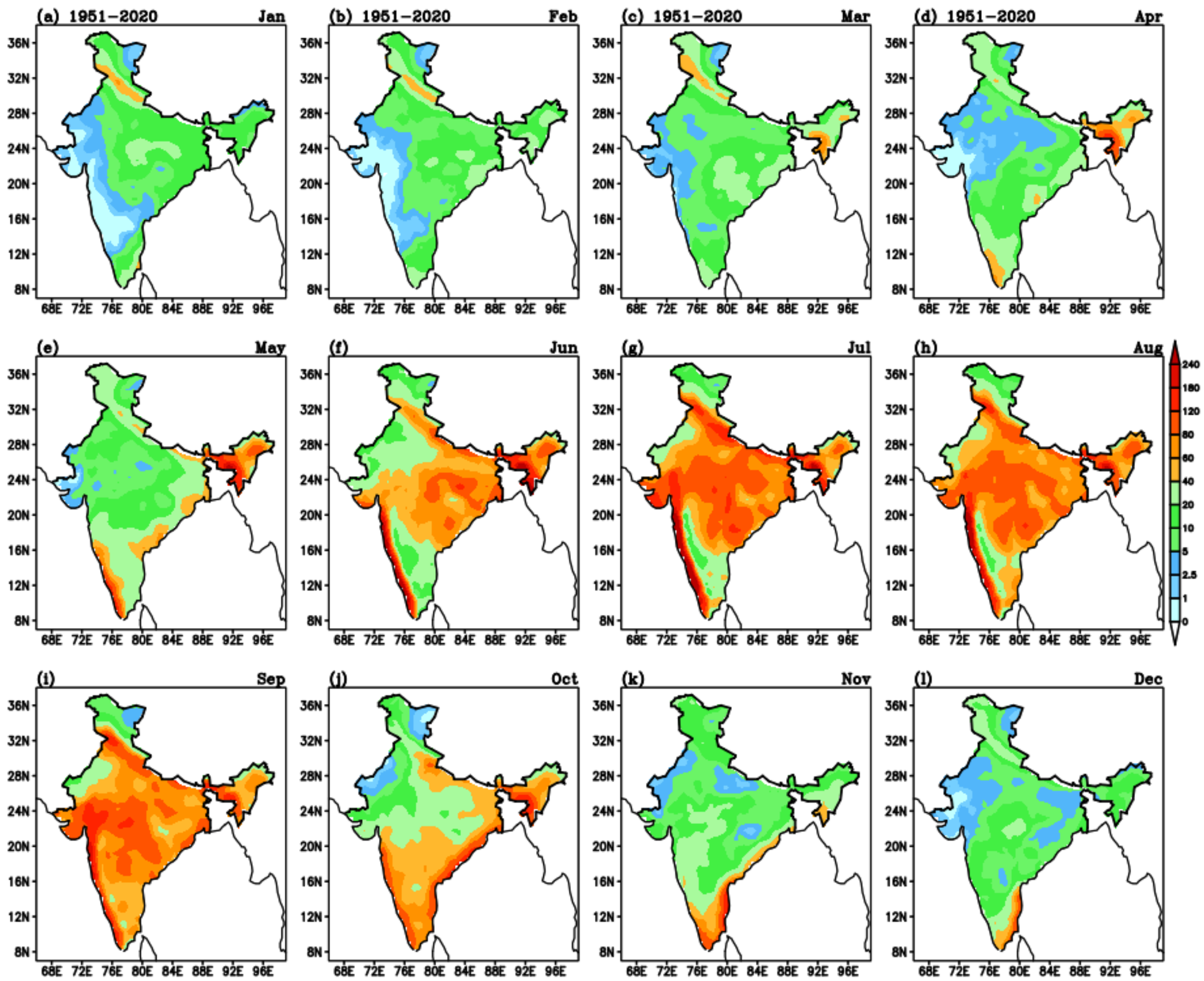

Fig. 8 Same as Fig. (7), but for standard deviation (mm) during the period of 1951-2020.

Consequently, Fig. 7 (a-l), and Fig. 8 (a-l) is the same as Fig. 7 (a-l), but for the SD rainfall during 1951-2020. The maximum SD of rainfall has noticed in June to September (Fig. f-i). However, second maximum of SD has noticed in October to November months as shown in Fig.

8 (j) and (k). The monthly trends of rainfall showed relative fluctuation from the different months, as presented in Fig. 9 (a-l). The maximum negative trends are revealed over the west coast and northeast India during the months of May to June, as shown in Fig. 9 (e) and (f). However, central India has shown a positive trend in central India in the month of June. During the months of July to October, very significant negative trends have been noticed over the Indo-Gangetic planes. However, the PI has shown moderately positive trends over the PI. The statistical details of monthly rainfall are shown in Table 2. The maximum SD of rainfall has been noticed in July and September month. Moreover, among the 12 months, only four months, such as February, April, September, and November month showed a positive trend, and other months showed a negative.

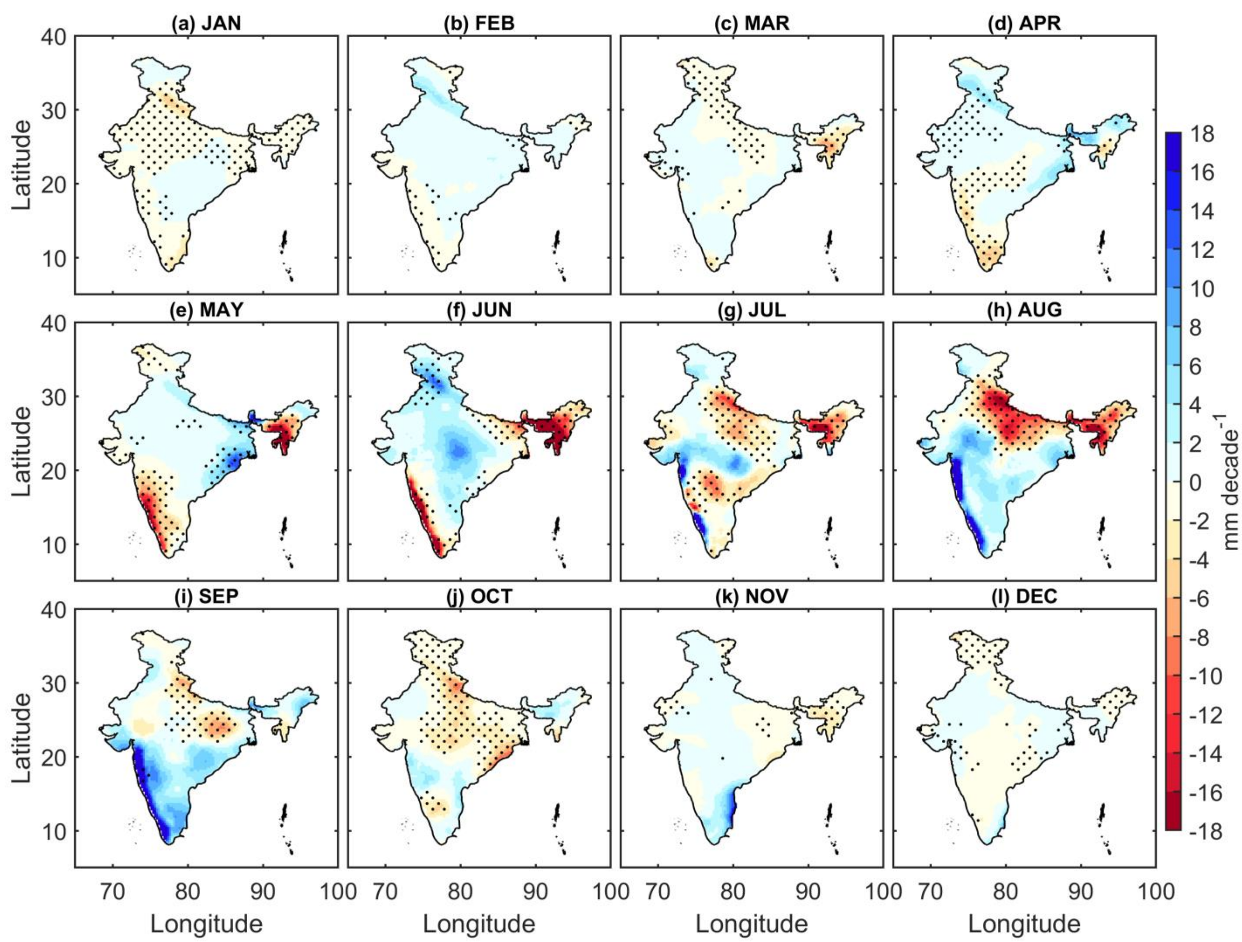

Fig. 9 Same as the Fig. (8), but for monthly trends in mm/decades during the period of 1951-2020 derived from CRU data at 0.5-degree resolution (grid boxes hatched where trend is significant 95% confidence).

Trends in Indian rainfall records have been extensively studied, but the subject remains complicated by the high spatiotemporal variability of rainfall arising from complex atmospheric dynamics *(Sanjay et al., 2020)*. The linear trend in annual and seasonal rainfall shows a statistically significant decreasing trend over southern Kerala and Indo-Gangetic plain, West Bengal, part of Utter Pradesh, Konkan, and Goa. Moreover, Madhya Maharashtra, Rayalaseema, Coastal AP, North Interior Karnataka, Jammu, and Kashmir reveal increasing trends. Similar results are found in previous studies by *Guhathakurta and Rajeevan (2008)*.

Table 2. Monthly mean, standard deviation, and rainfall (mm) trends from 1951-2020 derived from CRU data at 0.5-degree resolutions.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average	12.4	12.2	17.7	30.7	56.0	158.1	289.0	255.6	173.6	82.8	28.3	12.3
SD	5.7	6.0	7.0	7.2	11.7	29.0	37.1	30.1	36.5	24.5	14.5	6.8
Trends/ decades	-0.47	0.31	-0.03	0.47	-0.05	-0.96	-0.98	-1.45	1.90	-0.73	0.91	-0.24

4. Temperature (Tmax and Tmin) °C pattern over India during 1951-2020

Temperature is an essential meteorological parameter; the quantity of temperature directly affects human and natural ecosystems. The global mean surface temperature is a key indicator of climate change because it increases quasi-linearly with cumulative greenhouse gas emissions, as documented in multiple assessment reports of the Intergovernmental Panel on Climate Change (IPCC), including the most recent Fifth Assessment Report *(AR5; IPCC 2023)*. Global warming will continue to increase in the near term (2021–2040), mainly due to increased cumulative CO_2 emissions in nearly all considered scenarios and modeled pathways.

The surface air temperature, typically measured at 2 m above the ground, varies from one region to another within India. This temperature also fluctuates naturally in interannual and decadal time scales in the background of human-induced changes in the climate. The section discussed the temperature (Tmax and Tmin) distribution in annual, seasonal, and monthly scales.

4.1 Tmax

4.1.1 Annual Tmax

Fig. 10 shows the spatial distribution of annual mean, SD, and trends for the Tmax during 1951-2020 in Fig 10 (a-c). The annual mean temperature over India has shown a maximum of 35 ^{o}C over Gujarat, Rajasthan, Telangana, and part of Utter Pradesh in Fig. 10 (a). The maximum SD has been recorded over the northern part of India, particularly the Jammu and Kashmir regions (Fig. 10b). There is an increased rate of warming of ~ 0.22 °C per decade for the annual mean, maximum 1951-2020, as shown in Fig. 10 (c). The time series of seven decades of Tmax over the land mass of the Indian region showed an increased trend of 0.001 °C per year, as presented in Fig. (11).

4.1.2 Seasonal Tmax

(a) Winter (JF)

The seasonal (winter, pre-monsoon, monsoon, and post-monsoon) Tmax is shown in Fig 12 (a-h). The spatial of distributions Tmax shows that the warming is not uniform during the season. In winter, maximum warming is shown over the PI compared to the northern part of India, as shown in Fig 12 (a). Fig. 12 (b) is the same as Fig. 12 (a), which shows the SD of Tamx in winter. The SD of Tmax value ~2 ^{o}C has been recorded and is reasonably uniform throughout the country. However, trends were shown positively in the entire country except for West Bengal and Northeast India (Fig 13 a). The time series shows the long-term trends of Tmax from 1951 to 2020; a positive trend was recorded in the winter season Fig. (13a).

(b) Pre-monsoon (MAM)

The pre-monsoon season (MAM) Tmax mean, and SD is shown in Fig. 12 (c-d). In Fig. 12 (c), appearances are relatively warmer than in other seasons, as shown in Fig. 12. A maximum temperature of 40^{o} C has been recorded in central India and particularly Telangana state (Fig. 12c). The SD of Tmax represents the maximum over northern India as compared to the PI (Fig. 12 d). In pre-monsoon, the positive trends were recorded, and dots showed 95% significance over the PI, as depicted in Fig. 13 (b). The time series shows the linear trends over India as positive trends are noticed from 1951 to 2020 in Fig. 14 (b).

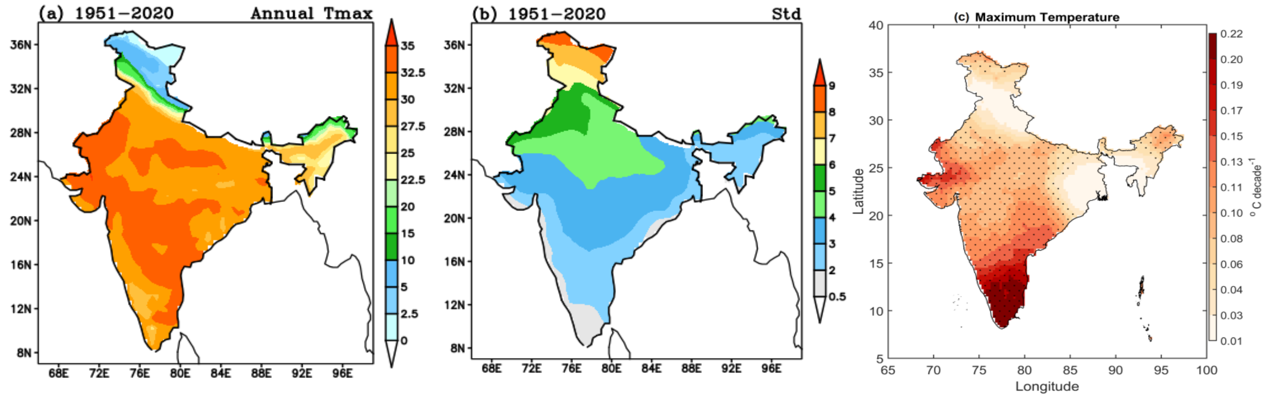

Fig. 10 Spatial distribution of annual maximum temperature (Tmax, ^{o}C) over India (a) mean, (b) stand deviation, and trends (^{o}C per decade) during the period of 1951-2020 derived from CRU data at 0.5-degree resolution (grid boxes are hatched where trend are significant 95% confidence).

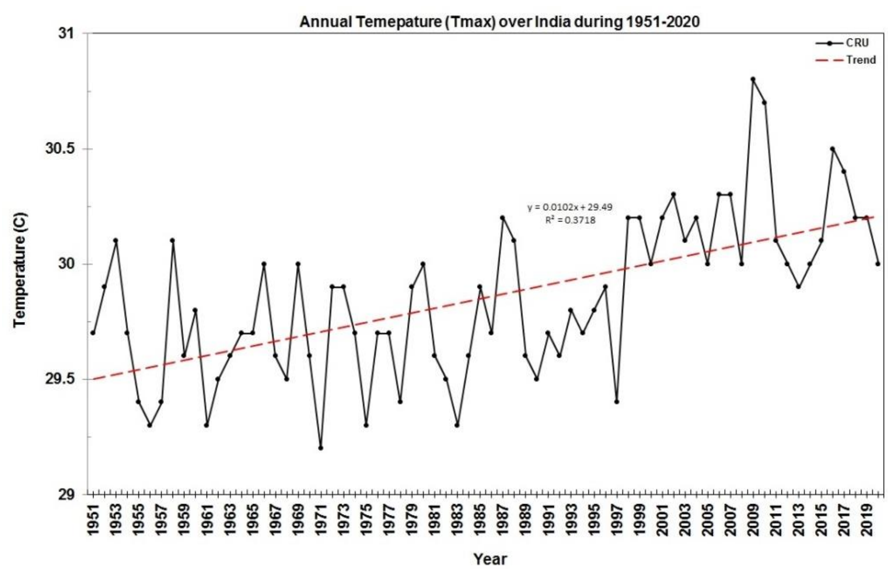

Fig. 11 The inter-annual variability of annual Tmax (**^{o}C**) over India during 1951-2020 (red-line shows trends at the rate in ^{o}C/year).

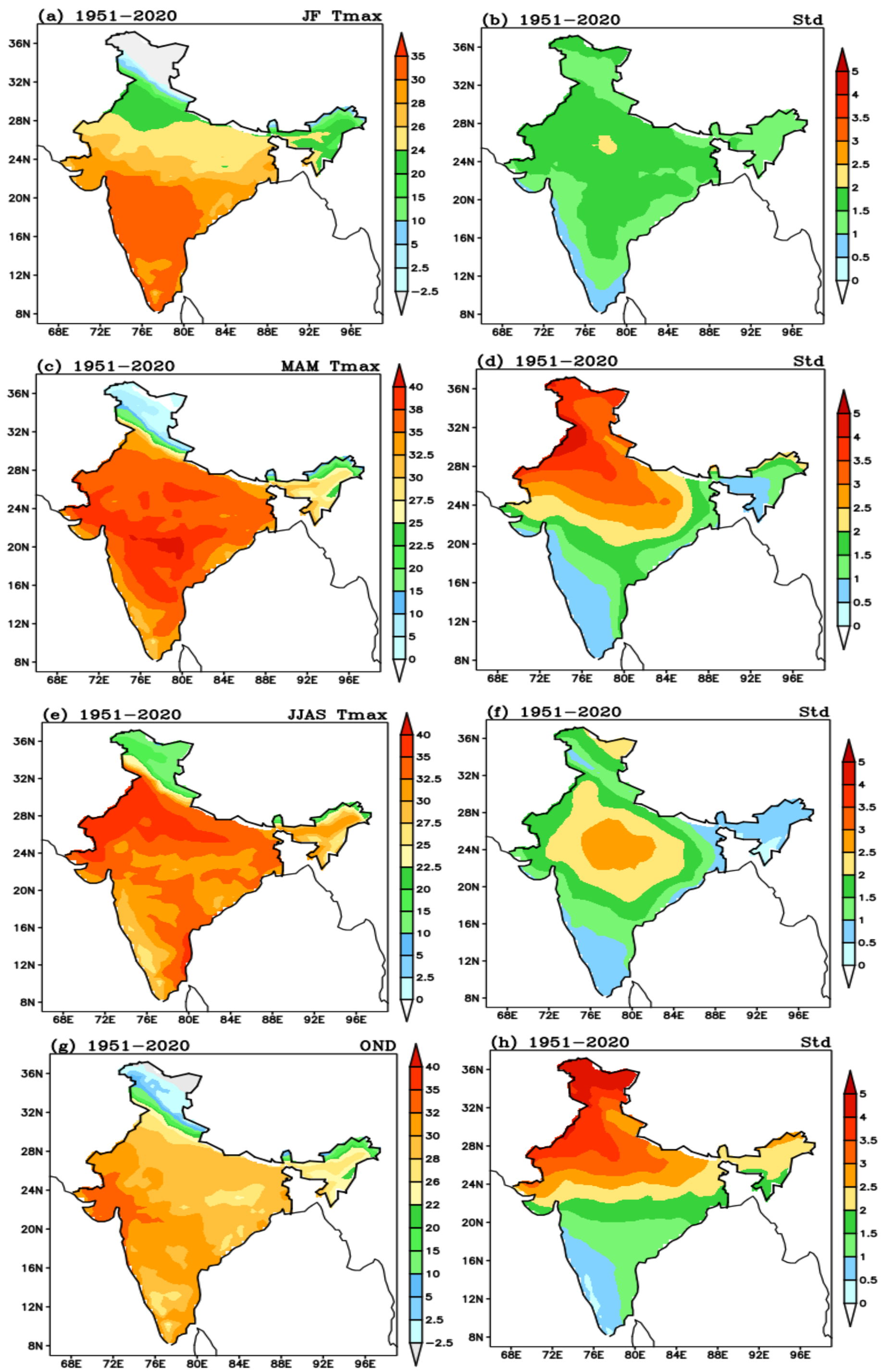

Fig. 12 Spatial distribution of seasonal mean Tmax (°C) for (left panel) (a) winter (January-February, JF), (c) pre-monsoon (March-May, MAM), (e) monsoon (June-September, JJAS), and (g) post-monsoon (October-December, OND) seasons during the period 1951-2020; Fig (b, d, f and h) same as (a, c, e and g), but for the standard deviation (°C) derived from CRU dataset at 0.5-degree resolutions.

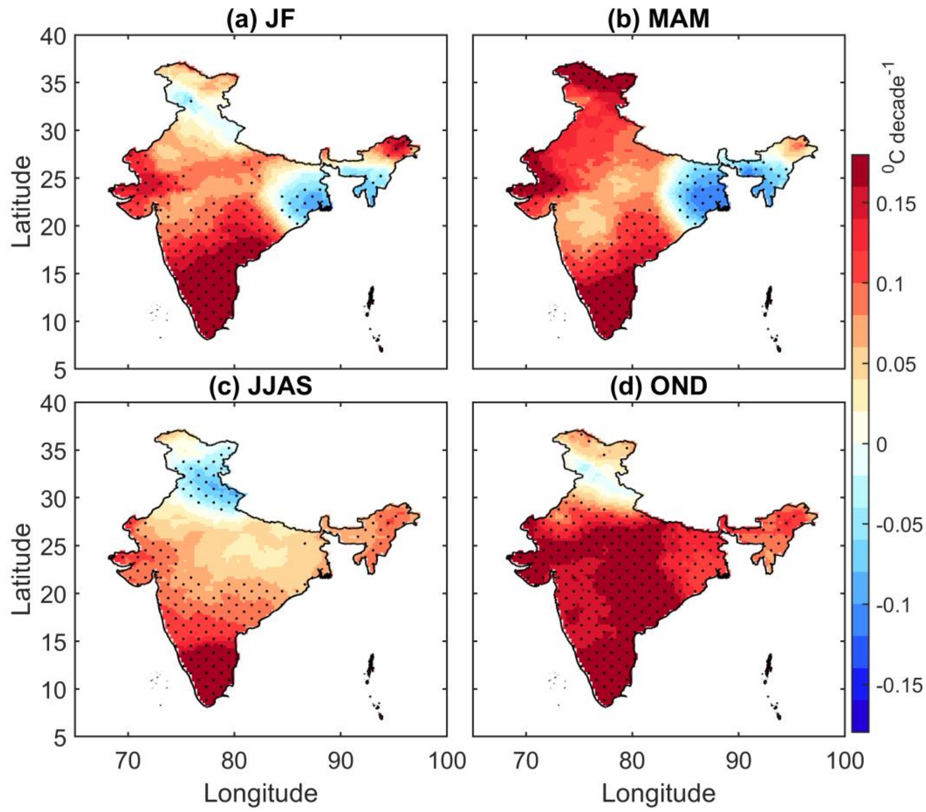

Fig. 13 Same as Fig. (12), but for seasonal trends in ^{o}C per decade (a) winter (JF), (b) pre-monsoon (MAM), (c) monsoon (JJAS), and (d) post-monsoon (OND) during the period of 1951-2020 derived from CRU data at 0.5-degree resolution (grid boxes are hatched where the trend is significant 95% confidence).

(c) Monsoon (JJAS)

The spatial distribution of Tmax mean and SD (^{o}C) during monsoon season is shown in Fig. 12 (e-f). Maximum Tmax has recorded (40 ^{o}C) in Indo-Gangetic planes and that extended towards part of Rajasthan and Gujarat region (Fig. 12e). However, the maximum SD of Tmax has been noticed over the monsoon zone, as depicted in Fig. (11f). The trends of Tmax during monsoon are shown in Fig. 12 (c), and the maximum positive trends are confined over the PI and Gujarat states. However, moderate positive trends were shown in the northern part of India, particularly the Indo-Gangetic plains, as shown in Fig. (13 c). The time-series analysis of Tmax trends during 1951-2020 showed positive trends in Fig. 14 (c).

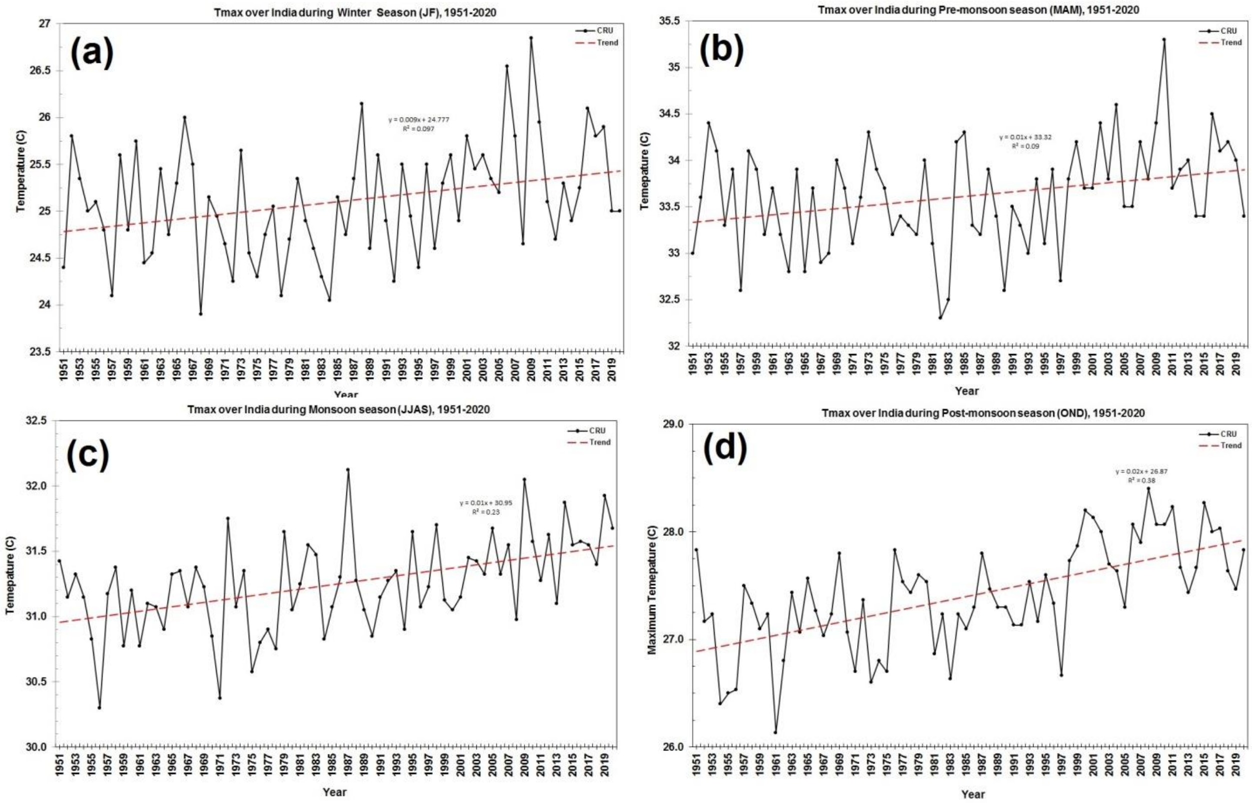

Fig.14 The intra-annual variability of seasonal Tmax (°C) over India during 1951-2020 (a) winter (JF), (b) pre-monsoon (MAM), (c) monsoon (JJAS) and (d) post-monsoon (OND) period. The red line shows trends in mm/year.

(d) Post-monsoon (OND)

The pattern of mean and SD of Tmax in post-monsoon season in Fig. 12 (g-h) is quite analogous to the monsoon season, but the Tmax intensity is relatively lower as compared to other seasons. The Gujarat state recorded warmer than other parts of India as shown in Fig. 12 (g). The SD of Tmax has shown an enrichment over northern India as compared to the PI, as presented in Fig. 12 (h). The spatial distribution trends, the Tmax increasing trends of 0.15 °C per decade as shown in Fig. 13 (d), over the entire country except the northern part of India such as Jammu and Kashmir and adjoining states. The time-series analysis of linear trends showed positive trends during the monsoon season of 1951-2020, as revealed in Fig. 14 (d).

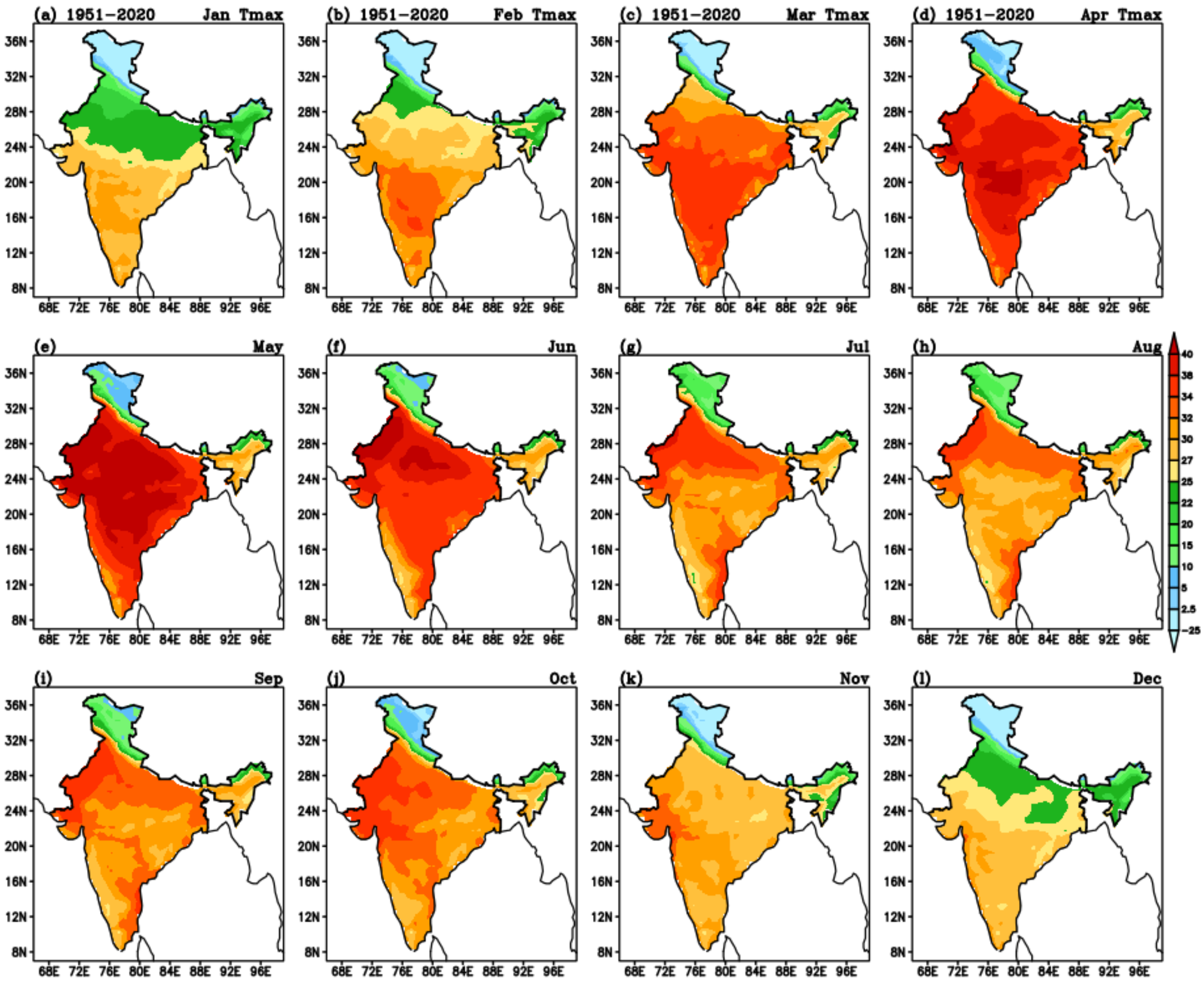

Fig.15 Spatial distribution of monthly Tmax (°C) mean for (a-d) January to April (top) panel, (e-h) May-August (middle panel), (i-l) September-December (bottom panel) during 1951-2020 derived from CRU data at 0.5-degree resolutions.

4.1.3 Monthly Tmax

The spatial distribution of monthly Tmax mean, SD, and trends in (°C) as represented in Fig. (15), (16), and – (17), respectively. The horizontal distribution of Tmax is not very uniform during the January to December months. The months of January, February, and December had shown relatively lower Tmax as compared to other months, as shown in Fig. 15 (a), (b), and (l), respectively. The month of March to June had shown warmer than other months as depicted in Fig. 15 (c-f).

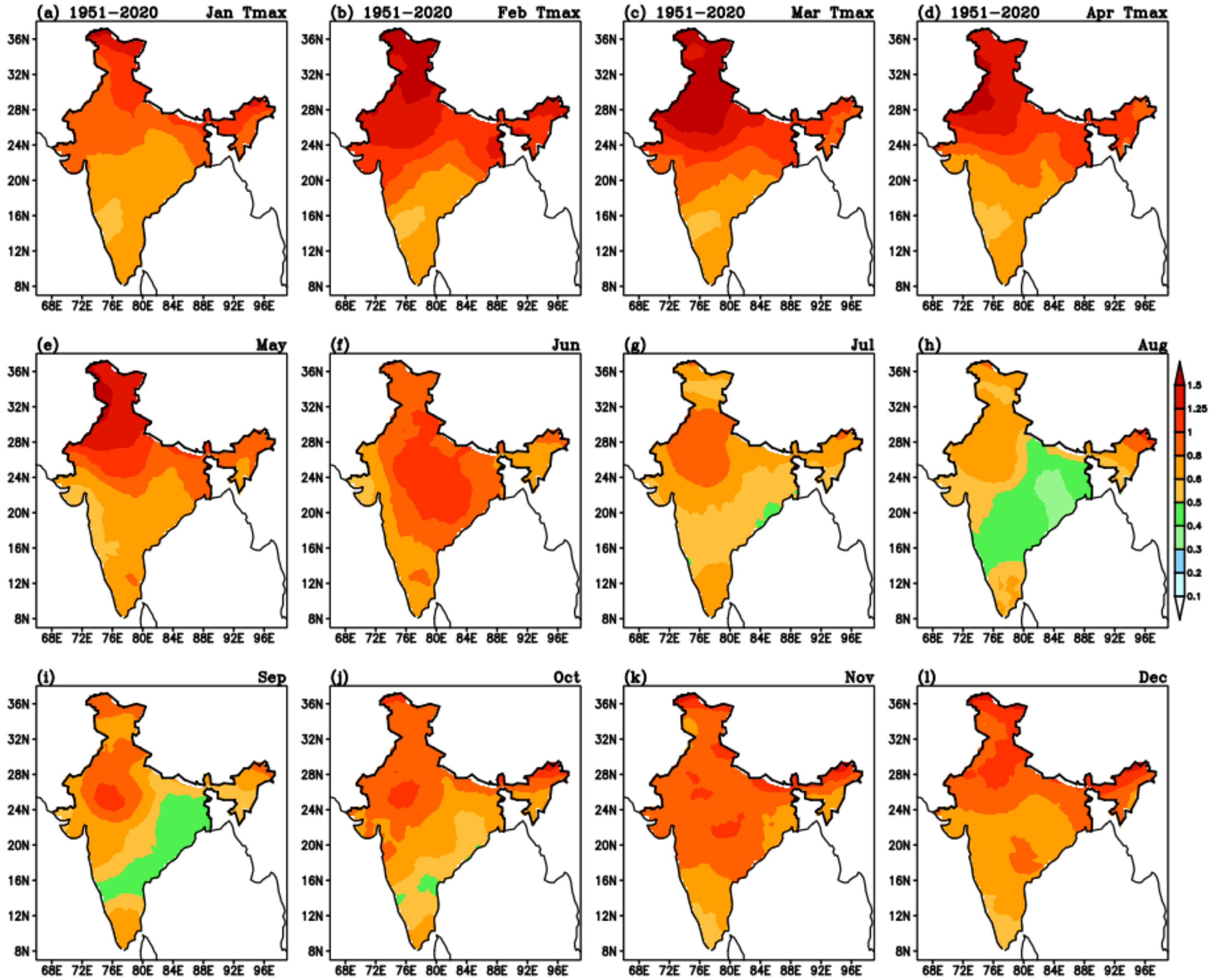

Fig. 16 Same as Fig. (15), but for standard deviation of Tmax (°C) during the period of 1951-2020.

After monsoon (both summer and winter) covered the entire part of India, and in the month of July, the Tmax has substantially reduced since November as shown in Fig. 15 (g-k). Fig.16 shows the distribution SD of the Tmax (°C) pattern is relatively similar to the Tmax mean as depicted in Fig. 15. In the months of March to June, the maximum SD of Tmax was shown over northern India decreases gradually towards the southern part of the Indian states. The spatial distribution of trends per decade shown in Fig 17 (a-l) recognized a positive trend over the country as a whole except for the northern part of India, Odisha, West Bengal, and northeast parts of India.

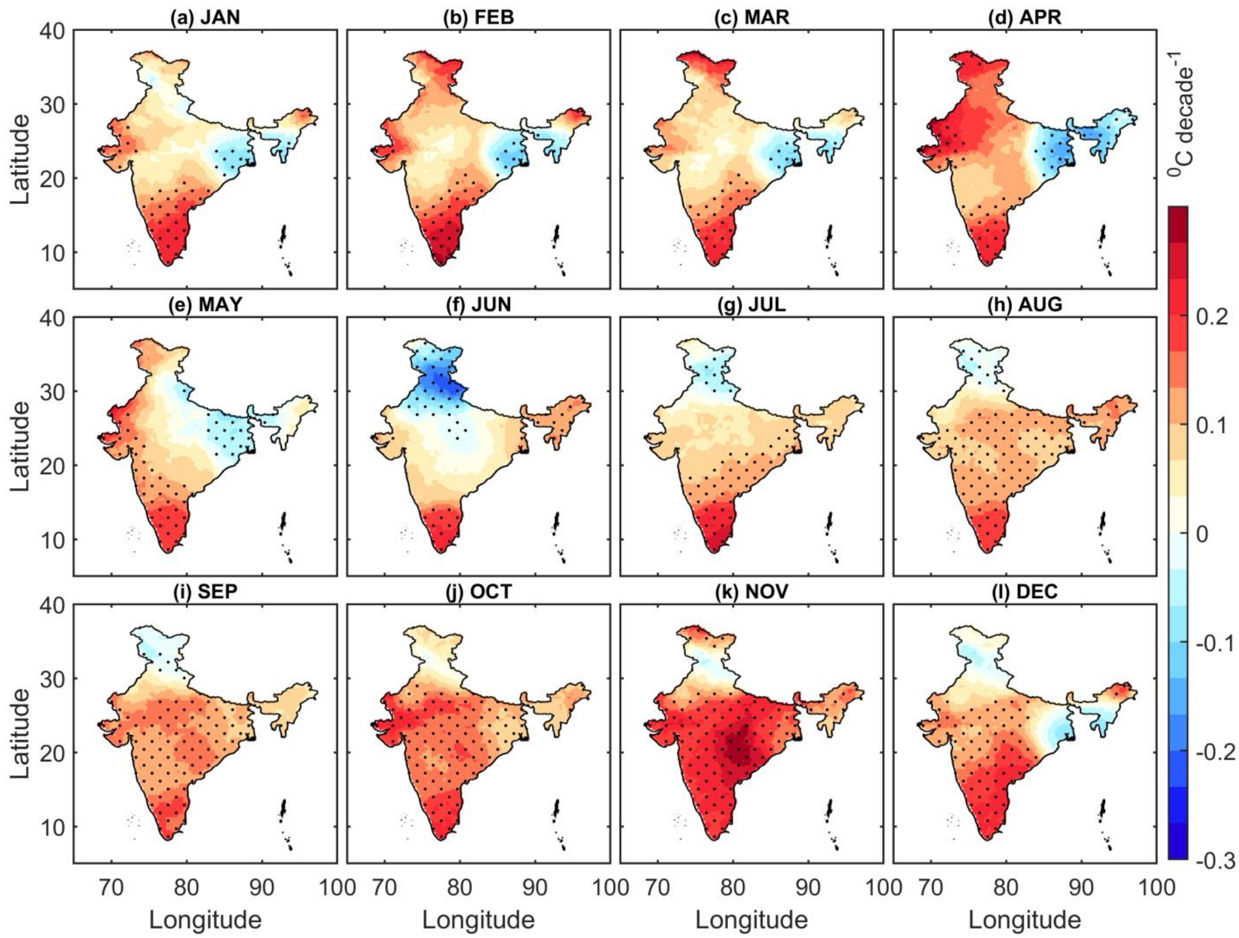

Fig. 17 is the Same as Fig. (16), but for monthly trends of Tmax (°C) during the period of 1951-2020 (grid boxes are hatched where the trend is significant with 95% confidence).

The mean, SD, and trends of Tmax are presented in Table 3. The monthly trends showed positive trends in each month, as illustrated in Table 3 below.

Table 3. Monthly mean, standard deviation, and trends maximum temperature (Tmax, °C) during 1951-2020 derived from CRU data at 0.5-degree resolutions.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average	23.8	26.4	30.8	34.3	35.8	33.9	30.8	29.9	30.4	30.2	27.5	24.6
SD	0.6	0.9	0.9	0.8	0.6	0.7	0.4	0.4	0.4	0.5	0.6	0.6
Trends/decades	0.13	0.18	0.17	0.15	0.10	0.06	0.09	0.10	0.12	0.15	0.22	0.17

4.2 Tmin

4.2.1 Annual Tmin

Fig. 18 shows the spatial distribution of the annual mean, SD, and trends for the Tmin in (^{o}C) from 1951 to 2020. The annual Tmin average mean over India has shown a maximum (22 ^{o}C) over Gujarat, Telangana, and part of Andhra Pradesh and Odisha in Fig. 18 (a). The maximum SD of Tmin has been recorded over the northern part of India (above 18 ^{o}N) particularly the Jammu and Kashmir region (Fig. 18b). There is an increased rate of warming of Tmin value around ~ 0.25 °C per decade for the annual mean, maximum 1951-2020 as shown in Fig. 18 (c). The time series of seven decades of Tmin over the land mass of the Indian region shows an increased trend of 0.001 °C per year, as depicted in Fig. (19).

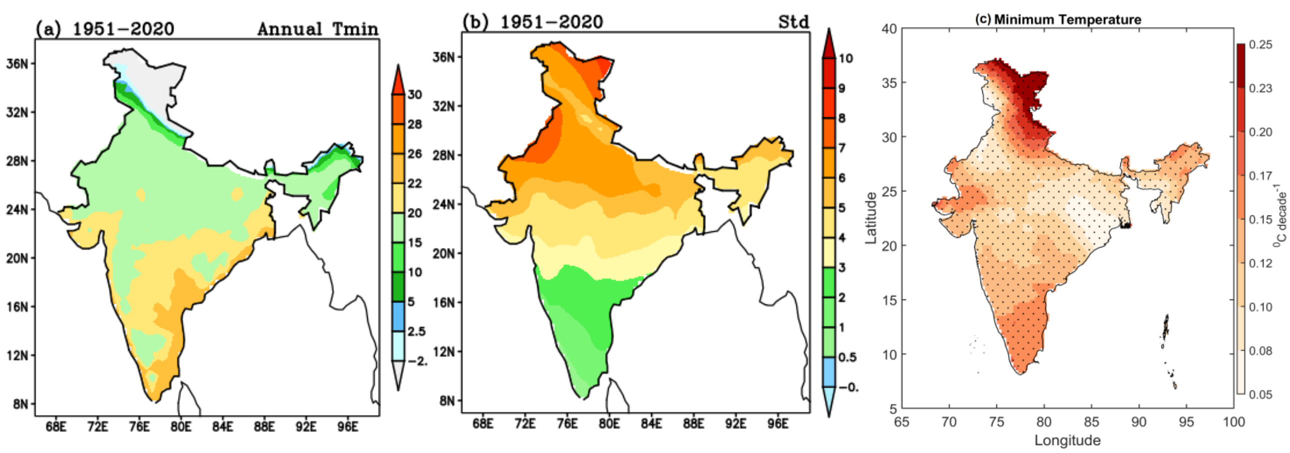

Fig. 18 Spatial distribution of annual minimum temperature (Tmin, ^{o}C) over India (a) mean, (b) stand deviation, and trends (^{o}C per decade) during the period of 1951-2020 derived from CRU data at 0.5-degree resolution (grid boxes are hatched where trend are significant 95% confidence).

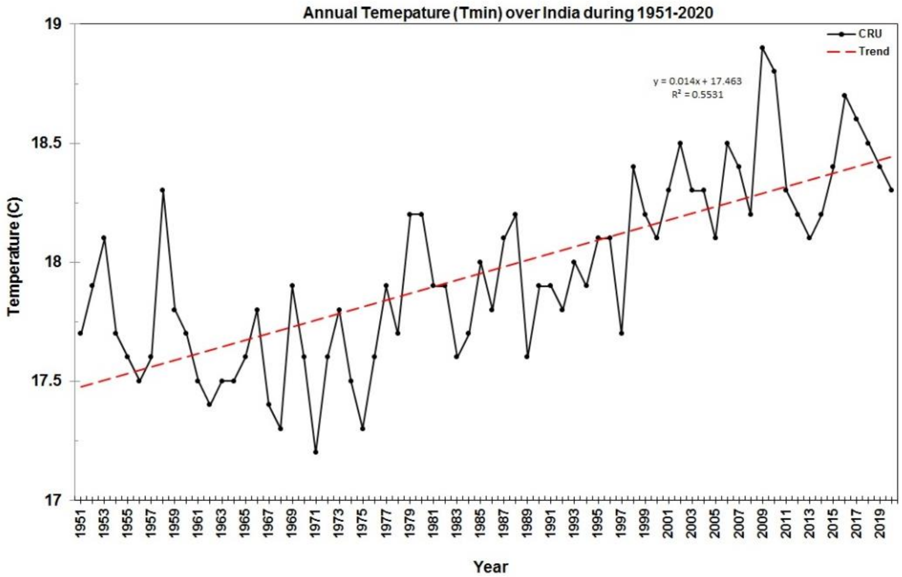

Fig. 19 The inter-annual variability of annual Tmin (°C) over India during 1951-2020 (red-line shows trends at the rate in °C/year).

4.2.2 Seasonal Tmin

(a) Winter (JF)

The seasonal (winter, pre-monsoon, monsoon, and post-monsoon) Tmin in (oC) is shown in Fig. 20 (a-h). The spatial distributions of Tmin disclose the warming, which is not uniform during all the seasons. In winter, maximum warming has shown over the PI as compared to the northern part of India, as shown in Fig. 20 (a). Fig. 20 (b) is the same as Fig. 20 (a), that shows the SD of Tmin in winter. The SD of Tmax value ~2.5 °C has been recorded and is reasonably uniform throughout the country. However, trends are shown positively in the entire country as presented in Fig 20 (b). The time series shows the long-term trends of Tmin from 1951 to 2020; a positive trend was recorded in the winter season. However, trends are shown positively in the entire country as presented in Fig. 21 (b). The time series shows the long-term trends of Tmin from 1951 to 2020; a positive trend has been recorded in the winter season in Fig. 22 (a).

(b) Pre-monsoon (MAM)

The pre-monsoon season (MAM) Tmin mean and SD has shown in Fig. 20 (c-d). In the Fig. 19 (c) appearances very warm than in other seasons as shown in Fig 19 (a-b). Maximum Tmin of 25 °C has recorded in central India and particularly Telangana state as represented in

Fig. 20 (c). The SD of Tmin represents maximum over northern India as compared to the PI (Fig. 20 d).

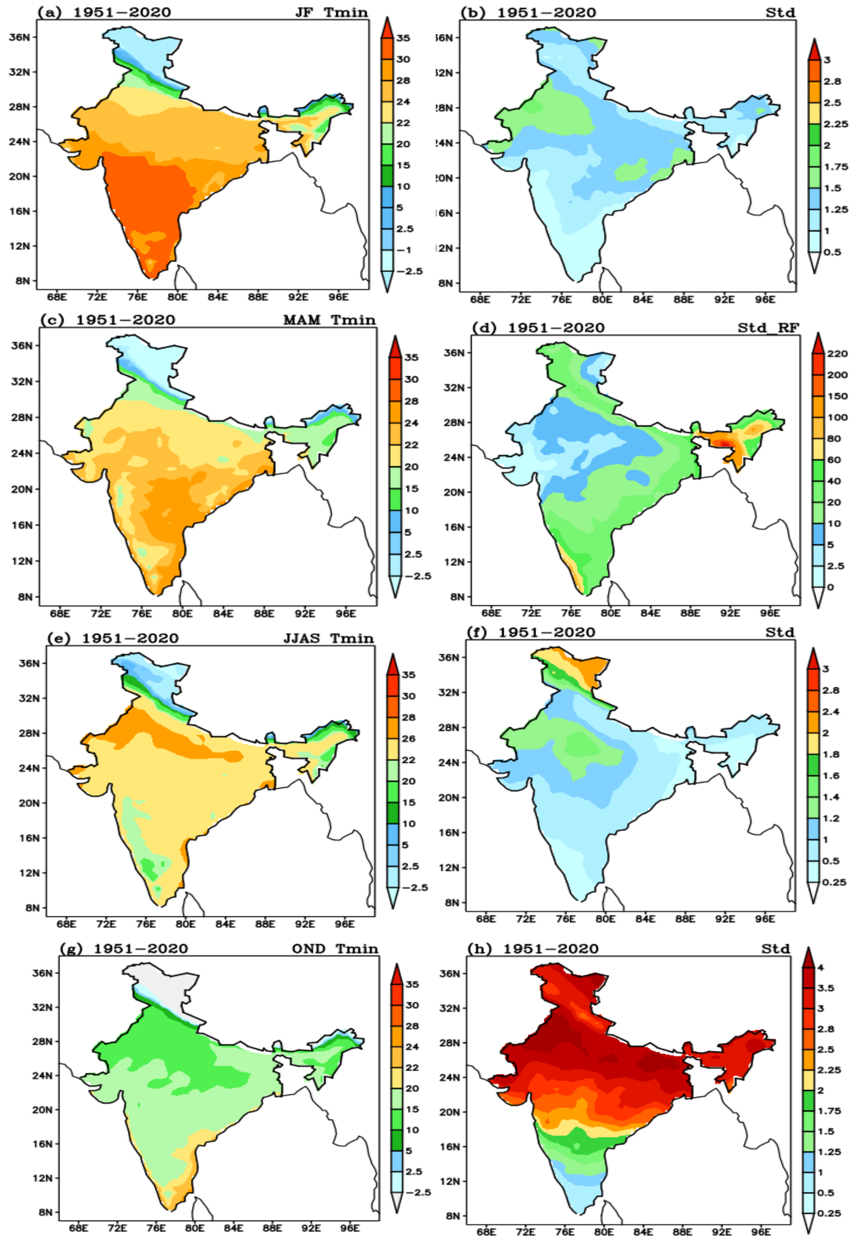

Fig. 20 Spatial distribution of seasonal mean Tmin (°C) for (left panel) (a) winter (January-February, JF), (c) pre-monsoon (March-May, MAM), (e) monsoon (June-September, JJAS), and (g) post-monsoon (October-December, OND) seasons during the period 1951-2020; Fig (b, d, f and h) same as (a, c, e and g), but for the standard deviation (°C) derived from CRU dataset at 0.5-degree resolutions.

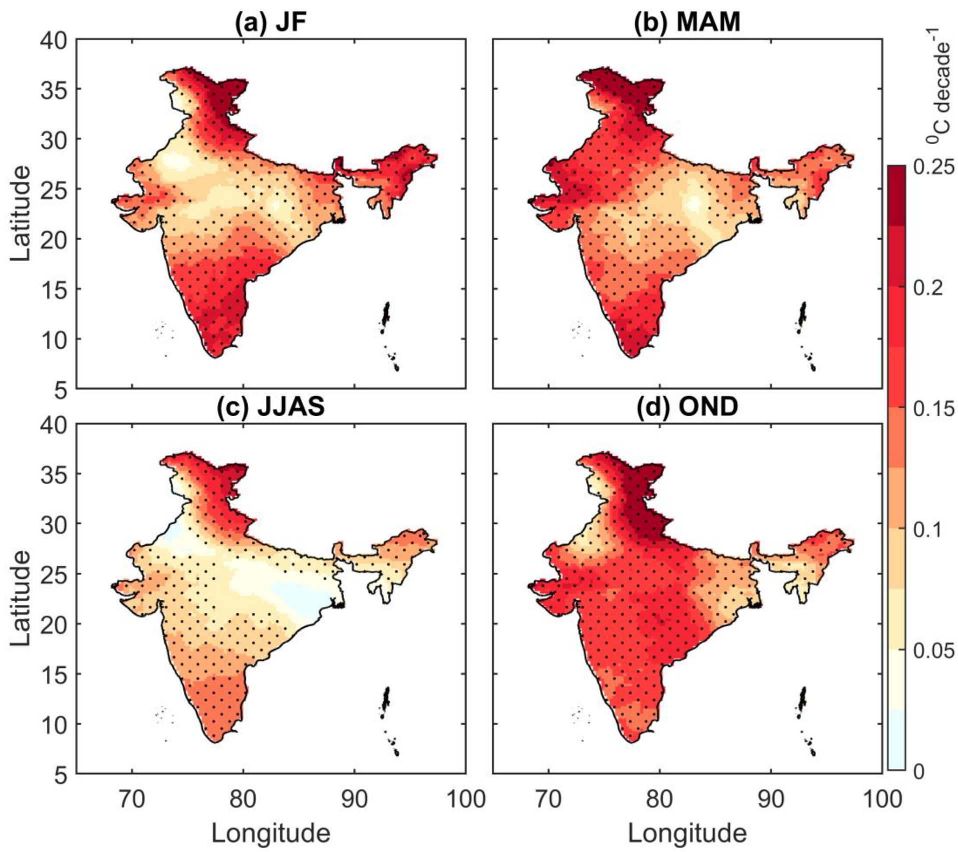

Fig. 21 Same as Fig. (20), but for seasonal trends of Tmin in ^{o}C per decade (a) winter (JF), (b) pre-monsoon (MAM), (c) monsoon (JJAS), and (d) post-monsoon (OND) during the period of 1951-2020 derived from CRU data at 0.5-degree resolution (grid boxes are hatched where trend is significant 95% confidence).

In pre-monsoon, the positive trends were recorded, and dots showed 95% significance over the PI, as depicted in Fig. 21 (b). The time series shows the linear trends over India as positive trends are noticed during 1951-2020 in Fig. 22 (c).

(c) Monsoon (JJAS)

The spatial distribution of Tmin mean and SD (^{o}C) during monsoon season is shown in Fig. 20 (e-f). Maximum Tmax has recorded (25 ^{o}C) in Indo-Gangetic planes and that extended towards part of Rajasthan and Gujarat region (Fig. 20e). However, the maximum SD of Tmin has been noticed over the monsoon zone, as depicted in Fig. (20f).

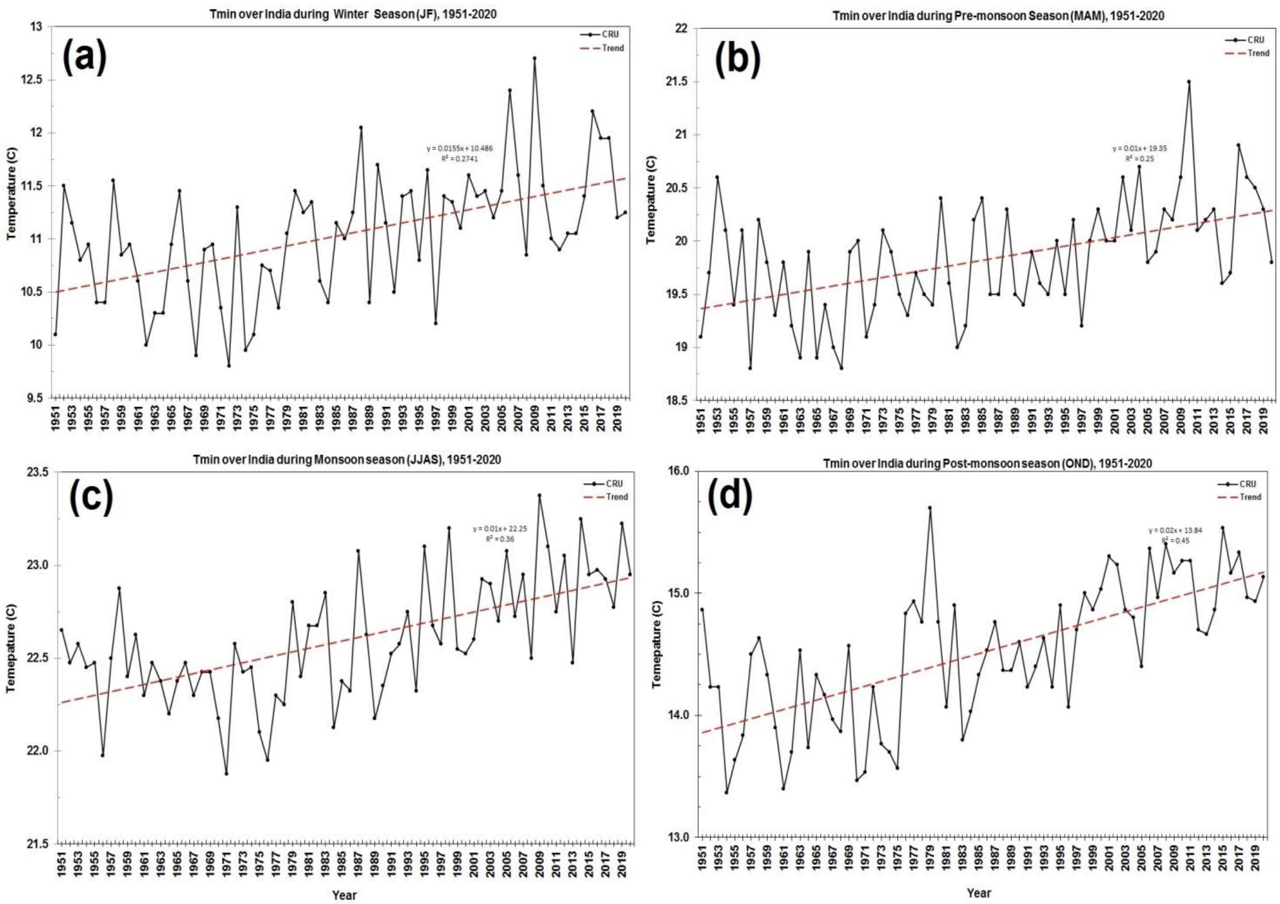

Fig. 22 The intra-annual variability of seasonal Tmin (°C) over India during 1951-2020 (a) winter (JF), (b) pre-monsoon (MAM), (c) monsoon (JJAS) and (d) post-monsoon (OND) period. The red line shows trends in mm/year.

The trends of Tmin during monsoon are shown in Fig. 21 (c), which shows the maximum positive trends are restricted over the PI, and northern states of India. However, moderate positive trends were shown in the northern part of India, particularly the Indo-Gangetic plains, as shown in Fig. (21 c). The time-series analysis of Tmin trends during 1951-2020 showed positive trends in Fig. 22(c).

(d) Post-monsoon (OND)

The pattern of mean and SD of Tmin in post-monsoon season (Fig. 20 g-h) is quite corresponding with monsoon season, but the Tmin intensity is relatively stumpy as compared to other seasons. The Rajasthan state recorded warmer Tmin than other parts of India as shown in

Fig. 20 (g). The SD of Tmin has shown an upgrading of over India as compared to the PI as presented in Fig. 20 (h).

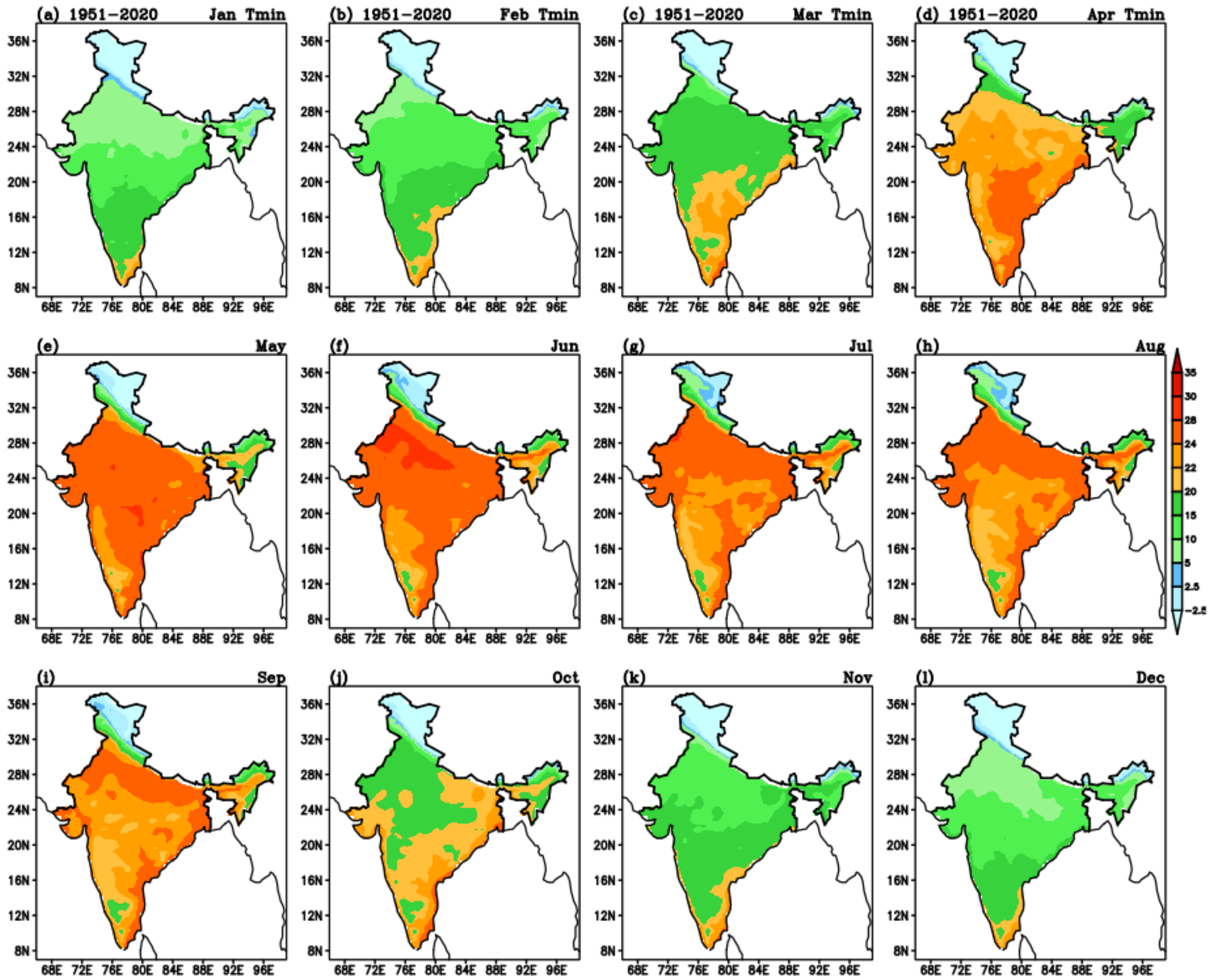

Fig. 23 Spatial distribution of monthly Tmin (°C) mean for (a-d) January to April (top) panel, (e-h) May-August (middle panel), (i-l) September-December (bottom panel) during 1951-2020 derived from CRU data at 0.5-degree resolutions.

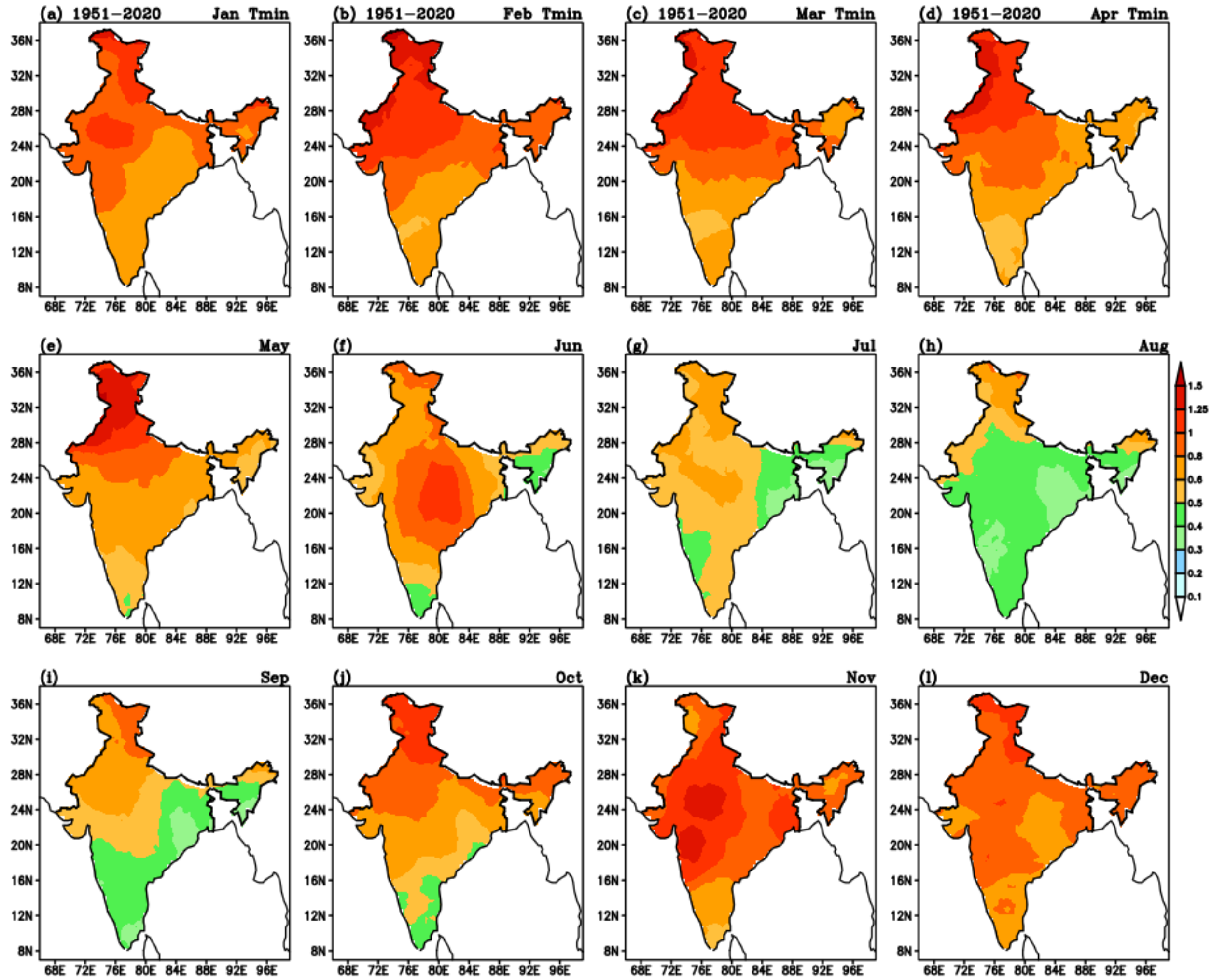

Fig. 24 Same as Fig. (23), but for standard deviation of Tmin (°C) during the period of 1951-2020.

The spatial distribution of Tmin trends per decade shown in Fig. 21 (d) shows a positive trend of 0.25 °C over the entire country except the northern part of India, such as Jammu and Kashmir and adjoining states. The time-series analysis of linear trends showed a positive trend during the monsoon season of 1951-2020, as shown in Fig. 22 (d).

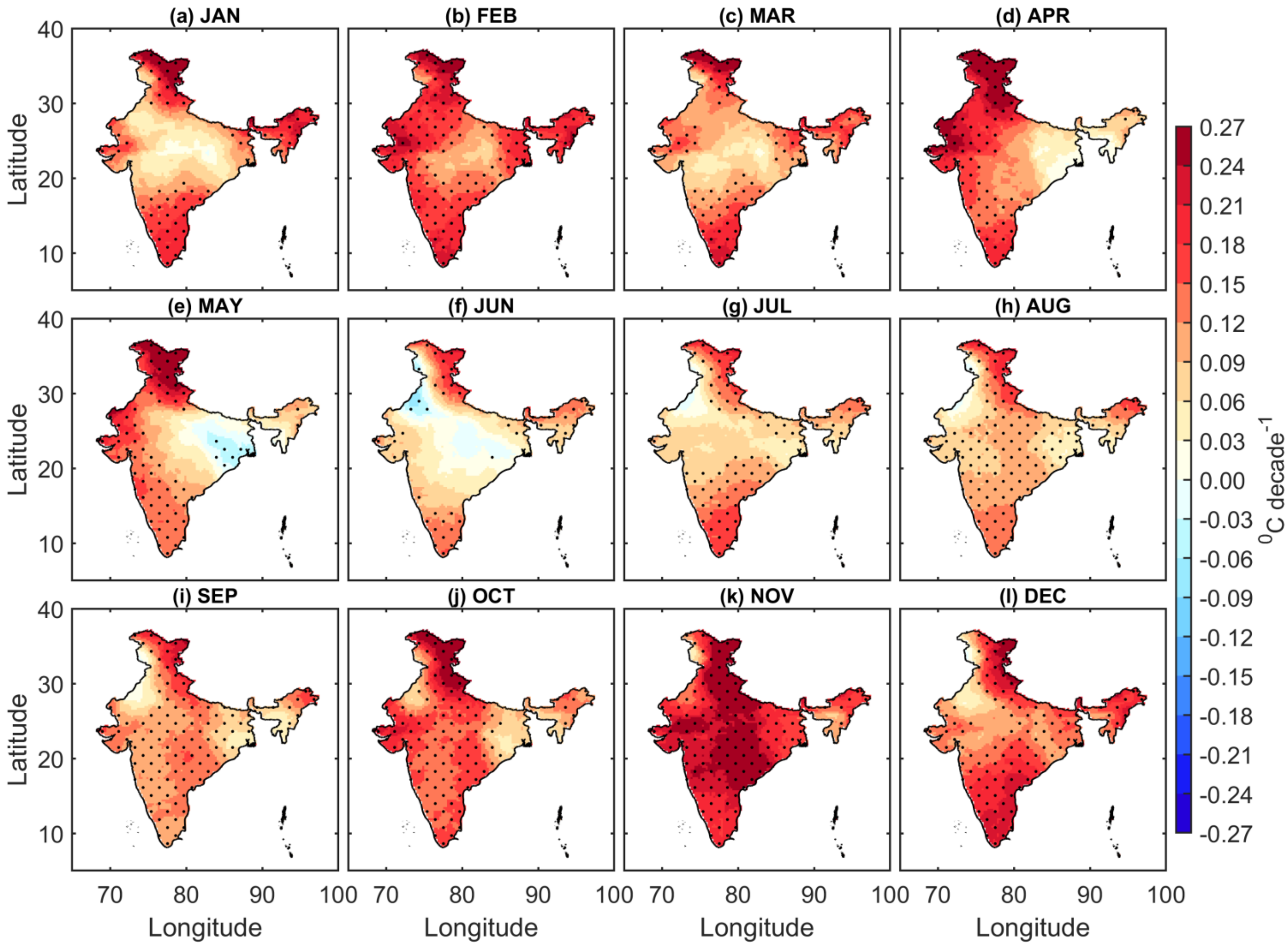

Fig. 25 Same as Fig. (24), but for monthly trends of Tmin (ºC) during the period of 1951-2020 (grid boxes are hatched where trend is significant 95% confidence).

4.2.3 Monthly Tmin

The spatial distribution of monthly Tmin mean, SD and trends in (ºC) as represented in Fig. (23), (24) and (25) respectively. The horizontal distribution of Tmin is not identical during January to December months. The month of January to July had shown relative higher Tmin as compared to other months as shown in Fig. 23 (a-g). The month of March to August and September had shown less value of Tmin. Fig. 24 shown the distribution SD of Tmin pattern is relatively similar as Tmax mean as depicted in Fig. 23. In moth of January to July has showed maximum SD of Tmax over northern India decreases gradually towards the south. The spatial distribution of trends per decade shown in Fig. 25 is familiar as a positive trend over the country as a whole of India. The mean, SD, and trends of Tmax are presented in Table 4. Tmin's monthly trends showed positive trends each month. These long-term changes in surface air temperature over India during the twentieth century also broadly agree with earlier assessments discussed in *Rupa Kumar et al. (1994); Kothawale and Rupa Kumar (2005).* The studies by *Kothawale et al. (2016), Kulkarni et al. (2017), and Srivastava et al. (2019)* have documented that annual mean land surface air temperatures have warmed by 0.6 °C century^{-1} between 1901 and 2018 over Indian region. However, the Tmax and Tmin have warmed by 0.11 and 0.14^{o} C per decade between 1951 and 2020, which is not very statistically significant.

5. Summary and Conclusions

The study focused on an assessment of climate conditions in India and their changes during the last 70 years (1951-2020). CRU datasets, such as precipitation, Tmax, and Tmin, are analyzed in different time scales, particularly annual, seasonal, and monthly. The mean climatology, SD, and trend analysis on these climatic parameters, the major findings are discussed below:

- Climatological results indicate that the mean annual precipitation over the entire India ranges from 300-1100 mm/year except for parts of Gujarat, Rajasthan, Jammu, and Kashmir states (150mm/year). The highest precipitation amounts, around ~1000 mm/year, can be seen along the west coast, northeast states, and central part of India.
- Consequently, the SD pattern is quite similar to climatology, and a maximum SD of 140 mm/year is shown over the monsoon zone, Indo-Gangetic plains, west coast, and northeast states of India.
- The annual rainfall averaged over India shows decreasing trends -1.423/decade over the period of 1951-2020.
- The seasonal precipitation during winter and pre-monsoon is significantly less than during monsoon and post-monsoon periods. During the monsoon season, most parts of India receive the major share of the annual rainfall, whereas the PI emanates under the rain shadow region. Moreover, during post-monsoon season the rainfall zone shifted towards southern part of India due the major winds become northeasterly.

- The maximum monthly rainfall of 289 mm received during July whereas lowest monthly reported in month of January below 6.0 mm. In four months, particularly February, April, September, and November, the rainfall trends showed increasing trends of 0.321, 0.476, 1.91, and 0.91 mm per decade, and remain months are illustrated as negative trends. The maximum decreasing trend of -1.452 mm/decade shown in the month of August it's may be due to monsoon break conditions over India.
- In the case of temperature, the summary of annual maximum and minimum temperatures over India as a whole have shown a significant warming trend of 0.11 °C and 0.14 °C per decade, respectively. Since 1995, the Tmax annual has revealed exponentially increasing trends compared to previous decades.
- In the winter season, the Tmax and Tmin both have shown increasing trends (0.09 and 0.155 °C per decade. The Tmin value is nearly twice that of Tmax, and it seems the duration of cold days is reduced. During pre-monsoon season, both Tmax and Tmin represent a warming trend (0.12 and 0.13 °C per decade), which indicates increasing characteristics of heatwave conditions over India.
- During monsoon and post-monsoon seasons, maximum and minimum temperatures revealed an increasing trend, but the trend value in the post-monsoon period (0.22 °C) is higher than monsoon (0.13). Tmax and Tmin reveal relatively positive trends throughout the year, nearly ~0.1 °C per decade.
- The study reveals a statistically significant increasing trend in temperature, whereas a decreasing trend in precipitation was significantly observed from CRU datasets (1951-2020).

6. Future scopes

Climate change is a major challenge for developing nations like India, threatening to enhance risks already elevated by high levels of social vulnerability and climate variability. Through its 2016 Nationally Determined Contribution (NDC), India is committed to achieving by 2030: a reduction in the emissions intensity of its GDP by 33%–35% below the 2005 levels; the share of renewables in power generation at 40% contingent on technology transfer and availability of finance; and an additional cumulative carbon sink of 2.5–3.0 Gt CO_2 by 2030 with increased afforestation and tree cover. Other commitments are to better adapt to climate change by enhancing investments in development programs in sectors vulnerable to climate change, particularly agriculture, water resources, the Himalayan region, coastal regions, health, and disaster management.

This study is limited to three parameters and can be extended further using more climatic parameters (cloud, diurnal temperature, wet days, and vapor pressure) driving precipitation and temperature variability mechanisms. Using additional parameters such as diurnal temperature range (C), cloud (%), potential evapotranspiration (mm/d), vapor pressure (hPa), and wet day frequency (days) can be analyzed to assess the hydro-climate variability over India.

Details investigation of climatological mean and trends using regional and global reanalysis datasets such as Indian Monsoon Data Assimilation and Analysis (IMDAA) is a regional high-resolution atmospheric reanalysis over the Indian subcontinent *(Ashrit et al. 2020)* and NGFS can be performed for the past and recent decades. Moreover, the different climate indices and their teleconnections with seasonal climate processes over India were also studied using NCMRWF coupled model products.

7. Acknowledgements

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8. Authors Contribution

Dr. Prabodha Kumar Pradhan has performed the technical work and drafting of this report. Dr. Raghavendra Ashrit conceptualization this work. Dr. Mohan S. Thota and Dr. V. S. Prasad have directed the review and final editing of the report.

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Appendix-I

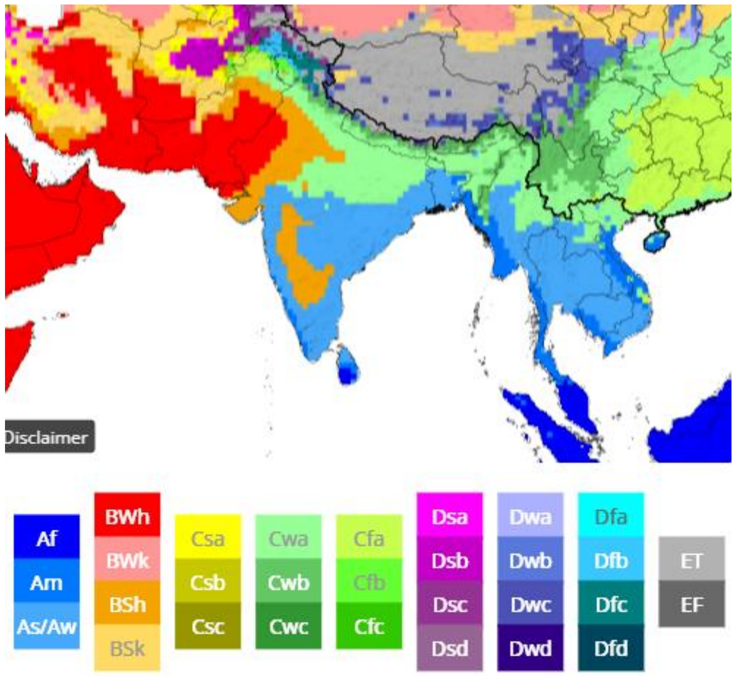

Fig. S1 Climate classification over South Asia (*source: World Bank Group, 2022*).

Climate zone classifications over South Asia

The BIMSTEC countries are part of South Asia. The climate zones are derived from Koppen-Geiger climate classification systems, which slits climate into five main climate groups based on seasonal rainfall (mm) and temperature (C) patterns over India, depicted in supplementary Fig. (S1). The five major groups are A (tropical), B (dry), C (temperate), D (continental), and E (polar). Climate classifications over India is confined to tropical and continental climate conditions. However, the Western Ghats have shown dry climate conditions. Countries like Nepal and Bhutan have continental climates, whereas Bangladesh, Myanmar, Thailand, and Sri Lanka are coming under tropical climates, as depicted in Fig. S1.

In Fig. S2, World Bank reported that, the average temperatures range from 12°C to 38°C throughout the year, with an experienced average temperature of 24.2°C (CCKP, 2021). The months with the highest temperatures align with the period of rainfall (March-June), whereas colder and less humid conditions distinguish the winter season (December-February). The rainfall maximum occurred in June to October. The details are discussed in CCKP portal (https://climateknowledgeportal.worldbank.org/sites/default/files/country-profiles/15503-WB_India%20Country%20Profile-WEB.pdf).

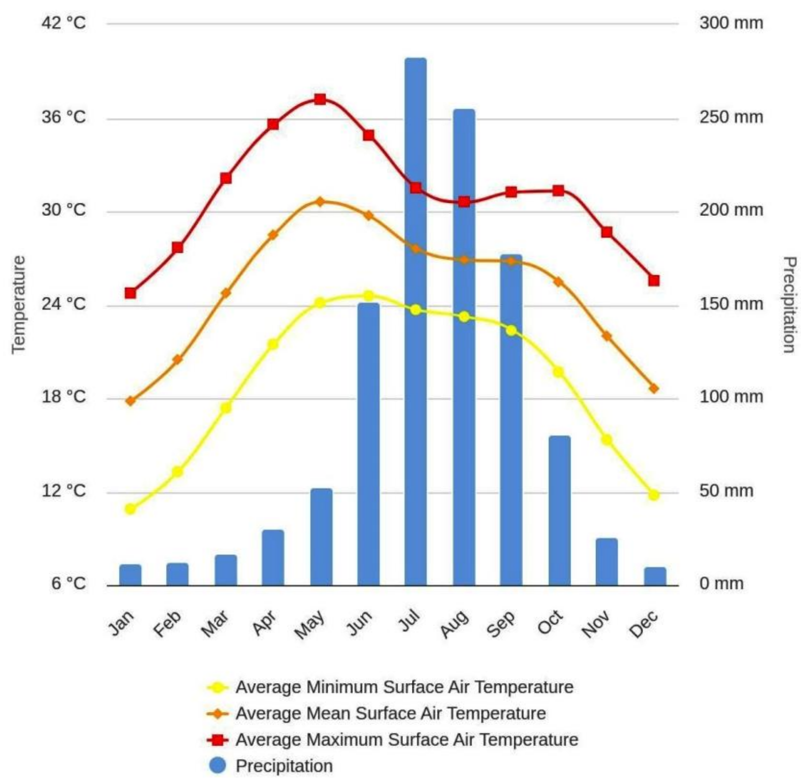

Fig. S2 Average Monthly Mean, precipitation, maximum, and minimum temperatures over India for the period of 1991–2020. (*Source: World Bank Group, 2022*).