

REVIEW

A post-AR6 update on observed and projected climate change in India

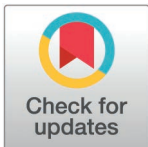
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Abstract

This article provides an update on observed and projected climate change in India. India's average temperature has risen by approximately 0.89°C during 2015–2024 relative to 1901–1930. Models project additional warming of about 1.2–1.3°C over India by mid-century under SSP2-4.5 (relative to the recent past (1995–2014)). The tropical Indian Ocean has warmed at 0.12°C per decade since 1950 and is projected to warm at 0.17°C per decade through 2100 under SSP2-4.5. Marine heatwave days are projected to rise from about 20 days per year historically (1970–2000) to nearly 200 days per year by mid-century. Mean southwest monsoon rainfall has declined by 0.5–1.5 mm day⁻¹ every decade over the Indo-Gangetic plains and northeast India during 1951–2024. Extreme precipitation events have also intensified, with coastal Gujarat experiencing about 0.15 additional extreme events every decade during 1951–2024. CMIP6 models project about 6–8% increase in all-India mean southwest monsoon rainfall by mid-century relative to the recent past, though with high spatial variability. The Hindu Kush Himalaya have witnessed accelerated warming of about 0.28°C per decade (1950–2020); glacier mass losses accelerated from -0.17 m water equivalent (w.e.) yr⁻¹ (2000–2009) to -0.28 m w.e. yr⁻¹ (2010–2019), and models indicate a 30–50% reduction in glacier volume by 2100 at 1.5–2°C global warming levels. In the Arabian Sea, maximum pre-monsoon cyclone intensity has increased by 40% over 1982–2019. Sea levels in the north Indian Ocean have risen at 3.3 mm year⁻¹ (1993–2017), with extreme sea level events increasing 2–3 fold. Historical one-in-hundred-year extreme sea level events along the Arabian Sea coastline are projected to become annual occurrences by mid-century under SSP2-4.5. We also report increasing trends in compound hot-dry extremes in parts of India. Our findings highlight spatially differentiated hotspots of climate change across India and provide policy-relevant insights.



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1. Introduction

The 2023 Synthesis Report by the Intergovernmental Panel on Climate Change [1] has asserted that, “Human activities, principally through emissions of greenhouse gases, have *unequivocally* caused global warming, with global surface temperature reaching 1.1°C above 1850–1900 in 2011–2020.” According to the report, this warming has contributed to unprecedented rates of ice melt, sea level rise, and a surge in extreme weather events globally. The impacts of this warming are extensive, affecting every component of the climate system, disrupting natural and human systems across the globe [1]. The IPCC’s AR6 asserts with *high confidence* that climate change is influencing weather and climate extremes in every region around the world [2]. These changes manifest as increasingly intense and frequent extreme weather events such as heatwaves, heavy precipitation, droughts, and tropical cyclones, which are attributed to anthropogenic emissions with different levels of confidence depending on the quality of data and the available lines of evidence [3].

While global assessments provide crucial context, regional climate change trends may not align with large-scale signals, and studying them is essential for effective and regionally relevant adaptation planning. Adaptation strategies must be based on the most current scientific understanding since outdated or incomplete information could lead to maladaptation [4], leaving communities vulnerable to emerging and rapidly complexifying risks. This is particularly critical for India, with its diverse geography spanning the Himalaya mountains to coastal regions, relatively high baseline temperatures, and reliance on monsoon precipitation, where different regions face unique and complex climate risks that require carefully tailored adaptation responses. Furthermore, the rapid pace of climate change means that adaptation strategies developed using older assessments may no longer be sufficient for addressing current and emerging risks.

The ‘Assessment of Climate Change over the Indian Region’ published in 2020 [5] provided the first comprehensive analysis of observed and projected climate change specific to India. However, several factors necessitate an updated assessment:

1. The assessment in [5] was based on the previous generation of climate models (i.e., CMIP5). The current generation of models (CMIP6) shows notable improvements, particularly in simulating the climatological mean rainfall patterns of the Indian monsoon although representation of key ocean-atmosphere interactions remains a challenge [6,7].
2. The IPCC AR6 [8], released in 2021, reported on regional climate change through its Atlas chapter but focussed on sub-continental scale changes (e.g., South Asia as a whole). Thus, spatial resolutions are generally too coarse to capture geographic differences in climate trends across a vast, geographically and climatically diverse country like India within the South Asian region.
3. Scientific literature post the AR6’s release in 2021 has enhanced our understanding of key climate trends and mechanisms for India. In particular, the emergence of literature on how different climate hazards interact and compound each other has revealed risks that may not have been fully appreciated in previous assessments.

In the light of these observations, the aim of this paper is to provide an update on key observed and projected climate trends within India by integrating findings from, 1. Updated observational data, and 2. Projections reported in recent scientific literature (especially post-AR6) based on the latest generation of climate models, i.e., CMIP6. This integration of new knowledge is crucial for ensuring that adaptation planning remains responsive to the latest understanding from the physical science of climate change.

This assessment is designed to provide the most current understanding of regional changes in key climate variables and processes in order to assist policymakers, scientists, and the public. We note that the focus of this paper is on changes in physical climate and not on impacts, adaptation, or mitigation. In other words, it is intended to be a regional analogue of the IPCC's *WG1* report. Therefore, while policy-relevant, our findings are not policy-prescriptive, aiming instead to inform the future development of targeted adaptation measures appropriate to different regions of India based on the current state of knowledge.

The paper is structured as follows: Section 2 describes the data and methods used for the analysis performed in this paper, Section 3 presents updated assessments of observed and projected changes in six key climate components: land temperature (3.1), Indian Ocean warming and marine ecosystem changes (3.2), precipitation (3.3), cryosphere (3.4), tropical cyclones (3.5), and sea level rise (3.6). Section 4 discusses the emergent understanding of compound events in the Indian context, with a particular focus on heatwave-drought events. Section 5 synthesizes these findings into a quantitative table summarizing key assessments of this paper, and a qualitative *regional climate hotspots map* for India.

2. Data and methods

Unless otherwise noted, changes across variables are reported against the standard IPCC AR6 baseline 1995–2014, which is referred to as the “recent past” [9].

We performed original analysis to produce Fig 1,2 and 4. The datasets and methods used for the analysis are described below.

2.1 Data

We describe the datasets used to produce each figure below.

2.1.1. Fig 1. Land temperature anomalies are plotted using CRU TS4.09 Land Surface Temperature dataset containing monthly mean air temperature data on a $0.5^\circ \times 0.5^\circ$ grid [10]. These data can be downloaded from: <https://crudata.uea.ac.uk/cru/data/hrg/>.

Ocean temperature anomalies are plotted using the HadSST v4.1.1 Sea Surface Temperature dataset comprises monthly SST on a $1^\circ \times 1^\circ$ grid [11]. Data can be downloaded from: <https://www.metoffice.gov.uk/hadobs/hadsst4/>. The Indian Ocean Basin is defined as 40–120E, 30S–30N.

Both datasets span the period 1901–2024.

2.1.2. Fig 2. We use the Indian Meteorological Department (IMD)'s Daily gridded maximum and minimum temperatures at $1^\circ \times 1^\circ$ resolution spanning 1951–2024. These can be downloaded from https://www.imdpune.gov.in/cmpg/Griddata/Max_1_Bin.html (maximum temperature) and https://www.imdpune.gov.in/cmpg/Griddata/Min_1_Bin.html (minimum temperature). These observational gridded datasets are generated from quality-controlled station data [13].

2.1.3. Fig 4. We use IMD Daily Gridded Rainfall Data available at $0.25^\circ \times 0.25^\circ$ resolution spanning 1951–2024 [14], which can be downloaded from https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_NetCDF.html.

2.2 Methods

In this section, we describe the extremes indices chosen for analysis, and trend and significance testing to produce Fig 2 and 4.

Annual Mean Temperature Anomalies (1901-2024)

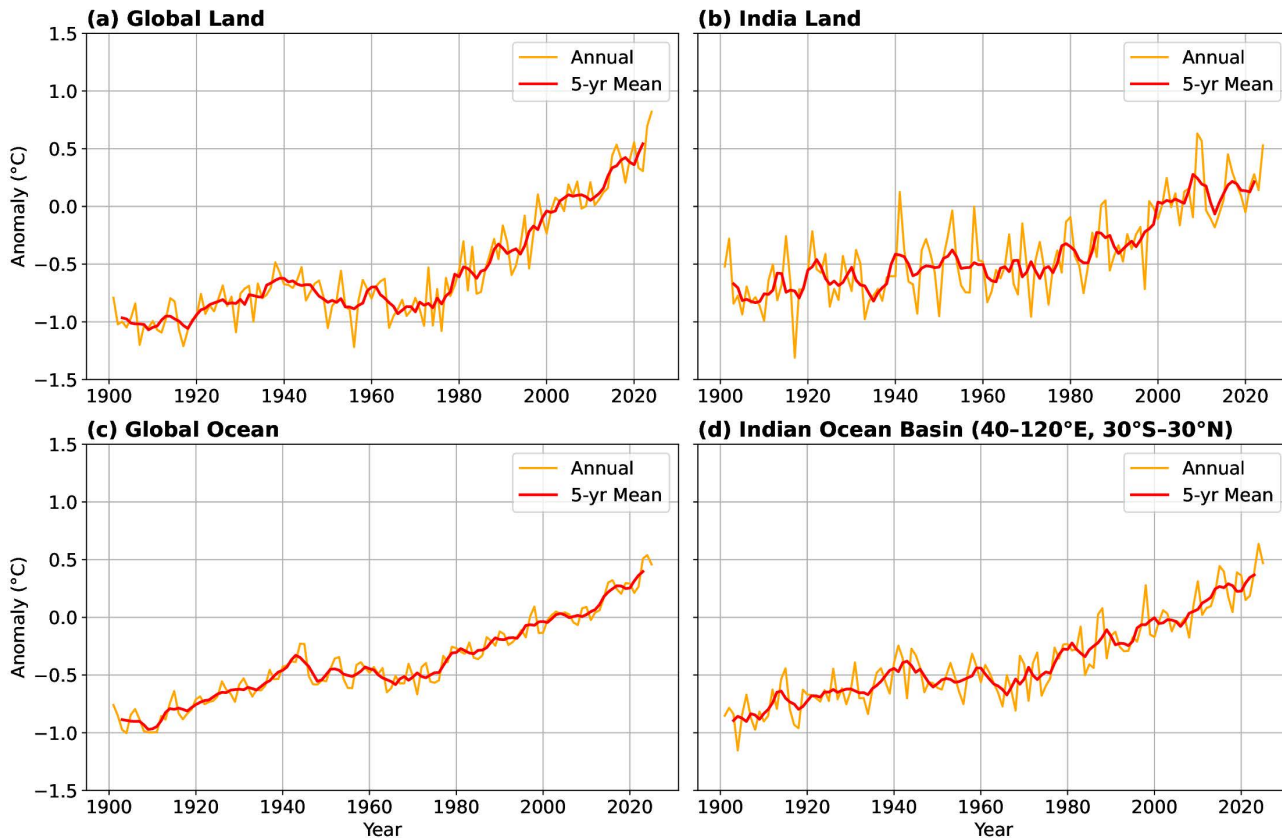


Fig 1. Annual mean temperature anomalies (°C) relative to the near future (1995–2014) period for (a) global land, (b) India land, (c) global ocean SST, and (d) Indian Ocean basin SST (40–120E, 30S–30N). Annual anomalies are indicated by thin orange lines, and 5-year rolling means by thick red lines. Data: CRU TS4.09 land surface temperature [10] and HadSST 4.1.1 sea surface temperature [11].

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2.2.1 Analysis of extreme temperature. We analyze trends in standardized extreme indices of warm days (TX90p) and warm nights (TN90p) ([16]: Annex VI) over the Indian land region during the 1951–2024 period in Fig 2. TX90p (TN90p) refers to the percentage of days with daily maximum (minimum) temperatures exceeding 90th percentile calculated over a baseline period.

IMD’s daily gridded maximum (minimum) temperature dataset is used to compute the 90th-percentile temperature threshold during the 1995–2014 baseline for each calendar day of year at each grid cell. To avoid possible inhomogeneity across the in-base and out-base periods, we follow Zhang et al. [12].

The maximum temperature index for year y at each grid cell is calculated as:

$$TX90p(y) = \sum_d Tmax(d, y) \text{ for } Tmax(d, y) \geq Qmax(d)$$

Where, $Tmax(d, y)$ is the maximum temperature on day d in year y , and $Qmax(d)$ is 90th percentile maximum temperature threshold for day d calculated over the baseline period.

The minimum temperature index at each grid cell is defined analogously:

Temperature extremes over the Indian region (1951-2024)

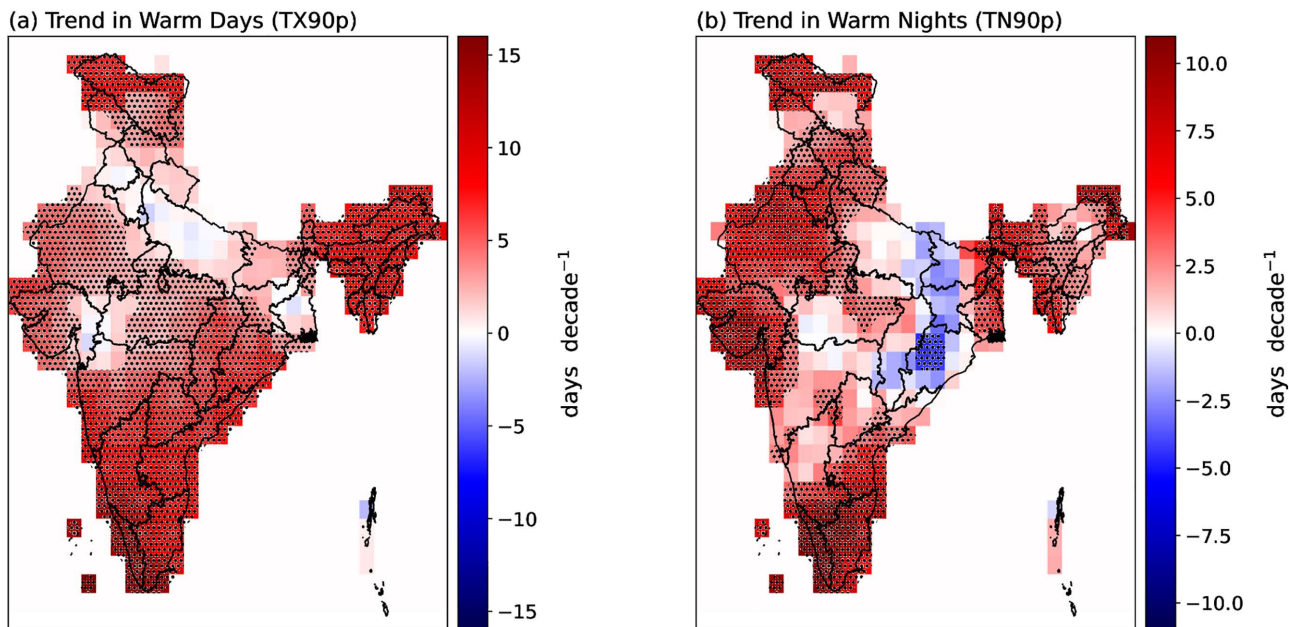


Fig 2. Linear trends (days decade⁻¹) over 1951–2024 in (a) the annual number of days when daily maximum temperature exceeds its 90th percentile (TX90p), and (b) the annual number of days when daily minimum temperature exceeds its 90th percentile (TN90p). Percentiles were calculated for the 1985–2014 baseline, with inhomogeneities across in-base and out-base periods corrected following Zhang et al. [12]. Stippling indicates trend values significant at 95% confidence level (two-tailed). Data: IMD 1°x1° gridded daily maximum and minimum temperature data available from: <https://imdpune.gov.in/lrfindex.php> [13].

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$$TN90p(y) = \sum_d Tmin(d, y) \text{ for } Tmin(d, y) \geq Qmin(d)$$

Trend in TX90p and TN90p counts is estimated from a linear least-squares regression for the 1951–2024 period. Trends significant at the 95% level following a two-tailed Student’s t-test are shown stippled in Fig 2.

2.2.2 Rainfall mean and extremes. In Fig 4A, at each grid cell, we average daily rainfall during June–September (JJAS) for each year to obtain the JJAS mean rainfall (mm day⁻¹). Extreme rainfall trends in Fig 4B were analyzed using the standardized R150mm index, which represents the annual count of days when daily precipitation ≥ 150 mm ([16]: Annex VI). The threshold of 150 mm/day for daily extreme precipitation over the Indian region was chosen following Goswami et al. [17], Rajeevan et al. [18], and Roxy et al. [19]. We limited the analysis to latitudes $\leq 32.5^\circ$ N since rain gauge stations are sparse at higher latitudes [20].

Trends in mean and extreme rainfall are estimated from a linear least-squares regression for the 1951–2024 period. Trends significant at the 95% level following a two-tailed Student’s t-test are shown stippled in Fig 4.

3. Climate change assessments

This section provides updated assessments on observed and projected regional changes in climate across India.

3.1 Land temperature change

Land temperatures have a direct impact on humans and have significant variations based on the adjoining topography and features.

3.1.1. Observed changes. The regional climate change assessment for India in 2020 reported that India's average warming was around 0.7°C over 1901–2018, warming at a rate of about 0.15°C per decade during 1986–2015 [21]. It further reported that warming has been geographically uneven with parts of north India having experienced warming rates exceeding 0.2°C per decade, with others lower than 0.1°C per decade.

Here, we update the estimate of India's average surface warming to 0.89°C in 2015–2024 over 1901–1930 based on our analysis of CRU TS4.09's gridded monthly land temperature dataset spanning the 1901–2024 period (Fig 1B). This makes India's warming muted compared to the global land temperature warming of about 1.42°C over the same period (Fig 1A), which has been attributed to a variety of factors such as lower warming rates of the tropics, air pollution, and irrigation, among others [22].

Despite the muted warming, several previous studies have reported that temperature extremes have become more frequent across many parts of India [23,24,25]. Fig 2 illustrates trends in temperature extremes over the Indian land region over the 1951–2024 period based on our analysis of IMD datasets for daily maximum and minimum temperatures. Fig 2A indicates that the majority of the country, except parts of the Indo-Gangetic plains and isolated regions in central India, have witnessed significant increases in the number of Warm Days (TX90p) by about 5–10 days per decade. Northeast and peninsular India have witnessed the most prominent rise, with rates as high as 10–15 days per decade. Likewise, Fig 2B indicates that large parts of the country have witnessed an increase in Warm Nights, with the most prominent trends seen over Rajasthan, Gujarat, and Southern and Northeast India. Parts of central India have witnessed smaller changes or even a slight reduction, attributed in part to aerosol loading [26].

Concurrently, trends in the intensity of the warmest day of the year (annual maximum of daily maximum temperatures; also called TXx) exhibit notable spatial patterns, with parts of India such as Western India and the Northeast having witnessed warming of about 1.5–2°C over 1951–2024 (Fig A in S1 Text; panel a), which is notably higher than India's centennial-scale mean surface warming. However, the warmest night of the year (annual maximum of daily minimum temperatures; also called TNx) does not exhibit notable trends or spatial patterns over 1951–2024 (Fig A in S1 Text; panel b).

Moreover, the frequency, amplitude, cumulative magnitude, and duration of summertime heatwaves have also increased over many parts of India over 1951–2020, most prominently in Northwest India [27].

3.1.2. Projected changes. Recent studies using CMIP6 models project substantial increases in temperature across India [28]. Based on our survey of pertinent literature (Table A in S1 Text), we assess that the projected all-India warming under SSP2-4.5 is about 1.2–1.3°C (multimodel mean) by mid-century (2041–2060 average) relative to the recent past (1995–2014). More extreme changes are anticipated in the coldest and hottest times of the year; the median temperature rise projected for the coldest night is about 1.6°C by mid-century, which is more than the projected warming for the hottest day of about 1.3°C [28].

Projected changes in the annual maximum temperature are sensitive to the trajectory of future global emissions, with projections ranging from 1.1°C to 1.6°C in the near future (2025–2054) and 1.5°C to 4.1°C in the far future (2065–2094) for emissions following the SSP1-2.6 to SSP5-8.5 scenarios, relative to the 1985–2014 baseline [29]. The Western Himalayan region shows particularly high sensitivity to warming, with projected far-future increases of 5.6°C under SSP5-8.5 [29].

The probability of exceeding observed hottest summers is projected to increase seven-fold in a 2°C warmer world and twenty-fold in a 3°C warmer world compared to the present climate, with Northwest, North Central, Northeast, and parts of the Interior Peninsula being most affected [30].

Furthermore, more intense and prolonged heatwaves occurring with greater frequency are projected over India [31]. Recent analysis using statistically downscaled, bias-corrected climate model data from CMIP6 ([32], b) suggests increases of around one to two months in heatwave season duration, i.e., the difference between the last and first heatwave day in a season, over entire India in the near future (2025–2054) relative to the 1985–2014 baseline [27]. The compound effects of heat and humidity are particularly concerning in the Indo-Gangetic plains, already experiencing high

levels of heat stress, which are projected to become more common and widespread at the 1.5°C global warming level, and twice as likely in a 2.0°C world [33]. Week-long heatwaves are projected to affect around 50% of India's population under SSP5-8.5 [29]. More recently, Arulalan T et al. [34] used a large ensemble of simulations to analyze future heatwaves in India, predicting a threefold increase in joint frequency of long duration and large area heatwave events under a +1.5°C scenario and a fivefold increase under a +2.0°C scenario relative to 2006–2015.

While extreme land temperatures, heat stress and heatwaves are important for managing day to day anthropogenic activities especially for marginalised groups, genders and communities, it is important to review the impact of heat on marine ecosystems as they are important for maintaining ocean health, an important component in climate modulation.

3.2 Indian ocean warming and marine ecosystem changes

The Indian Ocean spanning ca. 70 million km² provides protein food sources and livelihood to about a third of the global population. This ecologically diverse ecosystem hosts 30% of the coral cover, 40,000 km² of mangroves, and some of the world's largest estuaries [35]. The landlocked nature of the northern boundary of the Indian Ocean and the resultant seasonally reversing wind and sea surface circulation patterns (monsoon winds and currents) are unique features [35,36]. The distinct monsoon circulation drives northern coastal and open water upwelling, and high rates of primary productivity [36–40]. The Indian Ocean boasts of rich biodiversity of zooplankton, fish, sea mammals [41–49] and is home to numerous endangered marine species [50,51]. Despite its importance, the Indian Ocean is recognized as one of the least studied among the world oceans.

3.2.1. Observed changes. The tropical Indian Ocean (40-120E, 30S-30N) is experiencing rapid warming, at a rate of 0.5°C per century through the observational record from 1870 to 2020 (Fig 3). The basin recorded one of the fastest surface warming among the world's oceans in recent decades, with Roxy et al. [15] reporting a basin-wide surface warming rate of 0.12°C per decade over 1950–2020, which has increased to 0.13°C per decade considering the extended 1950–2024 period (Fig 1d). The highest increase of ~0.9°C was observed in the south-central region over 1982–2021, during which time the Indian Ocean Warm Pool (the area of surface waters >28°C) has significantly increased by expanding into the northern-central basins [40]. An extreme temperature scenario for the oceans are marine heatwaves (MHWs), which are periods of hot ocean temperatures above the 90th percentile that last for days to months which have been recorded as a common phenomenon in recent years [52,53]. Previous studies suggest that the basin-wide warming of the Indian Ocean plays a significant role in the increasing frequency and intensity of marine heatwaves, by elevating background Sea Surface Temperatures (SSTs), enhancing upper-ocean heat content, and weakening vertical mixing—conditions that favour the formation, persistence, and amplification of these extreme events [54,55].

Marine heatwave events cause marine habitat destruction due to coral bleaching, seagrass destruction, and loss of kelp forests, affecting the fisheries sector adversely. In addition, with the increase in atmospheric CO₂, the sea surface waters are subject to ocean acidification (OA). Surface seawater pCO₂ of the Indian Ocean has increased on average at ~1.6 μatm yr⁻¹ [56]. A 40-year study shows that both pH and calcium carbonate (e.g., aragonite) levels in the Indian Ocean are significantly decreasing, especially in the south [40], and approaching critical thresholds of ca. 3.0 for corals [57–59]. Decreasing aragonite saturation states threatens calcified organisms by lowering calcification and/or increasing dissolution rates [60,61]. Furthermore, the rapid increase in surface temperatures will intensify anoxic [lower levels of O₂ in seawater] conditions [62].

Historical observations reveal that oxygen minimum zones [OMZs] have increased in the Indian Ocean concurrently with the decrease in O₂ concentrations [62–65]. Observations of the horizontal distribution of the OMZ (1960–2019) zones in many global oceanic areas have shown consistently larger OMZ areas after the late 2000s than in previous years [65]. These authors show that expansion of OMZ area after 2000 in the Arabian Sea increased from ca. 1 to 4*10⁶ km² and in the Bay of Bengal ca. 1 to 3 *10⁶ km² (DO < 20 μmol/kg), corresponding with warming.

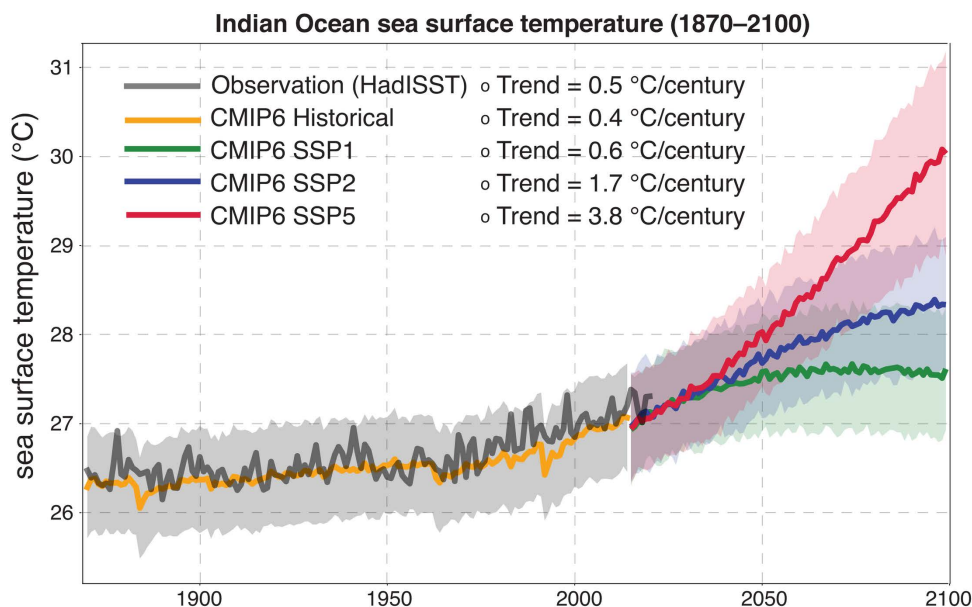


Fig 3. Time series of SST in the tropical Indian Ocean (40–120°E, 30°S–30°N) in observations and CMIP6 simulations. The lines represent the observations (HadISST, 1870–2020, black) and CMIP6 multimodel ensemble mean of historical simulations (1870–2014, orange) and the future projections (2015–2100) under low (SSP1-2.6, green), medium (SSP2-4.5, blue), and high (SSP5-8.5, red) emission scenarios. Shading represents the intermodel uncertainty (intermodel standard deviation). Fig adapted from Roxy et al. [15].

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Satellite estimates of long-term (1998–2022) net primary production (NPP) show large interannual variability with weak decreasing trends, particularly in northern Indian Ocean. The NPP is highest during the southwest and northeast monsoons in the northwestern Indian Ocean (mean 1.10 and 1.42 g C m⁻² d⁻¹ respectively), followed by the northeastern (mean 0.89 and 1.16 g C m⁻² d⁻¹), with the south central regions having the lowest values (mean 0.42 and 0.45 g C m⁻² d⁻¹ respectively).

Fisheries production in the Indian Ocean region is vital as fish is a main source of protein for people [66,67]. Unregulated fisheries and climate change impacts threaten food security in the region [48,66]. The major portion of the world’s commercially important tuna catches comes from the Indian Ocean. A recent modelling study of 43 species from waters off Kenya and Tanzania projects severe decreases (56–76%) in average fish biomass during the 21st century [48]; however, comprehensive studies over coastal Indian Ocean waters are limited. Sustainability of Indian Ocean fisheries is therefore a growing concern among policy makers [68].

3.2.2. Projected changes. CMIP6 models project Indian Ocean warming to accelerate to 0.17°C per decade over the course of this century under the SSP2-4.5 scenario, and the number of marine heatwave days to increase from ca. 20 days per year in recent decades (1970–2020) to nearly 200 days per year by mid-century under SSP2-4.5 [15]. In other words, the Indian Ocean is projected to experience a marine heatwave-state for over six months of the year by 2050.

Furthermore, climate models project an increase in surface seawater pCO₂ of the Indian Ocean to 8.3 μatm yr⁻¹ by 2061–2100 under the high emissions RCP8.5 scenario [69]. However, model (CMIP5 and CMIP6) projections are unsure of the direction of levels of O₂ concentrations [70,71]. Decreasing dissolved O₂ concentrations, particularly in the northern Indian ocean could impact organisms in this highly productive region.

Projections of net primary productivity in the northern Indian Ocean exhibit large uncertainty [71,72] despite indications of currently decreasing net primary productivity in some areas of the northern Indian ocean [40]. For example, the values in the models ranged from -5 (low) to -20 (high) in the north west and in the north east from +5 (low) to +30 (high) under

CMIP6 runs [71]. Net primary productivity is likely the biggest source of future uncertainty in the region, among other due to lack of in situ observations and understanding of key processes.

Long term biological times series are almost absent in the Indian Ocean, hence, monitoring of resources and climate impacts studies are rather limited. This is particularly true for zooplankton [73], a vital link bridging primary producers to higher trophic levels. CMIP6 projections show negative zooplankton biomass trends under low (SSP1-2.6) to high emission scenarios (SSP3-7.0, SSP5-8.5), respectively from 15 to 40% [73–75].

3.3 Precipitation changes

India receives precipitation mainly from the southwest (June–September) and northeast (October–December) monsoons, with contributions from synoptic systems such as western disturbances.

The southwest monsoon that occurs during June–September (JJAS) over the Indian subcontinent [76] contributes more than 78% of the annual rainfall over India [77] and affects almost the entire country [78]. Changes in precipitation and variability of the southwest monsoon occur over a range of spatiotemporal scales, from changes in the onset dates, to synoptic scale variations, to length of the monsoon season and the response to the teleconnections to natural modes of variability such as the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Atlantic Niño, and the Pacific Decadal Oscillation, which modulate the monsoon circulation and rainfall at intraseasonal, interannual, and decadal timescales [79,80]. In recent decades, the role of anthropogenic greenhouse gases and aerosols, as well as land use and land cover change in the modulation of the southwest monsoon has also been extensively studied [81].

In this review, we have focused on the observed and projected changes in the mean and extremes of the southwest and northeast monsoon rainfall, including sub-national precipitation trends, where available.

3.3.1. Observed changes. Changes in the southwest monsoon. The southwest monsoon precipitation (JJAS) declined by around 6% from 1951 to 2015 [82]. This decline has been attributed to the weakening of the monsoon circulation in response to multiple factors, including continued greenhouse gas-induced warming over the Indian Ocean, aerosol-induced cooling over the Indian subcontinent, and land use land cover changes [81,83–85].

An analysis of the expanded 1950–2024 period using IMD's gridded daily precipitation dataset [14] reveals that changes in JJAS precipitation have been spatially non-uniform, with significant drying trends over the Indo-Gangetic plains of around $0.5 \text{ mm day}^{-1} \text{ decade}^{-1}$, with even more severe drying trends in parts of the northeast (Fig 4A). On the other hand, northwestern India has generally experienced a wetting trend of about $0.5\text{--}1 \text{ mm day}^{-1} \text{ decade}^{-1}$ over the same period [86]. Fig 4B illustrates the trend in extreme precipitation events, considering the annual number of days with daily precipitation exceeding 150 mm (R150mm) over 1951–2024. There is an increasing tendency in extreme events over most of central India, with significant increasing trends over coastal Gujarat of around $+0.15 \text{ events decade}^{-1}$. Parts of northeast India exhibit a sharply decreasing trend of nearly $-0.2 \text{ events decade}^{-1}$. These findings are in line with other earlier studies that have reported an increasing trend in extreme rainfall events across central India and parts of the Western Ghats [17,19,84]. In addition, it is reported that extreme rains are observed around urban regions of India suggesting an urbanization feedback [80].

Changes in the Northeast monsoon. The northeast monsoon is important to the southern peninsular region and contributes about 20% of the annual rainfall to the Indian landmass. It exhibits more than twice the interannual variability of the southwest monsoon [80]. The observed changes in the northeast monsoon include increased variability and a rise in seasonal rainfall in certain parts. Specifically, Nageswararao et al. [87] found that the variability of the northeast monsoon rainfall has increased during the period 1959–2016. Moreover, seasonal rainfall has increased over southern peninsular India, primarily due to an increase in the number of high-intensity rainfall events observed in the recent period compared to the first half of the 20th century [87]. Shahi and Rai [88] studied the spatio-temporal characteristics of northeast monsoon with a special emphasis on extreme events and their impact over southeast India using IMDAA and regional climate model datasets. Their study confirmed an increase in intensity and variability of rainfall and

JJAS precipitation over the Indian region (1951–2024)

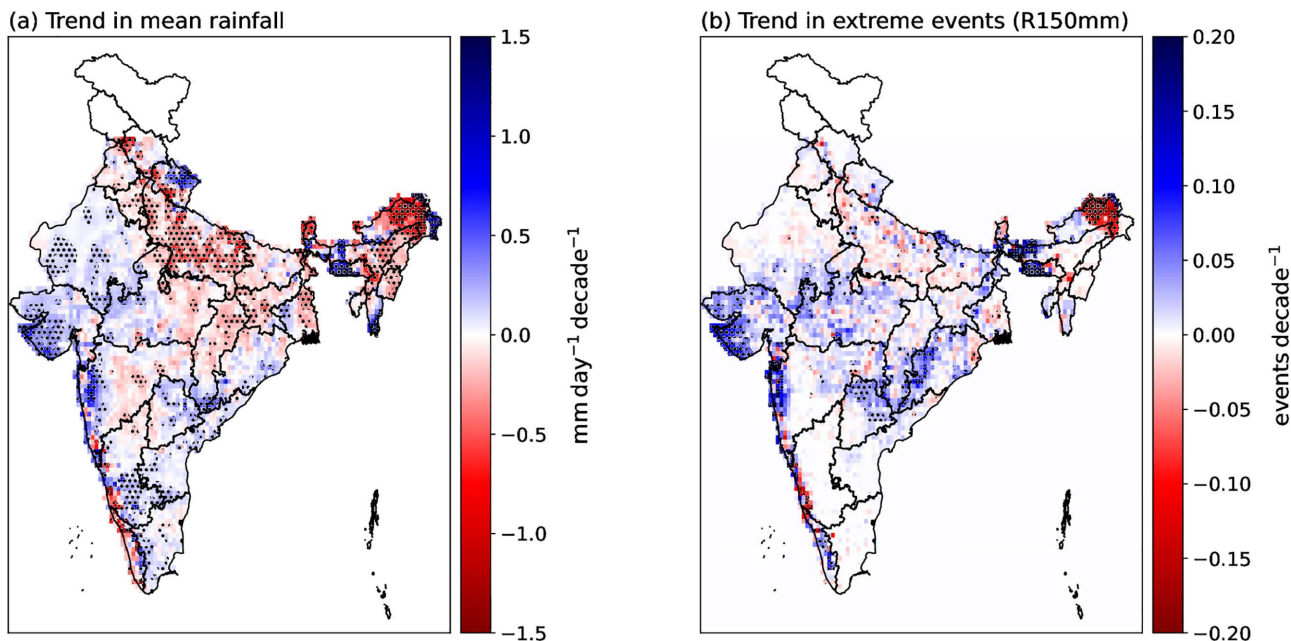


Fig 4. Linear trends over 1951–2024 in JJAS (a) mean precipitation ($\text{mm day}^{-1} \text{decade}^{-1}$), and (b) extreme events (defined as daily rainfall $\geq 150 \text{ mm}$) ($\text{events decade}^{-1}$). Stippling indicates trend values significant at 95% confidence level (two-tailed). Latitudes above 32.5°N have been excluded from analysis. Data: IMD $0.25^\circ \times 0.25^\circ$ Daily Gridded Rainfall Data [14].

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a substantial increase in widespread extreme precipitation events. Their study also highlighted the biases of regional models and the need to improve models in simulating the features of northeast monsoon and the intensity of extreme precipitation events.

3.3.2. Projected changes. Changes in the Southwest monsoon. Future changes in the mean and extremes of southwest monsoon rainfall, based on climate model projections, reveal significant spread among models [80,89]. This ambiguity has been attributed to the complex processes and teleconnections within the southwest monsoon system along with its strong spatio-temporal variability. Based on our survey of pertinent literature (Table A in S1 Text), we assess that the all-India average multimodel mean JJAS precipitation will increase by about 6–8% under SSP2-4.5 relative to the recent past, despite a weaker overall monsoon circulation [90]. The projected enhancement in monsoon precipitation has been attributed to the dominance of the thermodynamically driven increase in precipitation over the expected dynamically driven decrease in the strength of the monsoon circulation [91,90,92].

Kumar et al [89] have shown a spatially non-uniform increase in southwest monsoon rainfall by up to 20% with spatial patterns similar to the changes seen in Fig 4a, specifically over northwest India. Furthermore, a significant increase in the number of extreme rainfall events are projected during both southwest and northeast monsoon rainfall, albeit with large spatial variability [89].

Saha and Sateesh [93] conducted a comprehensive study on the spatio-temporal variations of heavy to very extreme southwest monsoon rainfall and have highlighted regions most susceptible to increasing rainfall extremes. In the SSP 2-4.5 scenario, Saha and Sateesh [93] show that the most susceptible areas are Mumbai, Pune, Panaji along the west coast, Itanagar and Shillong in the North-East India, which are projected to witness 4–6 additional events of heavy rainfall ($64.5 < R \leq 115.5 \text{ mm day}^{-1}$) per year by mid-century (average over 2036–2060) relative to the near future. Likewise, Bhubaneswar and Hyderabad in the east, and Bhopal in Central India are projected to experience an increase of 2–4 heavy

rainfall events per year. The authors have suggested that the extreme events along the west coast and northeast are likely due to forced ascent over mountains, while those occurring in central India are induced by the movement of low pressure systems which originate in the Bay of Bengal.

Changes in the Northeast monsoon. CMIP6 models project a marked increase in northeast monsoon precipitation in the range of 15–40% (depending on the region) under SSP 2-4.5 relative to the 1985–2014 baseline, with larger changes seen in the far future period (2051–2070) compared to the near future (2021–2050) period [89]. This increase is even more pronounced (about 40% over the southern peninsular region) in the far future period in the SSP5-8.5 scenario [89].

The considerable spread in precipitation projections among CMIP6 models arises from the complexity of monsoon dynamics involving representation of sub-grid-scale cumulus convection, and coupling among several key elements of moist convection viz., surface fluxes, sub-grid scale turbulence, mid-tropospheric moisture, clouds, latent heating, large-scale circulation; while parameterization schemes used in numerical models depend on many parameters that are not well constrained by observations [94,95]. Therefore, a reasonably accurate simulation of the southwest monsoon and its associated teleconnections remains a significant challenge for the modelling community, as highlighted by Choudhury et al. [6] in their comprehensive evaluation of CMIP3, CMIP5, and CMIP6 models. The analysis reveals persistent systematic biases, notably in the position of the Intertropical Convergence Zone, and precipitation biases manifesting as continental dry anomalies and oceanic wet anomalies, though CMIP6 exhibits reduced bias magnitude and enhanced spatial pattern correlation. A significant number of studies have focused on assessing the fidelity of CMIP6 models in simulating the regional patterns of southwest monsoon over India, its variability and its teleconnections where different permutations of models and metrics have been employed to understand model performance [6,7,29,96,97]. The emergent consensus among these studies is that there is an improvement in simulating spatial features of the southwest monsoon and largescale circulation in multi model ensembles, but CMIP6 models still suffer from significant wet biases and biases in simulating the strength of teleconnections. These studies also demonstrate that there is a large spread among models in simulating the climatological features, variability and extreme events, but multimodel ensembles (MMEs) show a better agreement with the observations overall. Thus, while CMIP6 models exhibit progress in simulating aspects of the southwest monsoon characteristics, there is a necessity for enhanced representation of coupled ocean-atmosphere dynamics and extreme event mechanisms in future models.

3.4 Cryosphere changes

The Hindu Kush Himalaya cryosphere, comprising glaciers, snow, and permafrost, is undergoing unprecedented changes driven by climate change. The impacts of these changes are becoming increasingly evident, with increased warming at higher elevations, accelerated melting of glaciers [98], increasing permafrost thaw [99], declining snow cover, and more erratic snowfall patterns [98]. Recognized as the “water towers” of the Hindu Kush Himalayas, these critical sources for downstream regions are among the most vulnerable to these changes globally.

As per the inventory published by the Geological Survey of India (GSI), which is the nodal government agency on survey and monitoring of glaciers in the country, there are as many as 9775 glaciers in the Indian Himalayan Region (IHR). The summary of glacier inventory for the entire Indus, Ganga and Brahmaputra basins have been published by Sharma et al. [100] with a total glacierized area of 71,182.08 km² in 32,392 glaciers.

3.4.1. Observed changes. Mean temperature is increasing significantly in all regions of the Hindu Kush Himalayas with an average observed increase of +0.28°C per decade for the period 1951–2020 [98]. The rate of warming is found to be amplified in higher elevations due to temperature dependent warming [101]; at elevations higher than 4,000 m the rate of warming was around 0.34°C per decade.

As a consequence of this accelerated warming, the rate of glacier mass loss has increased in most areas of the Hindu Kush Himalayas between 1970 and 2019 [98]. Since 1974 the Indian Himalayan glaciers in situ mass balance

observation shows mostly negative mass balance years [102]. The mass balance of glaciers for 1975–1999, 2000–2009, and 2010–2019 in the HKH region and its sub regions are discussed in detail in Jackson et al. [103]. Studies indicate that during the last two decades, the rate of glacier mass loss has accelerated from -0.17 meters water equivalent (m w.e.) per year during 2000–2009 to -0.28 m w.e. per year during 2010–2019 [103]. In India, Chhota Shigri Glacier provides the longest continuous mass balance series since 2002 with a mean annual mass loss of -0.46 ± 0.40 m w.e. per year over 2002–2019 [104].

One of the consequences of sustained glacier melt is an increase in the number and volume of glacier lakes. Globally, glacial lakes have increased and expanded as a result of glacier recession. In particular, the total area and number of glacial lakes have increased significantly since the 1990s. Specifically, between 1990 and 2018, the number of known glacial lakes globally had increased to 14,394 (53% increase), with a total area of 8.95×10^3 km² (51% increase), and an estimated volume of 156.5 km³ (48% increase) [105]. Likewise, numerous studies have been conducted on glacial lakes in High Mountain Asia, the Hindu Kush Himalayas, and the Third Pole [106–111]. Li et al. [110] identified 9,673 glacial lakes in the Hindu Kush Himalayas in 2020, with an increase in their number by 5,974 and in their area by 409 km² in the 30 years since 1990.

Glacier melt is expected to result in lake expansions downstream and create new hotspots of potentially dangerous glacial lakes, with implications for glacial lake outburst flood (GLOF) hazards and risk. For instance, the study by Sattar et al., [112] showed that the South Lhonak lake in Sikkim increased significantly in size from 1962 to 2018. Several other studies also found the South Lhonak lake had shown rapid growth in its spatial extent over the past four decades [113,114] which resulted in a GLOF in October 2023.

3.4.2. Projected changes. Projected changes in regional temperatures and precipitation over the twenty-first century will affect the snow cover and mass balance of glaciers in the Hindu Kush Himalayas [115,116]; therefore, changes in the volume of, and seasonality in, snowmelt and glacier melt are expected.

The Hindu Kush Himalayan region is projected to warm by $2.5 \pm 1.5^\circ\text{C}$ under the RCP4.5 scenario and by 5.5 ± 1.5 for the extreme emissions scenario, RCP8.5 by the end of the 21st century relative to 1976–2005 [Krishnan et al., 2019b].

ICIMOD [98] has conducted several assessments for the Hindu Kush Himalayas. For a global warming level between 1.5°C to 2°C , the Hindu Kush Himalayas glaciers are expected to lose 30%–50% of their volume by 2100 relative to the recent past. This loss of ice mass will continue, with the specific mass balance rate remaining negative, even though it will become less negative by the end of the century as glaciers retreat to higher elevations. At a global warming level of $+3^\circ\text{C}$, the Hindu Kush Himalayas glaciers are expected to lose 55%–80% of their volume by 2100 relative to the recent past, with the specific mass balance rates becoming more negative throughout the twenty-first century. It is estimated that with accelerated glacier melt, ‘peak water’ will be reached around mid-century in most Hindu Kush Himalaya river basins, and overall water availability is expected to decrease by the end of the century [98].

The study by Furian et al. [117] found the glacial lakes in the High Mountain Asia to grow by 120–210% for SSP1-2.6 and SSP5-8.5 scenarios by the end of the century compared to 2018. Under SSP5-8.5 scenario tenfold increase in lake volume is estimated, from 3.9 km³ in 2018 to 43.6 ± 7.7 km³ in 2100. A significant number of potential transboundary GLOFs (e.g., a glacial lake may lie within the borders of one country, but the main impact of a GLOF event may be across the border in another country), primarily in the eastern Himalayas [109]. Under the high emissions SSP5-8.5 scenario, much of the region could already be approaching a state of ‘peak risk’ by the end of the twenty-first century, or even mid-century in some regions [118].

To minimize the risk of GLOFs it is necessary to conduct glacial lake risk assessments, including projected changes in lake extent and volume. However, there is a lack of standardized approach for hazard and risk assessments and uncertainties in permafrost estimates [98]. A combination of in situ measurements including ice and debris thickness, space-based observations and modelling can be used to study lakes of varying sizes including small ones to better understand the lake formation, its extent and its impacts downstream.

3.5 Tropical cyclones

The north Indian Ocean accounts for 6% of the global tropical cyclones annually, with the Bay of Bengal accounting for 4% and the Arabian Sea accounting for 2% of the cyclones [119]. Despite the small fraction of cyclones, some of the most devastating storms have formed in this basin, causing extensive damage to life and property in the north Indian Ocean rim countries.

3.5.1. Observed changes. Changes in cyclone characteristics in the north Indian Ocean differ by basin. While the Arabian Sea has exhibited a significantly increasing trend in frequency, duration, and intensity of cyclones during the last four decades, there has been a non-significant decline in the frequency of cyclones in the Bay of Bengal (Fig 5) [120].

Rapid warming in the north Indian Ocean, associated with global warming, tends to enhance the heat flux from the ocean to the atmosphere and favor the rapid intensification of cyclones [121,122], as observed with Cyclone Amphan in 2020, which intensified from a Category-1 cyclone (about 100 km/h) to Category-5 (about 250 km/h) in less than 24 hours. This quick intensification poses significant challenges for monitoring and forecasting, particularly due to gaps in in-situ ocean observations [123]. The rapid pace of these changes does not provide sufficient time for effective evacuation and disaster management along the densely populated coastlines of South Asia. Marine heatwaves have been associated with rapid intensification of tropical cyclones in the north Indian Ocean, for instance in the cases of cyclone Fani in 2019 [121] and cyclone Amphan [122]. However, other than a few case studies, an in-depth analysis of tropical cyclones in the Indian ocean basin, and their association with marine heatwaves, is lacking. The urgency of this analysis is underscored by the recent study by Choi et al. [124] of tropical cyclones in the western North Pacific and the Atlantic basins, which found that the average lifetime maximum intensity of tropical cyclones occurring during marine heatwaves in these basins is 35.4% higher than tropical cyclones not preceded by marine heatwaves.

Sea surface temperatures (SSTs) leading to cyclogenesis in the Arabian Sea have been 1.2°C–1.4°C higher in recent decades, compared to SSTs four decades ago [119]. During the last four decades, the maximum intensity of cyclones has increased by 40% (from 100 km/h to 140 km/h), in the Arabian Sea, during the pre-monsoon season (April–May) [120]. The Arabian Sea during the post-monsoon season (October–December) has witnessed a 20% increase in the intensity (from 100 km/h to 120 km/h). These changes in the Arabian Sea cyclones are associated with an increase in mid-level relative humidity, which is significantly correlated to an increase in SSTs and ocean heat content in the basin [120]. Meanwhile, long-term changes in the Bay of Bengal are not significant.

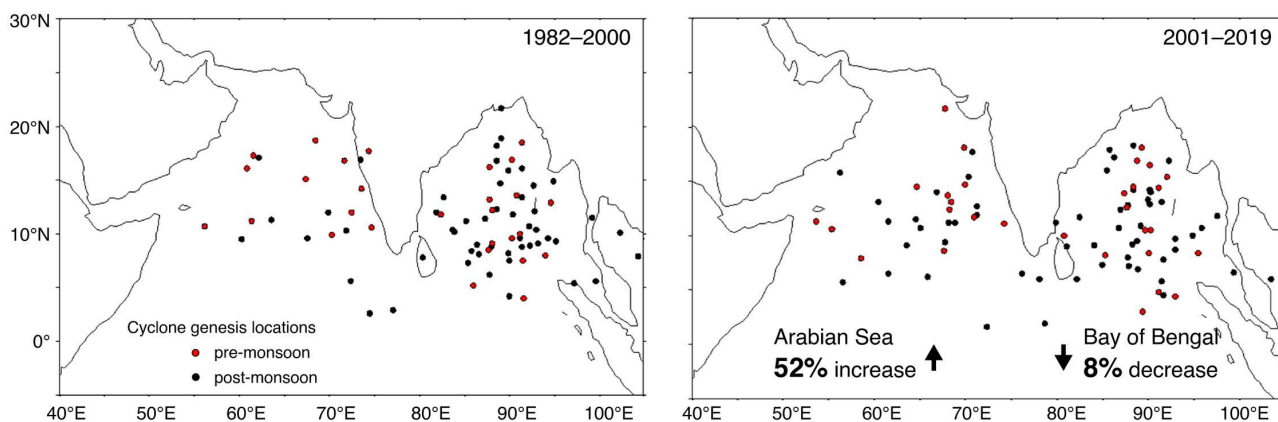


Fig 5. Tropical cyclone genesis locations for pre-monsoon (red dots) and post-monsoon (black dots) during 1982–2000 (left panel) and 2001–2019 (right panel). Figure adapted from [120].

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Anthropogenic warming has increased the probability of tropical cyclones in the Arabian Sea [125]. The intensification of cyclone activity in the Arabian Sea is linked to rising ocean temperatures and increased moisture availability. A global slowdown in tropical-cyclone translation speed has raised the potential for prolonged rainfall at landfalls [126]. However, the north Indian Ocean is an exception, with no observed slowdown and even faster motion over land [126]. Cyclone-induced precipitation coverage has expanded rapidly over the north Indian Ocean, making it one of the fastest-growing basins globally [127]. At the same time, land-based precipitation from tropical cyclones has also increased, particularly along northeastern India and Bangladesh, driven by more frequent activity in this region and the rising intensity and duration of Arabian Sea storms, with likely additional inland amplification from orography [127].

3.5.2. Projected changes. Future projections of tropical cyclone activity in the north Indian Ocean show complex regional and seasonal variations. Swapna et al. [128], using Earth system model experiments, indicated that anthropogenic greenhouse warming has a potential in increasing the cyclone intensity over the north Indian Ocean, higher than the global tropics by the end of the 21st century. The Arabian Sea is projected to experience substantial increases in TC frequency (30–64% in [129]; 46% in [130]), while the Bay of Bengal shows decreases (22–43% and 31% respectively). Vellore et al. [131] assessed an increase in cyclone intensity and cyclone-induced precipitation in the north Indian Ocean. These regional projections align with global assessments for a 2°C warmer world that the median global tropical cyclone intensity will increase by about 5%, the proportion of tropical cyclones reaching very intense (Category 4–5) levels will rise by about 13%, and tropical cyclone precipitation rates will increase by approximately 14% [132]. This precipitation increase closely aligns with the rate of tropical water vapor increase at constant relative humidity.

The increase in cyclone intensity can be linked to the anthropogenically-induced rise in SSTs, which provide greater energy for cyclone development and intensification [133]. Additionally, stronger cyclones are expected to carry and release more moisture, leading to an increase in precipitation rates from these cyclonic events [125]. This implies stronger winds and substantial increases in rainfall, heightening the risks of flooding and storm surge-induced damages.

Despite the evident risks posed by cyclonic storms, there are almost no studies that have reported the projections of tropical cyclones over the north Indian Ocean under different Shared Social Pathways and the projections exhibit significant uncertainty. However, one of the impacts of tropical cyclones, namely storm surges and sea level rise have been reviewed in the next section.

3.6 Sea level rise

Sea level rise is a significant consequence of climate change that is posing an increasing threat to lives, livelihoods, and infrastructure along coastlines. The melting of glaciers along with the thermal expansion of water has led to a pervasive increase in global sea levels, presenting significant threats to coastal communities and infrastructure worldwide. With more than 7000 kms of coastline, sea level rise and extreme sea levels (ESL), associated with storm surges and high tide, are major risks for India. Particularly vulnerable are coastal megacities such as Mumbai, Chennai, and Kolkata, which are not only densely populated, but also host critical infrastructure like power plants that rely on coastal locations for abundant water access essential for cooling [134]. In addition to the strategic importance of the metro cities, over 33% of the human population lives along the Indian coast which makes climate policy for mitigating sea level rise and flooding crucial [135].

3.6.1. Observed changes. In the north Indian Ocean, sea levels have risen at an average rate of 3.3 mm/year in recent decades (1993–2015), comparable to the rate of the global mean rise [136,137]. Despite the seemingly minimal average annual increase in sea levels of about 3 mm, the cumulative impact is substantial. Over a decade, this translates to a rise of 3 cm, which, when combined with the gentle average slope of the continental shelf of approximately 0.1°, results in a disproportionately significant intrusion of the land by sea. A mere 3 cm elevation can push the coastline by as much as 17 meters, amplifying the risks posed by rising sea levels [134]. In the Ganga-Brahmaputra delta, land subsidence rates of over 5 mm/year, driven by sediment compaction and groundwater extraction, exacerbate the impact of sea level rise, making this region particularly vulnerable [138].

Swapna et al. [136] assessed that over the north Indian Ocean region, sea level rise is dominated by thermal expansion due to ocean warming, whereas mass addition due to ice melt is a major contributor to the rise in the global mean sea levels [137]. On interannual to decadal timescales, sea level variations in the north Indian Ocean are influenced by modes of natural variability such as the ENSO and IOD [135,136].

A combined influence of mean sea level rise, which includes steric (thermal expansion) and eustatic (mass addition) components, and storm surges, driven by cyclonic storm activity, contributes to the risk of extreme sea level events [135]. It is found that frequencies of extreme events vary depending also on tidal range in a region, with low tidal range regions experiencing large increases [138]. The impact of extreme sea levels is of particular concern to islands and low-lying coastal regions, where the risk of flooding and infrastructure damage is significantly heightened. The Indian Ocean region, including the Sundarbans, faces significant challenges due to these rising sea levels [136,139,140].

Recent observations show that extreme sea level events have become more frequent, longer-lasting, and intense along the Indian Ocean coastlines. According to Sreeraj et al. [135], there has been a 2–3 fold increase in extreme sea level occurrences between 1995–2019, with higher risks observed along the Arabian Sea coastline and Indian Ocean Islands. The primary contributor to this increase is the rising mean sea level, which accounts for more than 75% of the observed extreme sea level increase, with additional contributions from intensifying tropical cyclones [135].

3.6.2. Projected changes. Projections with the current generation of CMIP6 models indicate a rapid rise in sea levels in the north Indian Ocean in the future [28]. Under SSP2-4.5, the median rise in north Indian Ocean sea level projected by CMIP6 models is about 0.2m by mid-century relative to the 1995–2014 baseline. This is projected to increase to 0.5m (median) by the end of the 21st century. These projections are nearly identical to those of the previous generation CMIP5 models, and the dominant changes are seen in the western Indian Ocean, especially in the Arabian Sea [141].

While the general trend of mean sea level rise is well understood globally, the specifics of extreme sea level rise along the Indian coast remain uncertain due to significant variability in ESL rise and its drivers [136]. This uncertainty is compounded by the lack of consistent, long-term observational data along the Indian coastline. Even so, rise in ESL is projected to significantly affect the equatorial region, with a historical one-in-a-hundred-year extreme sea level event along the Arabian Sea coastline expected to become an annual occurrence by 2050 under SSP2-4.5, and by 2100 even under the strong mitigation scenario SSP1-2.6 [135]. In general, regions with low tidal ranges are projected to experience a more significant increase in extreme sea levels compared to regions with higher tidal ranges [138]. For example, 100-year return levels of extreme sea-level events are projected to increase by 15–20% by the end of the 21st century in low tidal areas such as the southeast coast of India, whereas in regions of high tidal ranges (such as, northeast coast of India, and Kolkata), changes are below 5% [142].

4. Compound events (focus on heatwave-drought events)

It is increasingly recognized that disasters associated with climate change may be amplified by ‘compound events’: climate hazards that arise not in isolation but through their interaction. Compound events are characterized by the interaction of multiple climate or weather drivers and can lead to a more severe impact than any of the individual events alone would cause [2,143]. These events, which might not be extreme on their own, can interact or occur in succession to create significant consequences for human health, economic stability, and the environment.

4.1 Observed changes

In the Indian context, compound heatwave-drought events are of central concern. Sharma and Mujumdar [144] identified an alarming increase in the concurrent occurrence of meteorological droughts and heatwaves across India, particularly from 1981 to 2010. A study by Ganguli [145] found that urban areas across India have witnessed a significant increase in compound hot and dry spells, with a median 6-fold amplification in their joint frequencies relative to the expected annual number of local (univariate) 50-year severe heatwave episodes. Similarly, a recent study by Guntu and Agarwal [146]

documents a significant increase in compound dry and hot extremes (CDHE) in recent decades, having increased by 1–3 events per decade from 1977 to 2019 compared to the base period of 1951–1976. Notably, regions such as north-central, western, and north-eastern India, along with the southeastern coastlines, are emerging as hotspots for CDHE, facing increasing frequency and intensity that could severely impact local ecosystems and economies.

The mechanisms driving these compound events involve complex interactions between land and atmosphere. Soil moisture-temperature coupling has been identified as an important driver of CHDEs over India [147,148]. Research indicates that low soil moisture is responsible for 55–65% of CDHE occurrences in India. Soil moisture depletion - preconditioned by precipitation deficits - reduces evaporative cooling, creating a feedback loop that amplifies both hot and dry conditions [148].

4.2 Projected changes

Mishra and colleagues [149] analyzed climate projections under high-emission scenarios and reported a projected 1.5-fold increase in the frequency of concurrent hot and dry extremes in India by the end of the 21st century, despite an overall increase in projected precipitation. This paradoxical increase in CHDEs, despite the projected precipitation rise, is not well understood. Recent work by Ganeshi et al. [150] provides some insight - they analyzed the impact of soil moisture perturbations on temperature extremes over India for the historical period (1951–2010) and future (2051–2100) under a 4K warming scenario. Their research showed that more than 70% of the Indian landmass experienced significant changes in temperature extreme characteristics due to soil moisture perturbations. The impact was particularly pronounced over north-central India, which was identified as a regional hotspot for strong soil moisture-temperature coupling. In these regions, precipitation and soil moisture anomalies can significantly alter the frequency, duration and intensity of extreme temperatures by modulating surface energy partitioning, evapotranspiration and soil moisture memory.

Many other forms of compounded events can lead to magnified disasters such as compound flooding [151,152] and compound marine events [122,147,153].

The prevalence and intensity of compound hazards are projected to increase with warming [2], but studies on compound events are still sparse in the Indian context making it critically important that research on this topic is accelerated [154].

5. Synthesis and summary

This paper has provided a comprehensive update and review of observed and projected climate change trends across India, analyzing changes in temperature, precipitation patterns, Indian Ocean warming, ecosystem changes, cyclone activity, cryosphere changes, and sea level rise. These changes portend differential impacts across the country [134].

[Table 1](#) gives a compendium summary of key observed and projected changes in all the climate variables covered in this review. However, we iterate that [Table 1](#) is not exhaustive since we report only significant, robust findings. Detailed discussions are given in the corresponding sections. Each entry in [Table 1](#) can be traced to Sections 3 and 4. It is seen that more detailed regional information is provided for observed changes, which is not always accompanied by a corresponding entry for projections. This indicates avenues for future work to fill these knowledge gaps.

Moreover, in the interests of conveying a visual overview of regionally differentiated trends across India, we present a qualitative schematic overview of *observed changes* in [Fig 6](#). All reported changes and trends can be traced to [Table 1](#), and Sections 3 and 4. This format of presenting the results also uncovers regions experiencing rapid changes in multiple climate variables, which indicates the possibility of the emergence of compound extreme events in these regions. For example, [Fig 6](#) reveals that Western India has concurrently experienced a rise in extreme precipitation events and in compound hot and dry extremes, whereas Northeast India has concurrently experienced a decline in mean JJAS precipitation and an increase in warm days and warm nights. This visual representation helps to focus attention on regions that may

Table 1. Compendium table summarizing key updates on climate change in India. “Recent past” refers to 1995–2014.

Climate Variable		Observed Changes (period, baseline)	Projected Changes (scenario, period, baseline)
Temperature	Mean	+0.89°C (2015–2024 rel. to 1901–1930)	+1.2–1.3°C (SSP2-4.5; mid-century rel. to recent past)
	Extremes	Warmest day of the year (TXx): +1.5–2°C warming over Western and Northeast India (1951–2024) Warmest night of the year (TNx): No notable trends (1951–2024)	TXx: +1.3°C mean over land (SSP2-4.5; median of CMIP6 models; mid-century rel. to recent past) TNx: +1.6°C mean over land (SSP2-4.5; median of CMIP6 models; mid-century rel. to recent past)
JJAS monsoon Precipitation	Mean	Indo-Gangetic plains: Around -0.5 mm/day /decade (1951–2024) Northeast India: Around -1 to -1.5 mm/day/decade (1951–2024) Western India: Around +0.5 to +1 mm/day/decade (1951–2024)	Mean rainfall (All-India average): +6–8% (SSP2-4.5; multi-model mean; mid-century rel. to recent past). High spatial variability across models. Regional changes subject to high uncertainty.
	Extremes	Central India: Increasing tendency over most parts but not statistically significant. Coastal Gujarat: Around +0.15 events/decade (1951–2024)	Continued intensification and more frequent extremes projected but with large spread across models.
Indian Ocean (40–120E, 30S–30N)	SST	+0.12°C/decade (1950–2020)	+0.17°C/decade (SSP2-4.5; multimodel mean; 2020–2100)
	Marine heatwaves	20 days/year (1970–2000)	200 days/year (SSP2-4.5; mid-century rel. to 1970–2000)
	Sea level	Mean Sea Level Rise (North Indian Ocean): +3.3 mm/year (1993–2017) Extreme Sea Level events: 2–3x increase (1995–2019)	Mean Sea Level Rise (North Indian Ocean): +0.2 m (SSP2-4.5; median of CMIP6 models; mid-century rel. to recent past) Extreme Sea Level events (Arabian Sea coastline): 1-in-100-year event projected to become 1-in-1-year event (SSP2-4.5; mid-century rel. to recent past)
Hindu Kush Himalayas	Warming	Mean: 0.28°C/decade (1950–2020) with elevation dependent warming. Above 4000 m: 0.34°C/decade (1950–2020)	Mean: 2.5 ± 1.5°C (RCP4.5; multi-model mean and Standard Deviation; end of century rel. to 1976–2005)
	Glacier Mass Balance	-0.17 m water equivalent/year (2000–2009) -0.28 m water equivalent/year (2010–2019)	At Global Warming Level (GWL) of 1.5–2°C: 30–50% glacier volume loss (end of century rel. to recent past) At GWL of 3°C: 55%–80% glacier volume loss (end of century rel. to recent past)
Cyclone Intensity		+40% increase in maximum intensity of pre-monsoon cyclones in the Arabian Sea (1982–2019)	Continued intensification projected in the Arabian Sea with ocean warming but with large uncertainties
Compound hot-dry extremes		+1–3 events/decade (1977–2019 rel. to 1951–76). North-central, Western, Northeast India, and South-eastern coastlines are emerging as hotspots for these events.	Paucity of studies.

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be at elevated risk from climate change. A similar schematic for *projected* changes, while highly desirable, is not included since a wide spread persists among climate model projections making it difficult to synthesize robust regional signals of future changes. As before, this indicates the need for improved models and process representation to fill these knowledge gaps for the Indian region.

Fig 6 underscores the need for tailored adaptation strategies. Such strategies could include efforts towards the development of more resilient agricultural practices that are capable of withstanding simultaneous droughts and heatwaves, the enhancement of urban infrastructure to better manage extreme temperatures and precipitation, and the improvement of public health systems (with special focus on remote rural but climate vulnerable areas) to respond to increased risks

Regional hotspots of observed climate change in India

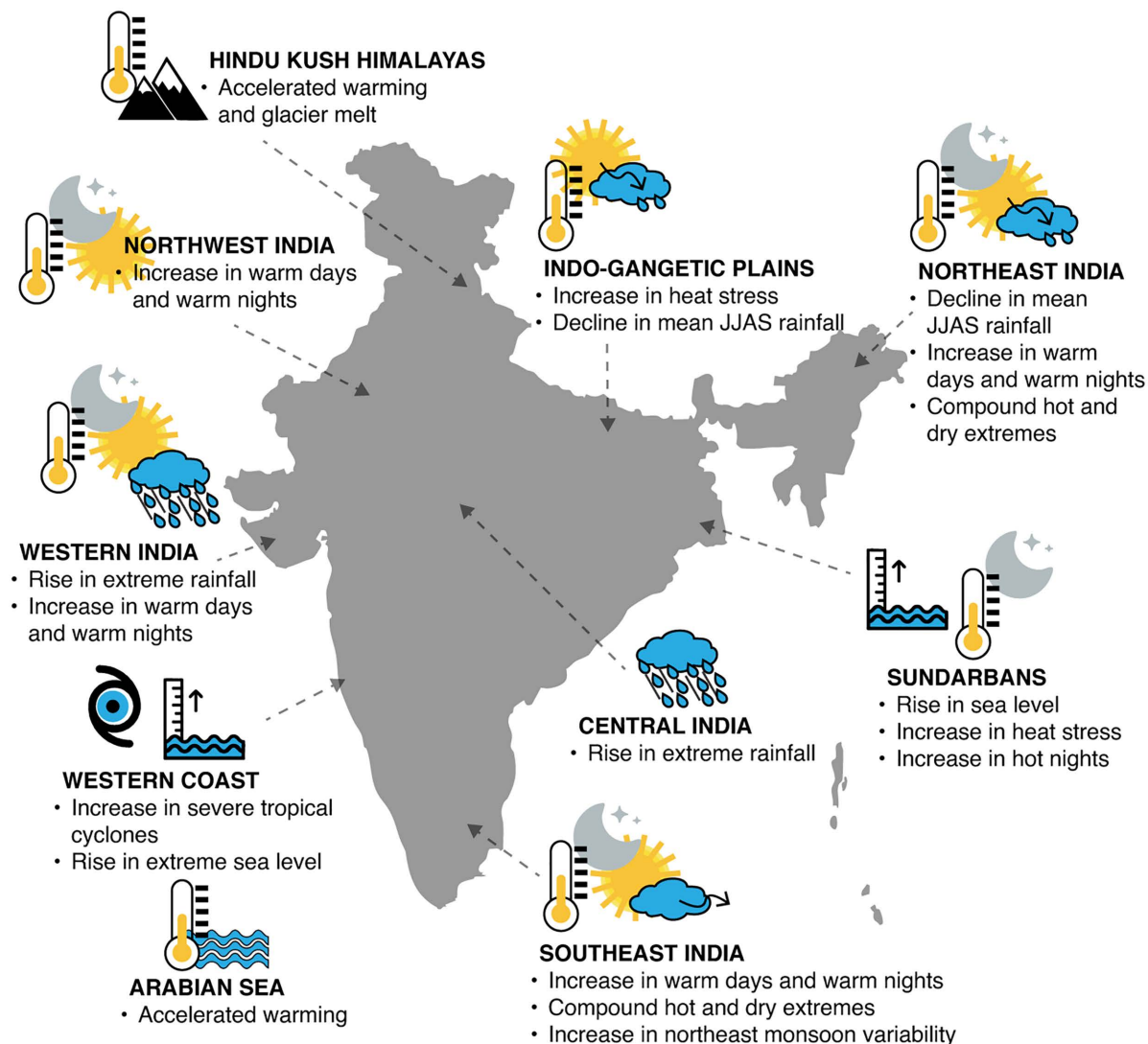


Fig 6. Regional hotspots of observed changes in climate across India. This schematic qualitatively synthesizes key trends reported in Sections 3.1-3.6 and Table 1, illustrating the spatially differentiated observed climate trends across the country. Each indicator represents documented changes, with detailed quantitative analysis provided in the referenced sections: temperature changes (Sec. 3.1), ocean warming (Sec. 3.2), precipitation changes (Sec. 3.3), cryosphere changes (Sec. 3.4), tropical cyclones (Sec. 3.5), sea level rise (Sec. 3.6), and compound events (Sec. 4). This synthesis highlights how different regions face distinct combinations of climate hazards, requiring tailored adaptation responses. Markers are indicative of regions. Schematic drawn by Roxy Mathew Koll in Adobe Illustrator.

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during compound events [155]. Ensuring that adaptation measures are grounded in robust, region-specific data will be crucial for enhancing resilience and effectively mitigating the impacts of climate change across India.

Supporting Information

S1 Text. Supplementary Information.

(DOCX)

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