

DOI: <https://doi.org/10.54302/mausam.v77i4.7636>Homepage: <https://mausamjournal.imd.gov.in/index.php/MAUSAM>

UDC No.551.583:551.582.2

Identifying the climate zones shifts of Indian meteorological subdivisions: insights from historical records

ANANYA KARMAKAR^{1*}, RAJIB CHATTOPADHYAY², PULAK GUHATHAKURTA¹,K S HOSALIKAR¹ and MRUTYUNJAY MOHAPATRA³¹India Meteorological Department, Ministry of Earth Sciences, Pune, India.²Indian Institute of Tropical Meteorology, Pune³India Meteorological Department, Ministry of Earth Sciences, New Delhi, India.

(Received 29 April 2026, Accepted 10 September 2026)

*Corresponding author's email: ananya.karmakar@imd.gov.in

सार – भारत के मौसम संबंधी डिवीज़न के क्लाइमेट ज़ोन, कोपेन-गीगर क्लाइमेट क्लासिफिकेशन के आधार पर छह क्लाइमेट क्लास में बंटे हैं। हाल ही में, लंबे समय तक क्लाइमेट में बदलाव के कारण इन क्लाइमेट ज़ोन में बड़े बदलाव हुए हैं। यह स्टडी 1951-2020 की अवधि में देखी गई बारिश और अधिकतम व न्यूनतम तापमान का इस्तेमाल करके भारतीय मौसम संबंधी डिवीज़न में हुए बदलावों का आकलन करती है। 30 साल का मूविंग क्लाइमेटोलॉजिकल औसत हर दशक में अपडेट किया जाता है, जिससे पता चलता है कि 1961-1990 और 1991-2020 की ऐतिहासिक अवधियों में शुष्क स्टेपी-गर्म और समशीतोष्ण (टेम्परेट) क्लाइमेट में बड़े बदलाव हुए हैं। भारतीय एकसमान क्षेत्र का इलाका उत्तर-पश्चिम भारत और उत्तर-पूर्व भारत में सूखे क्लाइमेट ज़ोन की ओर बदलाव दिखाता है - क्रमशः समशीतोष्ण से शुष्क स्टेपी-गर्म और ट्रोपिकल सवाना से समशीतोष्ण क्लाइमेट में। यह बदलाव भारत के कुल क्षेत्रफल का लगभग 7% है, जो तापमान में बढ़ोतरी और बारिश में कमी के कारण हुआ है; यह बदलाव विक्टोरिया मोड (VM) के नेगेटिव फेज़, नमी के ट्रांसपोर्ट में कमी और उत्तरी भारत के इंडो-गैंगेटिक प्लेन पर डायवर्जेंस से नियंत्रित होता है। क्लाइमेट ज़ोन में यह बदलाव भविष्य में उत्तरी भारत के एग्रो-क्लाइमेटिक ज़ोन में खेती पर बुरा असर डाल सकता है। कुल मिलाकर, यह स्टडी क्लाइमेट ज़ोन में बदलाव और इसलिए IMD के फोरकास्टिंग सिस्टम के बारे में जानकारी बढ़ाती है।

ABSTRACT. The climate zones of meteorological subdivisions of India consist of six climate classes based on the Köppen-Geiger climate classification. Recently, these climate zones have undergone significant changes due to long-term climate variability. Present study assesses the changes in Indian meteorological subdivisions using the observed rainfall, and maximum and minimum temperatures in the period of 1951-2020. The 30-year moving climatological mean is updated every decade revealing that there have been major changes in the Arid Steppe-hot and Temperate climate in the historical periods 1961-1990 and 1991-2020. The area of the Indian homogeneous region depicts a shift to the drier climate zone in North West India and North East India from Temperate to Arid steppe hot and Tropical savannah to Temperate climate respectively. The change is nearly 7% of the total area of India due to an increasing trend in temperature and a decreasing trend in rainfall which controlled by the negative phase of Victoria Mode (VM) decrease in moisture transport and divergence over Northern India Indo-Gangetic Plane. This climate zone shift could adversely impact the agriculture in the Northern India Agro-Climatic Zone in the future. Overall, this study enhances the knowledge about climate zone change and therefore the IMD forecasting system.

Key words – Climate change, Climate zone, Meteorological subdivision, Homogeneous region.

1. Introduction

Climate change has emerged as one of the most pressing global challenges of the 21st century.

Characterized by a sustained increase in global average surface temperatures, this phenomenon is largely driven by anthropogenic greenhouse gas (GHG) emissions. Since the mid-20th century, the Earth has warmed at an

unprecedented rate, with recent decades being the warmest in recorded history. According to the Intergovernmental Panel on Climate Change (IPCC), global surface temperature has increased by approximately 1.1 °C above pre-industrial levels by the end of the 20th century, with cascading effects on regional climates, hydrological cycles, ecosystems, and human systems. Beyond global averages, the impacts of climate change manifest distinctly at regional and local scales (Folland *et al.*, 2001, Zhang *et al.*, 2007, Rubel and Kotteck 1884, 4. Mahlstein *et al.*, 2013). One of the more nuanced consequences of long-term climate change is the modulation of climate zones (Loarie *et al.*, 2009, Sandel *et al.*, 2011, Williams *et al.*, 2007), which are typically defined based on temperature and precipitation regimes. Changes in these zones can alter the ecological and agricultural landscape, redefine biogeographical boundaries, and affect human livelihoods and infrastructure planning. As a result, understanding spatial and temporal shifts in climatic zones is essential for both climate science and policy formulation.

Among the various climate classification systems, the Köppen–Geiger classification (Köppen 1936) remains the most widely adopted. Developed on the basis of empirical thresholds of temperature and precipitation, it divides the globe into five major climate types, further subdivided into 30 sub-types. These classifications serve as a proxy for understanding climatic conditions and their relation to vegetation types, hydrological behavior, and ecosystem functioning (Feng *et al.*, 2012). Recent studies have highlighted that these climate zones are not static; rather, they are dynamically responding to ongoing climatic variability and change specially based on temperature and rainfall changes (Folland *et al.*, 2001, New *et al.*, 2001, Alkama 2014).

In a recent book (Krishnan *et al.*, 2020), it was shown that India has experienced an average temperature increase of approximately 0.7 °C in the past 120 years due to greenhouse gas-induced warming, anthropogenic aerosols, & other factors. It also displayed that the temperature of the warmest day of the year has risen by approximately 0.63 °C. This indicates that the peak temperature recorded annually, likely during the summer months, has increased over this period. The temperature of the coldest night of the year has risen by about 0.4 °C. This suggests that even during the coldest periods of the year, typically during winter nights, temperatures have shown an upward trend. Further, this book discusses that the RCP8.5 projection underscores the potential intensification of heat wave events in India under a high emissions scenario, highlighting the importance of climate mitigation and adaptation measures to reduce the impacts

of extreme heat on human health, agriculture, and ecosystems.

In the current study, we investigate historical records of shifts in climate zone modulation across Indian meteorological subdivisions, aiming to uncover the underlying drivers and patterns that have shaped India's climate landscape. By examining a wealth of historical data, including meteorological observations, proxy records, and historical accounts, we seek to unravel the complex behaviour of climate variability within the Indian subcontinent. Our exploration begins by examining the climatic zones defined by the India Meteorological Department (IMD), which divides the country into several subdivisions based on distinct meteorological characteristics.

Recent evidence suggests that India's climatic regions have undergone significant transitions in response to long-term climate variability. The "Assessment of Climate Change over the Indian Region" (MoES, 2020) reports that India's average temperature has increased by approximately 0.7 °C over the last 120 years. Notably, the maximum temperatures during summer months and minimum temperatures during winter nights have both shown a consistent upward trend. Rainfall trends, on the other hand, exhibit strong spatial heterogeneity. While regions such as the Western Ghats and Northeast India have seen declines in monsoonal precipitation, some coastal and northwestern regions have experienced modest increases. Several studies (Kumar *et al.*, 2010, Sankaran *et al.*, 2021) analysed these trends using long-term observational datasets. For instance, a century-scale analysis of rainfall by the India Meteorological Department (IMD) revealed increasing trends over Northwest India and the Peninsular region, and decreasing trends over Central India. Moreover, machine learning techniques applied to IMD's gridded rainfall datasets have recently identified significant negative trends in seasonal and annual rainfall across multiple meteorological subdivisions, including Chhattisgarh, Vidarbha, and parts of Northeast India.

Many previous studies have identified global climate classes and mapped them onto the Indian map. Peel *et al.*, 2007 redraw the Köppen–Geiger world map using global long-term monthly precipitation and temperature station data. The Köppen–Geiger climate classification system is one of the most widely used methods to classify climates. It categorizes climates into five main classes based on temperature and precipitation patterns, which are further divided into 30 subtypes. These classifications are based on empirical data such as average monthly temperatures and precipitation totals. Further, Kriticos *et al.*, 2012 produced the Köppen–Geiger world map by using high-

TABLE 1

Different Climate Classes description and criterion

Climate Class	Description	Criterion
Tropical (A)	Monsoon (m)	Not Arid & $T_{cold} \geq 18$ Not $P_{dry} \geq 60$ & $P_{dry} \geq 100 - MAP/25$
	Savannah (w)	Not $P_{dry} \geq 60$ & $P_{dry} < 100 - MAP/25$ $MAP < 10 \times P_{threshold}$
Arid (B)	Desert hot (Wh)	$MAP < 5 \times P_{threshold}$, $MAT \geq 18$
	Steppe hot (Sh)	$MAP \geq 5 \times P_{threshold}$, $MAT \geq 18$
	Dessert Cold (Wk)	$MAP < 5 \times P_{threshold}$, $MAT < 18$
Temperate (C)		Not Arid & $T_{hot} > 10$ & $0 < T_{cold} < 18$
	Dry Winter (w)	$P_{wdry} < P_{swet}/10$,
	Hot Summer (a)	$T_{hot} \geq 22$
Cold (D)		$T_{hot} > 10$ & $T_{cold} \leq 0$
	Dry summer (s)	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	Warm summer (b)	Not $T_{hot} \geq 22$ & $T_{mon10} \geq 4$
Both Cold climate regions (BWk and Dsb) are considered as Cold Mountain here		

resolution temperature and rainfall data. Beck *et al.*, 2018 draw global Köppen-Geiger climate classification maps at 1-km resolution. Raju *et al.*, 2013 studied a district- level climate classification in India using the Moisture Index for the period 1971-2005 and displayed the climate classes based on the Moisture Index.

It is clear from previous studies that India, like many other regions globally, is experiencing changes in temperature and rainfall patterns due to climate change. In response to these trends, adaptation strategies including water management, agricultural practices, urban planning, and disaster preparedness are crucial to mitigate the adverse effects of climate change on India's society and economy (Kothiyari and Singh 1996, Singh *et al.*, 2020). It is well-evident from past studies that a Global climate shift occurred during 1976/77 period and some researchers have proved that the climate shift affected the pattern of Indian Summer Monsoon (Miller *et al.*, 1994, Sahana *et al.*, 2015). In this changing rainfall and temperature scenario, a persistent pattern of rainfall shifts is observed; for example, India might have experienced a shift in climate class over the past few decades. Despite these findings, the relationship between the climate class shift and global teleconnections needs to be clearly understood. While those examine climate zone transitions without explicit dynamical attribution or connection to global teleconnection, neither addresses the role of climate variability in long-term climate reorganization. The present study focuses on this gap area. This study provides

a process-based framework linking climate zone shifts to the oceanic modes and examines the responsible mechanism for it. By integrating long-term observations (1951–2020), Köppen–Geiger classification, and dynamical diagnostics, this work establishes a direct connection between large-scale climate variability, physical mechanisms, and agro-climatic impacts.

From the Himalayan foothills in the north to the coastal plains in the south, each subdivision presents a unique climatic profile, influenced by factors such as latitude, altitude, proximity to the ocean, and the seasonal migration of weather systems. In this study, we investigate the historical archives, tracing back centuries to uncover evidence of climate variability and modulation within these subdivisions. Furthermore, this study examines the role of natural climate drivers and the Indian Summer Monsoon in shaping India's climate zones over time. By understanding the interactions between these large-scale climate phenomena and regional climatic dynamics, we gain valuable insights into the mechanisms driving climate variability within Indian territories.

2. Data and methodology

2.1. Climate data

In this study, we used IMD gridded rainfall and maximum and minimum temperatures for 1951-2020. The whole historical period from 1951-2020 of moving annual

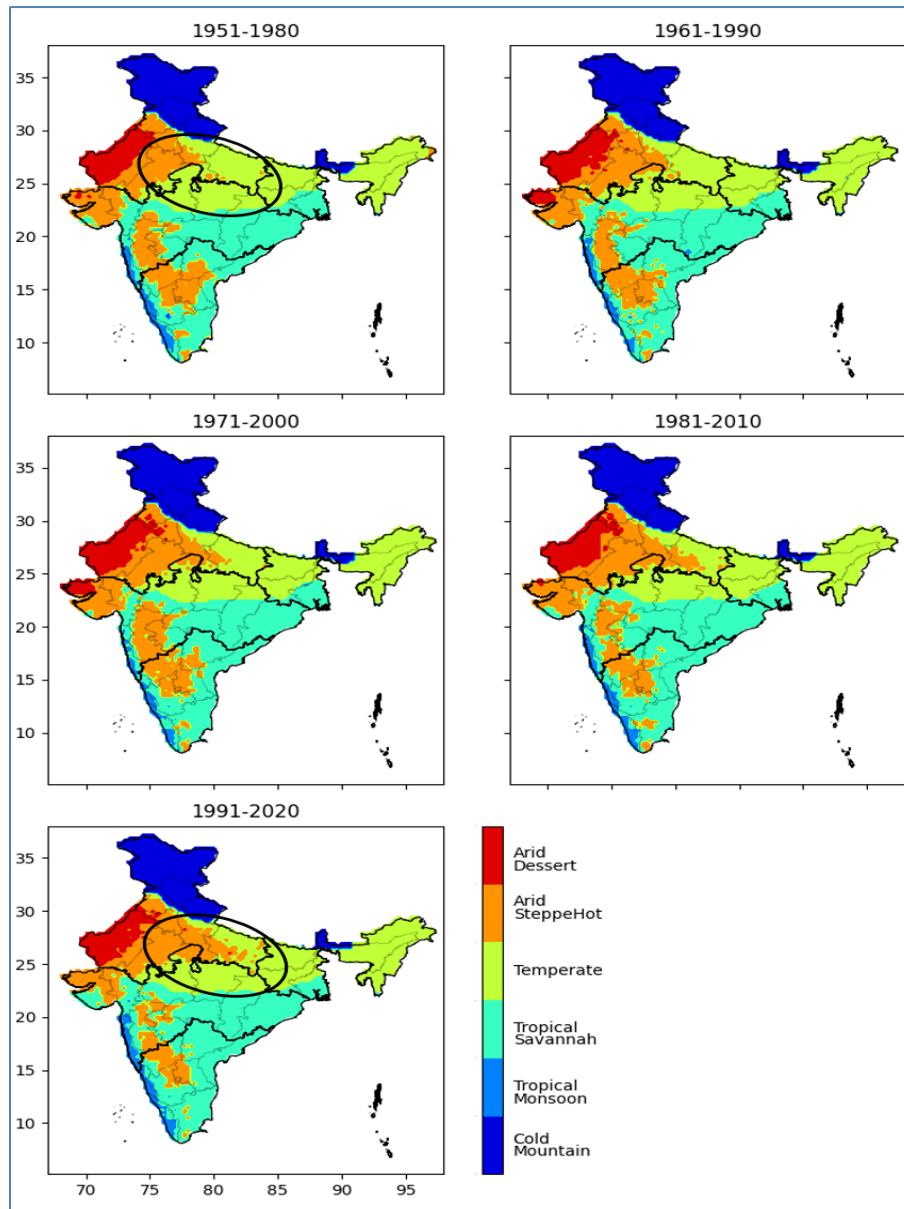


Fig. 1. Köppen-Griger classification of India subdivision

climatological mean 30-years updated every decade, in this way 5 climatological epochs a) Epoch1 (1951-1980), b) Epoch2 (1961-1990), c) Epoch3 (1971-2000), d) Epoch4 (1981-2010) and e) Epoch5 (1991-2020) are analysed thoroughly. The gridded rainfall data is $0.25^\circ \times 0.25^\circ$ resolution (Pai *et al.*, 2014) and the temperature data is $1^\circ \times 1^\circ$ resolution (Srivastava *et al.*, 2009). In this study to compute the classification criterion the temperature data is re-gridded to same as rainfall $0.25^\circ \times 0.25^\circ$ resolution. According to Peel *et al.*, 2007 The Köppen-Geiger different climate classes description and criteria are described in Table 1. Further, to understand the oceanic teleconnection between the change

in climate class and Indo-Pacific the monthly $1^\circ \times 1^\circ$ SST dataset used the Ocean Centennial in Situ Observation-Based Estimates of the Variability of SST and Marine Meteorological Variables (Hirahara *et al.*, 2014) (COBE 2 SST).

2.2. Methods

We follow the Köppen–Geiger climate classification as described in Peel *et al.*, 2007 which was also used by Kriticos *et al.*, 2012 (Table 1). This classification is identical to that presented by Köppen in 1936 with three differences. First, temperate climate is distinguished using

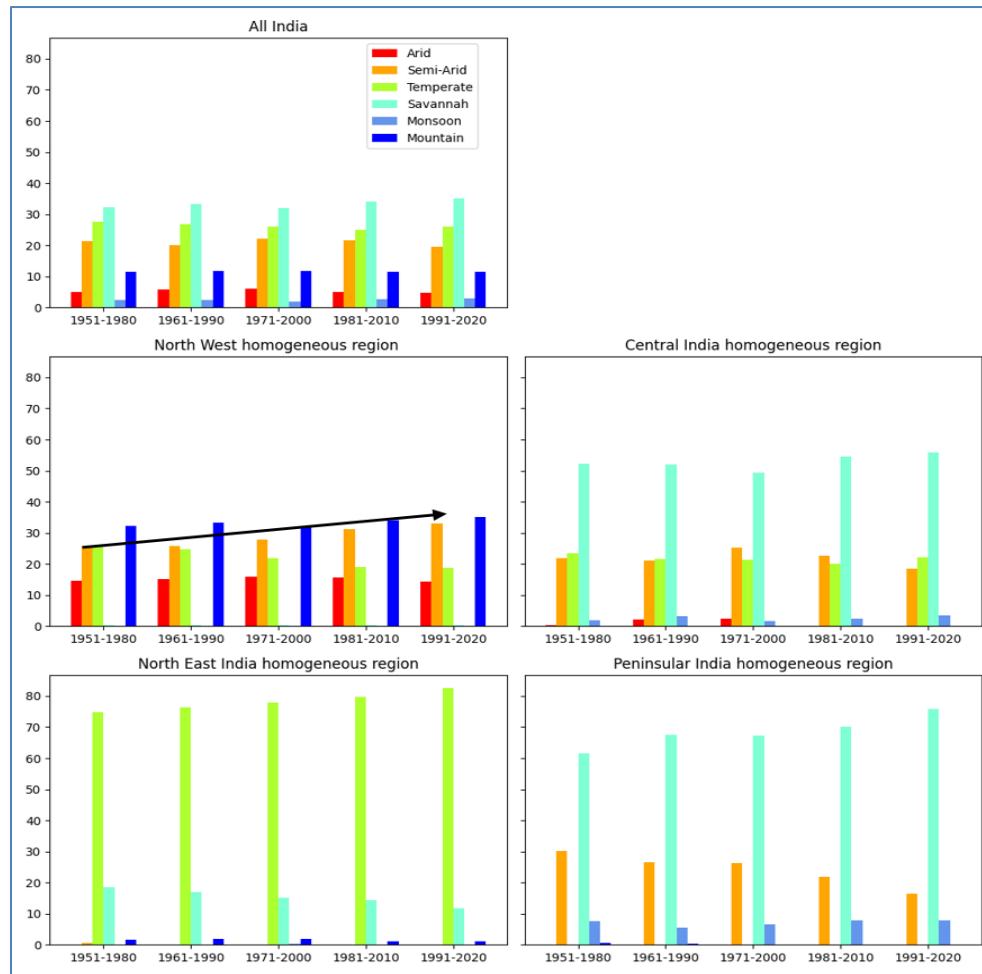


Fig. 2. Bar diagram of six climate zones in percentage (%) area over India

a 0 °C threshold instead of a 3 °C threshold. Second, the arid sub-climates desert and steppe were identified depending on whether 70% of precipitation occurred in summer or winter. Note that the tropical, temperate and cold climates are mutually exclusive but may intersect with the arid (B) class. To account for this, Arid climate was given precedence over the other classes. For each epoch yearly and monthly mean temperature and rainfall were calculated for 30 years from maximum and minimum temperature and rainfall. Further trend analysis for rainfall, maximum and minimum temperature computed for all climatological epochs. The statistical significance of the estimated trends was calculated using the Student's *t*-test at the 95% confidence level.

3. Results and discussion

3.1. Climate classification of India

The different climate classes description and their criterion are described in Table 1 according to Peel *et al.*,

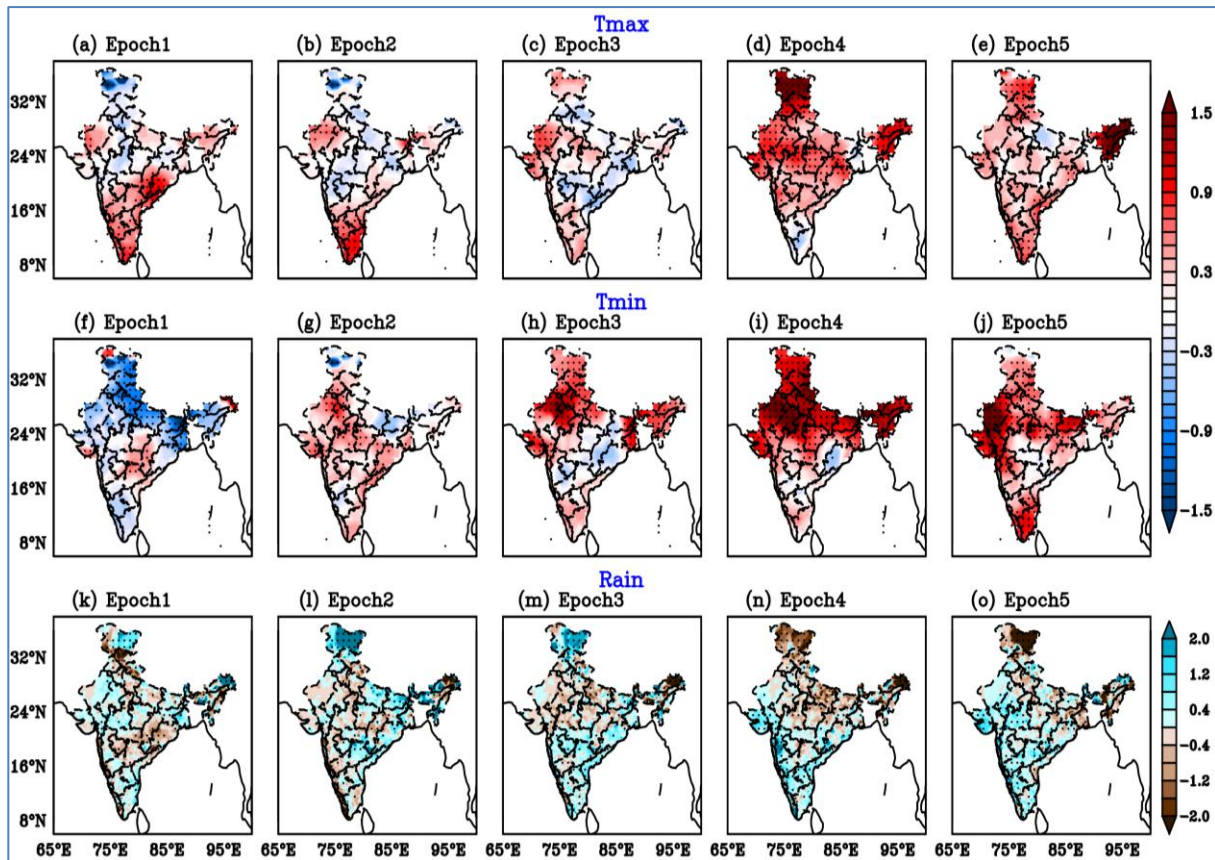
2007 and Beck *et al.*, 2018. India spans main four climate classes with a total of seven climate sub-classes as follows Tropical Monsoon (Am), Tropical Savannah (Aw), Arid Desert Hot (BWh), Arid Steppe Hot (BSh), Temperate Dry Winter Hot summer (CWa), Arid Steppe Cold (BSk) and Cold Dry Summer Warm Summer (Dsb). Here both cold climate regions (BWk and Dsb) are considered as Cold Mountain.

$$P_{threshold} = 2 \times MAT \text{ if at least 70\% Annual Precip in winter}$$

$$2 \times MAT/28 \text{ if at least 70\% Annual Precip in Summer}$$

$$2 \times MAT + 14 \text{ otherwise}$$

MAP = Mean Annual Precipitation, MAT = Mean Annual Temperature, T_{hot} = the air temperature of the warmest month (°C), T_{cold} = the air temperature of coldest month (°C), P_{dry} = precipitation in the driest month (mm/month), P_{wdry} = Precipitation in the driest month in winter



Figs. 3(a-o). The spatial patterns of the linear trend in (a-e) Tmax, (f-j) Tmin and (k-o) rainfall during epoch-1 - 5. The stippling indicates the regions with statistically significant at 95% confidence level

(mm/month), P_{swet} = precipitation in the wettest month in summer (mm/month). P_{dry} = precipitation of the driest month in summer, P_{wwet} = precipitation of the wettest month in winter. T_{mon10} = number of months where the temperature is above 10.

Fig. 1 shows the climate classification of India in five climatological epochs from 1951-2020. The six climatological zones span the meteorological subdivisions of India. Interestingly the Arid desert zone has increased at epoch3 (1971-2000) for the Gujarat subdivision. Arid Steppe-hot zone has increased progressively for northern India subdivisions from epoch1 to epoch5. This climate zone has increased from West UP to East UP from Epoch1 to Epoch5. It is noticed that there are major changes on the Arid and Semi-Arid climate zones in the historical periods 1961-1990 and 1991-2020. The western Saurashtra and Kutch sub-division is changed from Arid region to Semi-Arid region in the recent climate period. Apart from it during current climate period (1991-2020) the eastward extension of Arid Steppe Hot zone extended till East Uttar

Pradesh which was till West Uttar Pradesh in past period (1961-1990). In 1991-2020 west Vidarbha and Marathwada subdivision are in Semi-Arid climate zone however during 1961-1990 it was mostly in Tropical Savannah zone. There is a progression in the Tropical Monsoon zones over the sub-divisions Konkan & Goa, Coastal Karnataka and Kerala & Mahe from previous to recent period. The change in Arid and Semi-Arid zone is mainly due to the variation in maximum temperature and minimum temperature. Another noticeable shift in climate zones observed from Tropical Savannah to Temperate in Gangetic West Bengal subdivision during 1991-2020.

3.2. Relation with temperature and rainfall

To understand the exact area under each climate classes the percentage of area under each climate zone has over India. The bar diagram of Fig. 2 describes the six climate zones area percentage over India. From the bar diagram Fig. 2, both Arid regions are increased for Epoch3 (1971-2000).

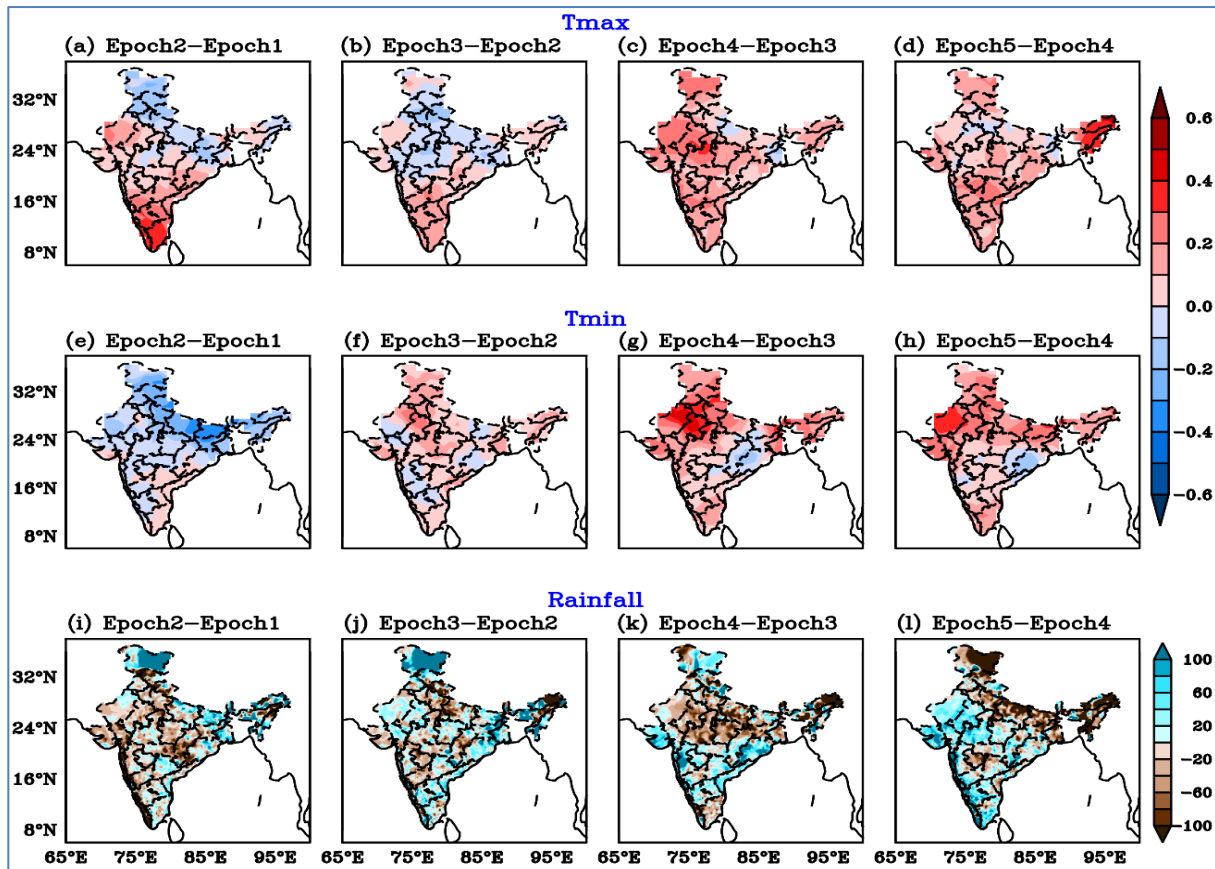


Fig. 4. Climatology maximum and minimum temperature and rainfall difference for each climatological epoch from its previous epoch

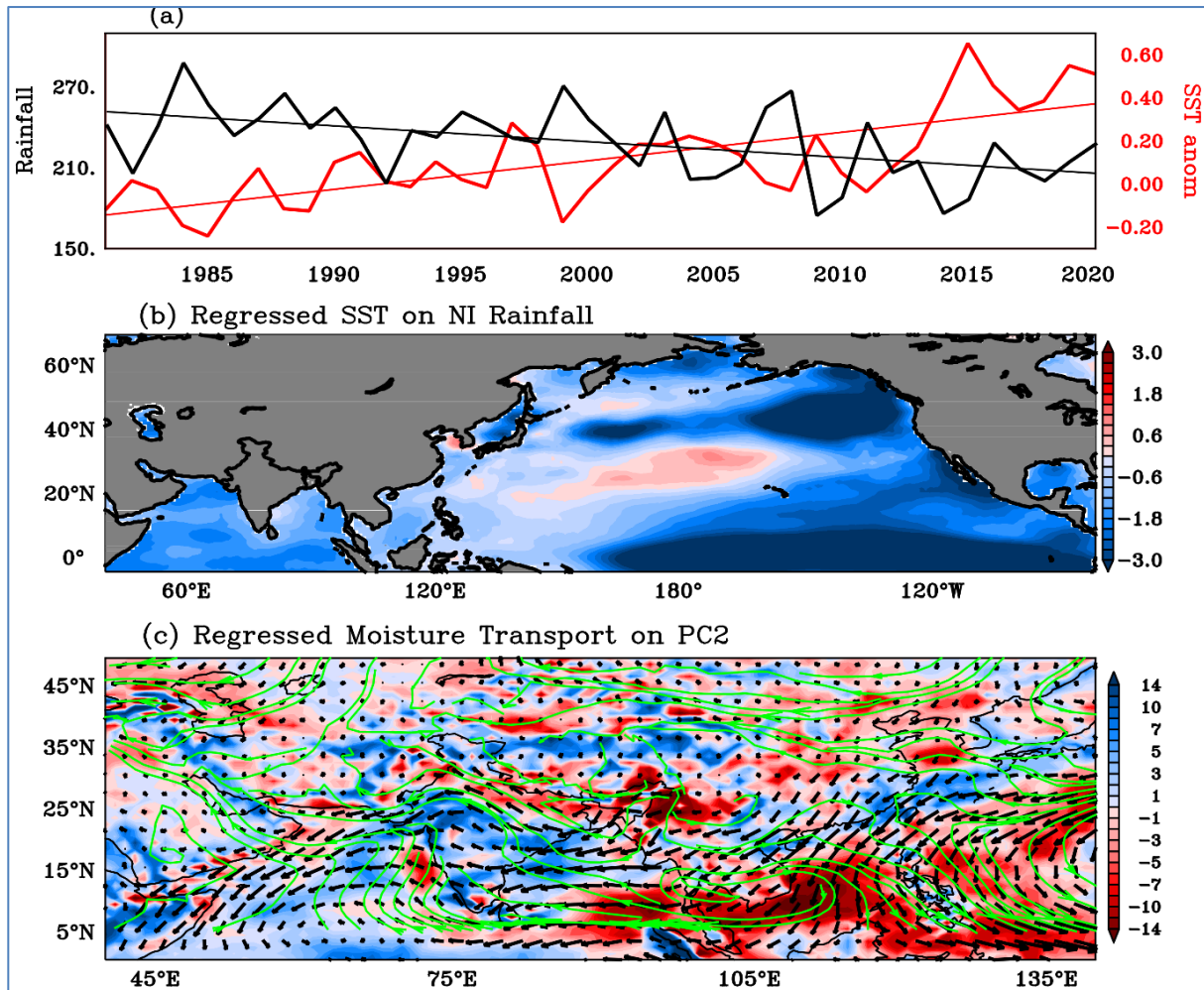
To better comprehend the changes in area percentage here four Indian homogeneous regions are calculated separately (Table 2). From Table 2 climate zones in percentage over North West homogeneous region display a clear increase of Arid Steppe Hot region and decrease in temperate region by nearly 7% from the earlier epoch to the recent epoch. Central India homogeneous region shows 2% increase in Tropical monsoon from the past to recent epoch (Table 2). North East homogeneous region converted from Tropical Savannah to Temperate climate class in recent climate epoch which indicates the increasing of highest air temperature over this region. However, Peninsular India homogeneous region transform to Arid Steppe Hot to Tropical Savannah ~15% which indicate the increase in Annual Rainfall or it's trend.

Further, trend analysis in Fig. 3 of maximum and minimum temperature and rainfall for each epoch support reflects the reason of typical growth and reduction of dryness for northern and southern India respectively. The maximum and minimum temperature has an increasing trend from epoch1 to epoch5 likewise Rainfall has a decreasing trend for northern India.

To understand the epochal modulation of temperature & rainfall than its previous one climatological difference for each epoch from its previous epoch calculated (Fig. 4). The Fig. 4 describes the gradual increase in maximum and minimum temperature from epoch 1 to epoch5 in contrast the rainfall shows the reduction in northern India but intensified for the southern India. In general, the changes over the climatic zone modulation for northern part of India is more alarming than the southern one as the northern part where the arid region has increased (west UP and east UP subdivision) is agriculturally active region for India.

3.3. Teleconnection with the North Pacific Ocean

Previous study suggests that knowing the phase of different oceanic variability of Indo-Pacific Ocean may lead to better long-term prediction of the seasonal monsoon rainfall (Krishnamurthy and Krishnamurthy 2014, Watanabe and Yamazaki 2014, Chowdary *et al.*, 2023, Kawamura *et al.*, 2005, Zhang *et al.*, 1997). In our study to understand the dryness of Northern India (NI) subdivisions regressed SST on the region rainfall. Fig. 5a



Figs.5(a-c). a) The yearly rainfall time series (in black) for Northern India Agro-Climatic Zone (West UP, East UP, Bihar, Gangetic West Bengal subdivisions) and The yearly SST anomaly time series (in red) for North Pacific for recent two climate epochs 1981-2020, b) Regressed SST on Northern India subdivision Rainfall and c) regressed vertically integrated (1000–300-hPa) moisture flux (shaded; mm/day) and vertically integrated moisture transport (vectors; kg/m/s) anomalies and the streamlines (in green contour) on second mode of North Pacific (PC2) SST anomaly

is the yearly rainfall time series from 1981 - 2020 for West UP, East UP, Bihar, and Gangetic West Bengal subdivisions where the pick of dryness in climate zone observed. To better understand the reason behind the rainfall deficit over NI, Indo-Pacific SST anomaly regressed on NI rainfall. This indicated the SST anomaly pattern as negative phase of Victoria mode (VM) which is the second mode of north pacific EOF analysis (19%, PC2) shown in Fig. 5b. It has been proved that the enhanced VM variability in recent decades which surpasses the PDO's variability in recent decades, signifying a notable shift (Zhang *et al.*, 2024a). Recent study shows that A positive phase of the VM is linked to reduced rainfall, which can result in a later arrival of the ISM (Zhang *et al.*, 2024b), impacting the agricultural and

livelihoods dependent on timely rainfall. Further Zhang *et al.*, 2024b showed the excitation of equatorial Rossby waves and the establishment of anomalous winds in the northern Indian Ocean. So, there is always a teleconnection with the VM and ISM rainfall. Further establish the relation regression analysis of vertically integrated moisture divergence/convergence and moisture transport (integrated from 1000 to 300 hPa), on PC2 done which revealed the moisture divergence pattern over NI as shown in Fig. 5c. It is important to note that weak dipole type convergence and divergence moisture transport pattern over India regressed on PC2. In addition, the regressed streamline analysis on PC2 (Fig 5c (green contour line)) show an anomalous anti-cyclonic pattern over Gangetic West Bengal and neighborhood.

TABLE 2

Climate zones in percentage (%) area over India's four homogeneous region

North West homogeneous region						
North West India	Arid Dessert	Arid Steppe-Hot	Temperate	Tropical Savannah	Tropical Monsoon	Cold Mountain
1951-1980	14.51	25.70	25.84	0.22	-	33.73
1961-1990	15.00	25.65	24.76	0.37	-	34.22
1971-2000	15.78	27.77	21.79	0.37	-	34.29
1981-2010	15.63	31.16	19.04	0.44	-	33.73
1991-2020	14.43	33.11	18.70	0.29	-	33.46
Central India homogeneous region						
Central India	Arid Dessert	Arid Steppe-Hot	Temperate	Tropical Savannah	Tropical Monsoon	Cold Mountain
1951-1980	0.33	21.94	23.49	52.25	1.98	-
1961-1990	2.23	21.03	21.62	52.06	3.06	-
1971-2000	2.36	25.20	21.42	49.44	1.57	-
1981-2010	0.19	22.76	20.11	54.48	2.45	-
1991-2020	-	18.43	22.23	55.94	3.40	-
North East India homogeneous region						
North East India	Arid Dessert	Arid Steppe-Hot	Temperate	Tropical Savannah	Tropical Monsoon	Cold Mountain
1951-1980	-	0.59	74.79	18.37	-	1.64
1961-1990	-	-	76.38	16.89	0.15	1.94
1971-2000	-	-	77.94	15.19	0.46	1.79
1981-2010	-	-	79.75	14.43	-	1.19
1991-2020	-	-	82.52	11.77	-	1.05
Peninsular India homogeneous region						
Peninsular India	Arid Dessert	Arid Steppe-Hot	Temperate	Tropical Savannah	Tropical Monsoon	Cold Mountain
1951-1980	-	30.27	0.12	61.61	7.52	0.48
1961-1990	-	26.60	0.12	67.58	5.45	0.24
1971-2000	-	26.19	-	67.26	6.43	0.12
1981-2010	-	21.93	-	70.06	7.89	0.12
1991-2020	-	16.39	-	75.73	7.76	0.12

3.4. Discussions

The epochal modulation of the surface extent of Indian climate zones, as defined by the Köppen–Geiger criteria, is analyzed in this study for the period from 1951 to 2020 using IMD gridded temperature and rainfall data.

Two significant findings came out of this analysis:

- (1) Over the historical period 1951–2020, the major change in climate zone is the shift to the drier region *i.e.*, Temperate to Arid steppe, hot and Tropical Savannah to

Temperate hot summer for the North West and North East homogeneous region, respectively (Fig. 1). The percentage area transformed to the drier region is nearly 7% in both homogeneous regions (Table 2). This modulation is mainly associated with the increasing trend in temperature and decreasing trend in rainfall (Fig. 3). For the Peninsular India homogeneous region, the climate zones shift towards the wetter zone, from Arid steppe hot to Tropical savannah by 15% (Table 2) due to a mainly increasing trend of rainfall (Fig. 3) in recent epochs (Fig 4).

(2) Finally, the climate classes shift to the drier climate zone in the Northern India Agro-Climatic Zone, which may affect paddy cultivation in the future. So, in terms of the cropping pattern agriculture calendar, the change is very important, and it needs to be monitored closely. Now it is vital to analyze how climate variability could lead to this dryness across meteorological subdivisions. Previous studies have already established the relation between the Indian Summer Monsoon and Indo-Pacific SST variability observed in the sea surface temperature (SST) of the North Pacific Ocean (Krishnamurthy and Krishnamurthy 2014, Watanabe and Yamazaki 2014, Chowdary *et al.*, 2023, Kawamura *et al.*, 2005). In recent papers (Zhang *et al.*, 2024a, Zhang *et al.*, 2024b) the positive phase of the Victoria Mode can delay the Indian Summer Monsoon onset by both tropical and extratropical pathways. A recent study shows that a positive phase of the VM is linked to reduced rainfall, which can result in a later arrival of the ISM (Zhang *et al.*, 2024b), impacting the agricultural calendar and livelihoods dependent on timely rainfall. Further this study showed the excitation of equatorial Rossby waves and the establishment of anomalous winds in the northern Indian Ocean. It has been shown that the enhanced VM variability in recent decades surpasses the PDO's variability, signifying a notable shift. In this study, for a better understanding of the reason behind the rainfall deficit over NI (West UP, East UP, Bihar, Gangetic West Bengal subdivisions), Indo-Pacific SST anomaly was regressed on NI rainfall. This indicated the SST anomaly pattern as the negative phase of the Victoria mode (VM), which is the second mode of the North Pacific EOF analysis (19%, PC2), shown in Fig. 5b. Further regression analysis of vertically integrated moisture divergence/ convergence and moisture transport (integrated from 1000 to 300 hPa) on PC2 was performed, revealing a moisture divergence pattern over NI (Fig. 5c). The main factor responsible for the suppression of rainfall over NI subdivisions is moisture divergence driven by the negative phase of VM. Overall, this study reveals that the negative phase of VM is the leading cause of shifting to the drier climate class in the northern India Agro-Climatic zone. The current shrinking and expected disappearance of the Tropical savannah and temperate climate zone will cause numerous problems related to food safety and local population displacement. This is something that must be taken into account in future socioeconomic development plans for the country.

The present study differs from Transition in Köppen Climate Zones and Its Impacts on Hydroclimatic Extremes Across India and Regional Drought Modulation by ENSO and IOD as Indicated by the Standardized Precipitation Index in both scope and methodology. While the former examines climate zone transitions without explicit dynamical attribution, and the latter focuses on drought

variability driven by El Niño–Southern Oscillation and Indian Ocean Dipole, neither addresses the role of North Pacific variability in long-term climate reorganization. In contrast, this study provides a process-based framework linking climate zone shifts to the Victoria Mode, highlighting its emerging dominance over the Pacific Decadal Oscillation. By integrating long-term observations (1951–2020), Köppen–Geiger classification, and dynamical diagnostics, this work establishes a direct connection between large-scale climate variability, physical mechanisms, and agro-climatic impacts.

Overall, the results suggest that the increasing influence of the negative phase of the Victoria Mode plays a pivotal role in modulating rainfall variability and driving the expansion of drier climate classes over Northern India. The continued contraction of tropical savannah and temperate climate zones poses serious risks to food security, water resources, and regional livelihoods. These findings underscore the importance of incorporating large-scale climate variability into long-term agricultural planning and climate adaptation strategies in India.

Acknowledgements

The authors acknowledge the use of temperature and precipitation gridded data from India Meteorological Department Pune Climate Prediction and Monitoring Group.

Data Availability

The gridded rainfall and temperature is available from the official website of IMD Pune <https://imd pune.gov.in/lrfindex.php>. COBE 2 SST downloaded from NOAA PSL website the link is <https://downloads.psl.noaa.gov/Datasets/COBE2/>.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Ananya Karmakar: Data analysis and Resources, Manuscript writing and editing.
Rajib Chattopadhyay: Conceptualization, Writing-review and editing. (email: rajibliss@gmail.com)
Pulak Guhathakurta: methodology support and guidance. (email: pquhathakurta@rediffmail.com)
K S Hosalikar: Supervision and advisory support. (email: hosalikar.ks@gmail.com)
Mrutyunjay Mohapatra: Supervision and advisory support. (email: mohapatraimd@gmail.com)

Disclaimer: The contents and views expressed in this research article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

- Alkama R., 2014, "Human influence on changes in the distribution of land precipitation". *J. Hydrol* **511**, 589–593. <https://doi.org/10.1016/j.jhydrol.2014.02.016>.
- Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., and Wood, E. F., 2018, "Present and future Köppen-Geiger climate classification maps at 1-km resolution", *Scientific data*, **5**, 1, 1-12. <https://doi.org/10.1038/sdata.2018.214>.
- Chowdary, J.S., Saikrishna, T.S., Ramu, D.A., Darshana, P., Parekh, A., Gnanaseelan, C. and Osuri, K.K., 2023. Symmetric and asymmetric response of Indian summer monsoon rainfall to different ENSO decay phases in observations and CMIP6 models. *Global and Planetary Change*, **220**, p.104000. <https://doi.org/10.1016/j.gloplacha.2022.104000>
- Feng, S., Ho, C.H., Hu, Q., Oglesby, R.J., Jeong, S.J. and Kim, B.M., 2012. Evaluating observed and projected future climate changes for the Arctic using the Köppen-Trewartha climate classification. *Climate Dynamics*, **38**(7), pp.1359-1373. <https://doi.org/10.1007/s00382-011-1020-6>
- Folland, C.K., Karl, T.R., Christy, J.R., Clarke, R.A., Gruza, G.V., Jouzel, J., Mann, M.E., Oerlemans, J., Salinger, M.J. and Wang, S.W., 2001. Observed climate variability and change. *Climate change*. <https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1256/0043.16502320517353>
- Hirahara, S., Ishii, M. and Fukuda, Y., 2014. Centennial-scale sea surface temperature analysis and its uncertainty. *Journal of Climate*, **27**(1), pp.57-75. <https://doi.org/10.1175/JCLI-D-12-00837.1>
- Kawamura, R., Uemura, K. and Suppiah, R., 2005. On the recent change of the Indian summer monsoon-ENSO relationship. *Sola*, **1**, pp.201-204. <https://doi.org/10.2151/sola.2005-052>
- Koppen, W., 1936. Das geographische system de klimare. *Handbuch der klimatologie*. <https://cir.nii.ac.jp/crid/1571980075115373056>
- Kothiyari, U.C. and Singh, V.P., 1996. Rainfall and temperature trends in India. *Hydrological processes*, **10**(3), pp.357-372. [https://doi.org/10.1002/\(SICI\)1099-1085\(199603\)10:3<357::AID-HYP305>3.0.CO;2-Y](https://doi.org/10.1002/(SICI)1099-1085(199603)10:3<357::AID-HYP305>3.0.CO;2-Y)
- Krishnamurthy, L. and Krishnamurthy, V.J.C.D., 2014. Influence of PDO on South Asian summer monsoon and monsoon-ENSO relation. *Climate dynamics*, **42**(9), pp.2397-2410. <https://doi.org/10.1007/s00382-013-1856-z>
- Krishnan, R., Sanjay, J., Gnanaseelan, C., Mujumdar, M., Kulkarni, A. and Chakraborty, S., 2020. Assessment of climate change over the Indian region: a report of the ministry of earth sciences (MOES), government of India (p. 226). Springer Nature. <https://doi.org/10.1007/978-981-15-4327-2>.
- Kriticos, D.J., Webber, B.L., Leriche, A., Ota, N., Macadam, I., Bathols, J. and Scott, J.K., 2012. CliMond: global high-resolution historical and future scenario climate surfaces for bioclimatic modelling. *Methods in Ecology and Evolution*, **3**(1), pp.53-64. <https://doi.org/10.1111/j.2041-210X.2011.00134.x>
- Kumar, V., Jain, S.K. and Singh, Y., 2010. Analysis of long-term rainfall trends in India. *Hydrological Sciences Journal–Journal des Sciences Hydrologiques*, **55**(4), pp.484-496. <https://doi.org/10.1080/02626667.2010.481373>
- Loarie, S.R., Duffy, P.B., Hamilton, H., Asner, G.P., Field, C.B. and Ackerly, D.D., 2009. The velocity of climate change. *Nature*, **462**(7276), pp.1052-1055. <https://doi.org/10.1038/nature08649>
- Mahlstein, I., Daniel, J.S. and Solomon, S., 2013. Pace of shifts in climate regions increases with global temperature. *Nature Climate Change*, **3**(8), pp.739-743. <https://doi.org/10.1038/nclimate1876>
- Miller, A.J., Cayan, D.R., Barnett, T.P., Graham, N.E. and Oberhuber, J.M., 1994. The 1976-77 climate shift of the Pacific Ocean. *Oceanography*, **7**(1), pp.21-26. <https://www.jstor.org/stable/43925525>
- New, M., Todd, M., Hulme, M. and Jones, P., 2001. Precipitation measurements and trends in the twentieth century. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, **21**(15), pp.1889-1922. <https://doi.org/10.1002/joc.680>
- Pai, D.S., Rajeevan, M., Sreejith, O.P., Mukhopadhyay, B. and Satbha, N.S., 2014. Development of a new high spatial resolution (0.25° × 0.25°) long period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. *Mausam*, **65**(1), pp.1-18. <https://doi.org/10.54302/mausam.v65i1.851>
- Peel, M.C., Finlayson, B.L. and McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and earth system sciences*, **11**(5), pp.1633-1644. <https://doi.org/10.5194/hess-11-1633-2007>
- Raju, B.M.K., Rao, K.V., Venkateswarlu, B., Rao, A.V.M.S., Rao, C.R., Rao, V.U.M., Rao, B.B., Kumar, N.R., Dhakar, R., Swapna, N. and Latha, P., 2013. Revisiting climatic classification in India: a district-level analysis. *Current Science*, pp.492-495. <https://www.jstor.org/stable/24098002>
- Rubel, F. and Kottek, M., 2011. Comments on: "The thermal zones of the Earth" by Wladimir Köppen (1884). *Meteorologische Zeitschrift*, **20**(3), p.361. DOI: [10.1127/0941-2948/2011/0285](https://doi.org/10.1127/0941-2948/2011/0285)
- Sahana, A.S., Ghosh, S., Ganguly, A. and Murtugudde, R., 2015. Shift in Indian summer monsoon onset during 1976/1977. *Environmental Research Letters*, **10**(5), p.054006. DOI: [10.1088/1748-9326/10/5/054006](https://doi.org/10.1088/1748-9326/10/5/054006)
- Sandel, B., Arge, L., Dalsgaard, B., Davies, R.G., Gaston, K.J., Sutherland, W.J. and Svenning, J.C., 2011. The influence of Late Quaternary climate-change velocity on species endemism. *Science*, **334**(6056), pp.660-664. DOI: [10.1126/science.1210173](https://doi.org/10.1126/science.1210173)
- Sankaran, A., Chavan, S.R., Ali, M., Sindhu, A.D., Dharan, D.S. and Khan, M.I., 2021. Spatiotemporal variability of multifractal properties of finer resolution daily gridded rainfall fields over India. *Natural Hazards*, **106**(3), pp.1951-1979. <https://doi.org/10.1007/s11069-021-04523-0>
- Singh, G., Panda, R.K. and Nair, A., 2020. Regional scale trend and variability of rainfall pattern over agro-climatic zones in the mid-Mahanadi river basin of eastern India. *Journal of Hydro-environment Research*, **29**, pp.5-19. [10.1016/j.jher.2019.11.001](https://doi.org/10.1016/j.jher.2019.11.001)
- Srivastava, A.K., Rajeevan, M. and Kshirsagar, S.R., 2009. Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. *Atmospheric Science Letters*, **10**(4), pp.249-254. <https://doi.org/10.1002/asl.232>

- Watanabe, T. and Yamazaki, K., 2014. Decadal-scale variation of South Asian summer monsoon onset and its relationship with the Pacific decadal oscillation. *Journal of Climate*, 27(13), pp.5163-5173. <https://doi.org/10.1175/JCLI-D-13-00541.1>
- Zhang, Y., Wallace, J.M. and Battisti, D.S., 1997. ENSO-like interdecadal variability: 1900–93. *Journal of climate*, 10(5), pp.1004-1020. [https://doi.org/10.1175/1520-0442\(1997\)010<1004:ELIV>2.0.CO;2](https://doi.org/10.1175/1520-0442(1997)010<1004:ELIV>2.0.CO;2)
- Zhang, X., Zwiers, F.W., Hegerl, G.C., Lambert, F.H., Gillett, N.P., Solomon, S., Stott, P.A. and Nozawa, T., 2007. Detection of human influence on twentieth-century precipitation trends. *Nature*, 448(7152), pp.461-465. <https://doi.org/10.1038/nature06025>
- Zhang, S., Hu, P., Huang, G. and Qu, X., 2024. Observed impacts of the North Pacific Victoria Mode on Indian summer monsoon onset. *Atmospheric Research*, 297, p.107126. [10.1016/j.atmosres.2023.107126](https://doi.org/10.1016/j.atmosres.2023.107126)
- Zhang, S., Qu, X. and Huang, G., 2024. Enhanced impacts of the North Pacific Victoria mode on the Indian summer monsoon onset in recent decades. *Geoscience Letters*, 11(1), p.6. <https://doi.org/10.1186/s40562-024-00324-y>

