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Review article

Temperature projections and heatwave attribution scenarios over India: A systematic review

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ABSTRACT

The average global temperature is rising due to anthropogenic emissions. Hence, a systematic approach was used to examine the projected impacts of rising global temperatures on heatwaves in India and provide insights into mitigation and adaptation strategies. With over 24,000 deaths attributed to heatwaves from 1992 to 2015, there is an urgent need to understand India's vulnerabilities and prepare adaptive strategies under various emission scenarios.This situation is predicted to worsen as heatwaves become more frequent, intense, and long-lasting. Severe heatwaves can exacerbate chronic health conditions, vector-borne diseases, air pollution, droughts and other socio-economic pressures causing higher mortality and morbidity. Heatwaves with severe consequences have increased and are expected to become more frequent in Indian climatic and geographical conditions. As per the future projection studies, the temperature could rise $\pm 1.2^\circ$ C to $\pm 3.5^\circ$ C and will start reducing by the end of 2050. The study also provides data from the research that employs climatic models and statistical approaches for a more precise characterization of heat extremes and improved projections. Also, the study appraises the past, present and future heatwave trend projections. Most of these studies compute future projections using the Coupled Model Intercomparison Project (CMIP5) models and Representative Concentration Pathway (RCP). Limited systematic reports have been found using CMIP6, whereas the best-suited and widely used method was the RCP8.5. The study findings will aid in identifying the zones most susceptible to heatwave risk and provide actionable projections for policymakers to examine the existing evidence for developing proper planning and policy formulation, considering the future climate and temperature projections.

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1. Introduction

The global average temperature has risen by more than 1.2 °C since the industrial revolution and is anticipated to increase the number of heat-related occurrences, extremes, and deaths worldwide [1]. While the planet as a whole is getting warmer, heatwaves have attracted worldwide attention due to their detrimental effects on human health and ecosystems [2,3]. Several regions of the world experience unequal warming trends depending on their geographic location and regional characteristics. Europe, US, Canada, and emerging countries like India, Pakistan, and Bangladesh, etc., have reported many heat-related deaths. Every 1 °C average temperature rise could increase mortality risks by 0.2%–5.5% [4], and some notable cases include the 2003 European heatwave, which claimed 77, 000 lives and the 2010 Russian heatwave, which was estimated to be linked to 55,000 premature deaths [5,6]. The temperature rise has already affected 68 million people by heat stress globally and if pre-industrial temperature increases by over 2 °C, a billion people will be affected due to heat stress by 2100 [7].

Looking at the current warming scenarios, global and regional climate models are essential tools for understanding present and future climate patterns, particularly extreme events where the intensity and frequency of heatwaves are predicted to increase in the 21st century, leading to more deaths. The Intergovernmental Panel on Climate Change (IPCC) 2014 report states that temperature extremes, exposure, as well as their degree of vulnerability to the society and ecosystem are the primary factors in determining the risks of climate change. In line with the Sustainable Development Goal (SDG) 13, building resilience and enhancing mitigation efforts for climate-related hazards, such as heatwaves, is critical to address [8]. Between 2000 and 2016, an estimated 125 million individuals were exposed to heatwaves, with 2015 seeing an increase of 175 million people over typically hot years [8].

There are various heatwave episodes reported worldwide. An all-time new record-breaking temperature (49.6 °C) was recorded on 29th June in Lytton, Canada, where wildfires spread was noticed on the following days [9]. Another study has linked 500 premature deaths in Canada's westernmost province due to an extreme heatwave and scientists warn of the dreadful toll from "heat dome" in the future [10]. Similarly, studies from Western Canada and the Northwest U.S. also reported all-time high-temperature records where CMIP6 climate models project continuous warming over the entire domain under the three future scenarios, with more significant warming over northern latitudes, up to 6 °C by the end of the century under SSP5-8.5 and increased risks of wildfires [11–13]. Similarly, future projections for temperature predict an increase in 3.82 ± 1.47 °C temperature over the Arabian Peninsula [14].

India's rapidly expanding industrialization and urbanization are already contributing to frequent, prolonged and intense heatwaves. Due to industrialization and urbanization, there is a change in Urban Land Cover Change (ULCC), which increased both Land Surface Temperature (LST) and air temperatures [15] and subsequently affected the surface climate [16]. Between 1901 and 2018, India's average annual temperature increased by about 0.7 °C, and if the current pace of greenhouse gas emissions continues, the global average temperature is anticipated to increase by almost 5 °C by the end of the 21st century [17].

India is facing new temperature-breaking records, where 2016 and 2020 have been the hottest years in the last century [18]. However, changing global climate and rapid anthropogenic activities can increase and amplify heatwaves' intensity, frequency and duration, and related events. Even Indian states which have not experienced heatwaves in the past, such as Himachal Pradesh and Kerala, are now exhibiting a higher frequency of extreme temperatures [19]. In 2010, over 1300 heatwave-related deaths were reported in Ahmedabad [20]. At the same time, Karnataka is predicted to warm by 2.0 °C by 2030, making the region more vulnerable to severe heat extremes, posing a higher risk to the vulnerable population [21]. In India, as per the National Disaster Management Authority (NDMA), 24,223 fatalities were attributed to heatwave-related deaths spanning from 1992 to 2015 [19]. In March 2022, intense heatwaves caused temperatures to climb above 40 °C in numerous Indian cities [22].

Further, high temperatures can aggravate long-lasting damage to human organs and exacerbate pre-existing comorbid conditions, including dehydration, kidney and heart problems, and mental health issues. The rising temperature could increase water scarcity in some regions like Rajasthan, as well as cause forest fires and urban fires, subsequently leading to air pollution. The increase in the desertification phenomenon underscores the value of using model data to analyze climate extremes and supplements limited station observations in regions such as Saudia Arabia [23]. While research has grown in recent years, projections of heat extremes in India remain subject to considerable uncertainty. Therefore, the current study aims to explore the existing scientific literature and examine the historical as well as projected climatic data. Further, characteristics and dynamics of heatwave projections over the different regions of India are also presented.

By examining the current state of heatwave projections over India and their potential impact on human health and the environment, this systematic study aims to contribute to the ongoing efforts to build resilience and enhance mitigation strategies for climate-related hazards. The various model analysis underscores the methodological limitations of current approaches, including coarse resolution and varied emissions scenarios. It makes a strong case for high-resolution coupled modeling incorporating interdisciplinary perspectives to capture heat-health impacts alongside attribution studies quantifying anthropogenic influence. The review stresses the need for granular projections focused on central and northern regions to inform localized adaptation strategies. This systems-based perspective integrating climatic and social dimensions can catalyze transdisciplinary collaborations to advance predictive capabilities and heat mitigation in India. Further, the observations will serve as a foundation for future research on heatwave-related issues in India, leading to the development of robust, evidence-based policies and strategies. This will help to build resilience and protect the most vulnerable populations from the adverse effects of climate change and extreme temperature events.

2. Methodology

A comprehensive approach was used to collect and analyze the relevant literature, drawing upon various sources to ensure an in-depth understanding of the heatwave projections. The methodology encompasses the identification, selection, and assessment of key and essential research papers, as well as the synthesis of their findings to shape the objectives and outcomes of the study. The following databases were used during the search process: Google Scholar, PubMed, Scopus, and Web of Science. The combination of terms used in the search criteria included "India", "climate change", "temperature", "heatwave", "extreme temperature events", "future projections", and "CMIP5/CMIP6". The literature search yielded numerous articles, which were subsequently subjected to a set of inclusion and exclusion criteria to ensure their relevance to the study. The inclusion criteria encompassed articles that (a) were published in English, (b) focused on the Indian subcontinent, (c) provided future temperature and heatwave projections based on climate models and statistical approaches, (d) employed CMIP5, CMIP6, or RCP in their methodologies. At the same time, the exclusion criteria included articles that do not offer projections for future temperature and heatwave scenarios.

The data extraction process commenced after identifying and selecting relevant articles. The essential information was extracted from each study, including the authors, publication year, research methods, main findings, and projected temperature and heatwave scenarios. The synthesized data was analyzed to generate insights into the study's trends, patterns, and implications. The quality of each study was evaluated based on its methodology, study area, data collection techniques, statistical analysis, and conclusion. The data obtained from the selected literature was evaluated and scrutinized to identify recurring patterns, tendencies, and areas of agreement or disagreement within the scholarly inquiry. The present investigation analyzed the following variables.

a. The projected range of temperature and heatwaves in India's future.
b. The methodologies employed by the studies, with a particular focus on using CMIP5, CMIP6 and RCP.
c. The geographic distribution and intensity of projected heatwaves.
d. The implications of these projections for policy development and adaptation strategies.

By examining these aspects, this literature review synthesized the findings of recent research on future temperature and heatwave scenarios in India, providing valuable insights for policymakers and stakeholders in their efforts to mitigate and adapt to the effects of climate change.

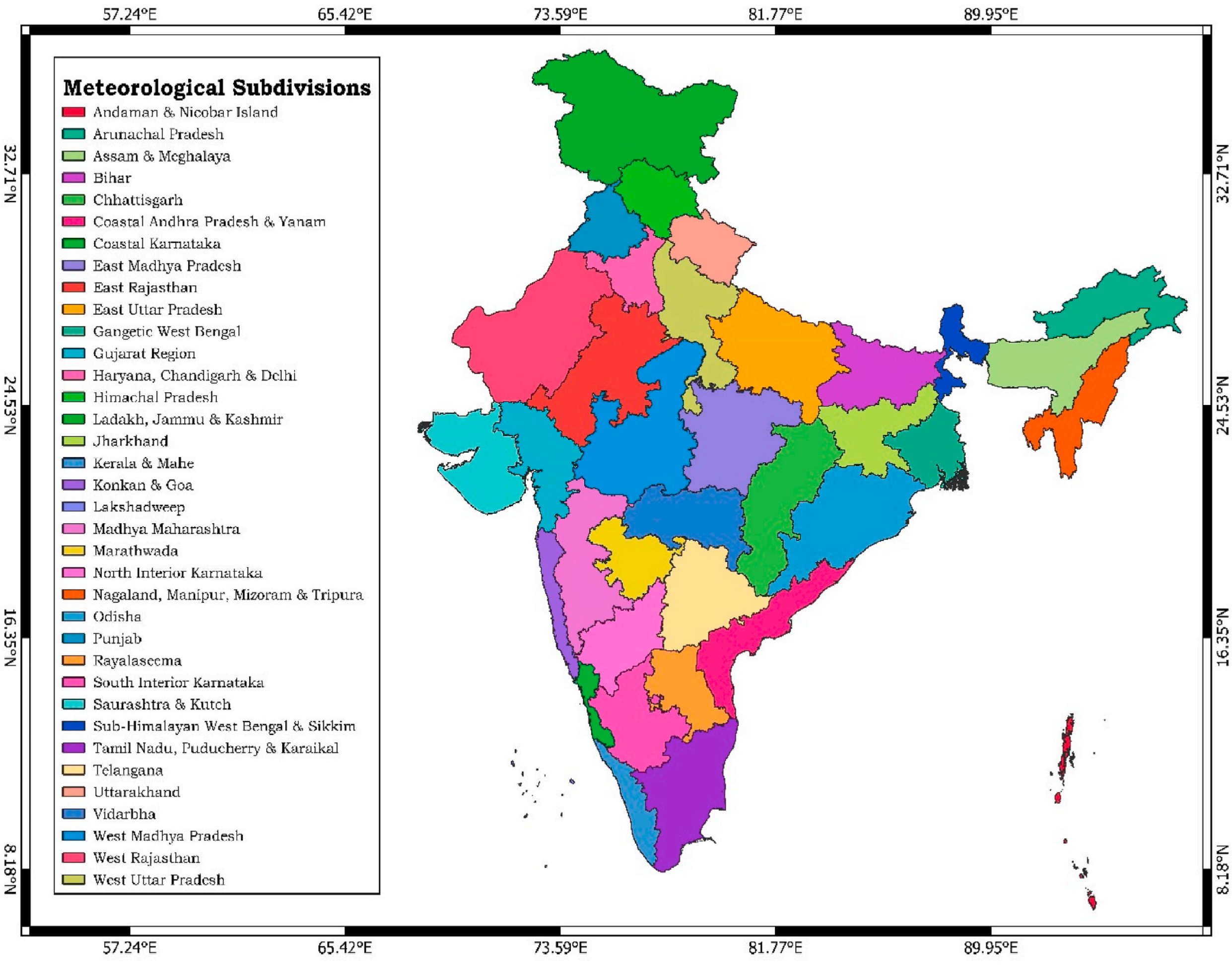

Fig. 1. Meteorological subdivisions of India as per the Indian Meteorology Department (IMD).

3. What makes India's heatwaves different?

India ranks among the most vulnerable to heatwaves due to its location in tropical and subtropical regions. The Indian Meteorological Department (IMD) has established guidelines based on temperature data and the departure from the average temperature for a given location to identify the heatwaves. Regarding the temperature threshold, IMD considers a heatwave to have occurred in plains regions when the maximum temperature reaches 40 °C or greater, while for hilly regions, it is set at 30 °C. When the normal maximum temperature for a location is less than or equal to 40 °C, a heatwave is defined as a departure from the normal temperature of 5 °C–6 °C, whereas a severe heatwave is defined as a departure from the normal temperature of 7 °C or more. Suppose the normal maximum temperature is greater than 40 °C. In that case, a heatwave is defined as a departure from the normal temperature of 4 °C–5 °C, and a severe heatwave is defined as a departure from the normal temperature of 6 °C or more.

Also, regardless of the normal maximum temperature, heatwaves may also be declared if the actual maximum temperature remains 45 °C or higher. The possible timeframe for the occurrence of heatwaves ranges from mid-March to June and may extend up to July [24]. Heatwaves also occur when the highest temperature in a specific location surpasses 45 °C for at least for 2 days. Therefore, for a heatwave to be declared, these conditions must persist at least two stations within a meteorological subdivision for at least two consecutive days. IMD indicates that the announcement will be made on the subsequent day or the second day. Fig. 1 shows the meteorological divisions of India. As per the IMD report, the decade 2001–2010 has been recorded as India's hottest decade, with an anomaly of 0.4 °C, surpassing the previous decade, i.e., 1991–2000, by 0.2 °C. The years 2015 and 2019 had the most prolonged heatwaves in India, with more than 40 °C daily maximum temperatures persisting for a month or around 45 days, depending on the location [25].

India has a diverse climate that can be broadly categorized into several major climate zones according to the Köppen Geiger classification system, also depicted in Fig. 2. The tropical wet climates are characterized by the zones Am, As and Aw. These are found in parts of western and northeastern India which receive heavy rainfall during the monsoon season. The tropical wet and dry climates are represented by zones BSh and BWh, found in interior parts of the Deccan plateau and western India which have a more pronounced dry season. The semi-arid steppe climate BSk is found in west-central India. The temperate climates are characterized by zones Cfa, Cwa and Cwb, found in the Himalayan north where there are temperate warm and cool summers. The alpine tundra climate ET is found in the higher Himalayan regions. The arid desert climate BWh dominates the western Thar desert regions along the India-Pakistan

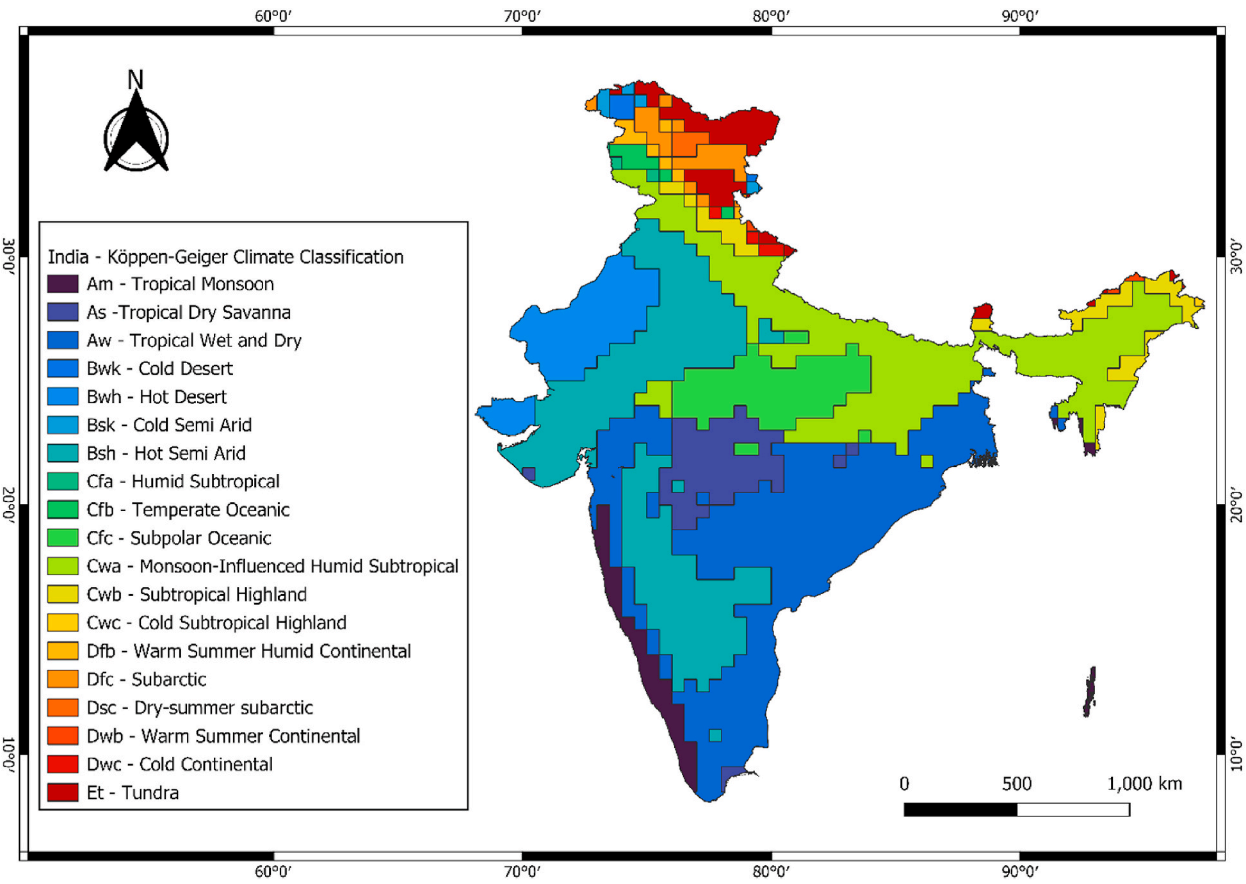

Fig. 2. Köppen-Geiger climate classification map of India.

border. The tropical monsoon climate Am is found along the southwest coast, southern Deccan plateau and Northeastern states, which receive heavy monsoon rainfall. India's climate is dominated by tropical wet, tropical wet and dry, and semi-arid zones, along with temperate climates in the north and arid deserts in the west [26].

The Bay of Bengal and the Arabian Sea, situated to the east and west, respectively, influence heatwave formation with their warm sea surface temperatures. This can exacerbate the effects of heatwaves, leading to higher temperatures and, humidity, and other impacts. Several factors contribute to the distinctiveness of India's heatwaves, including large-scale atmospheric patterns such as the sub-tropical persistent high and quasi-stationary Rossby waves over the mid-latitudes. These patterns play a role in heatwave formation and persistence in the region, interacting with factors like soil moisture and clear skies to amplify their effects [27]. Fig. 3 illustrates the trend in heatwave days across India's state from 1970 to 2021. Despite numerous studies on the effects of heatwaves on mortality in various parts of the world, the specific associations between excessive heat exposure and health in India remain

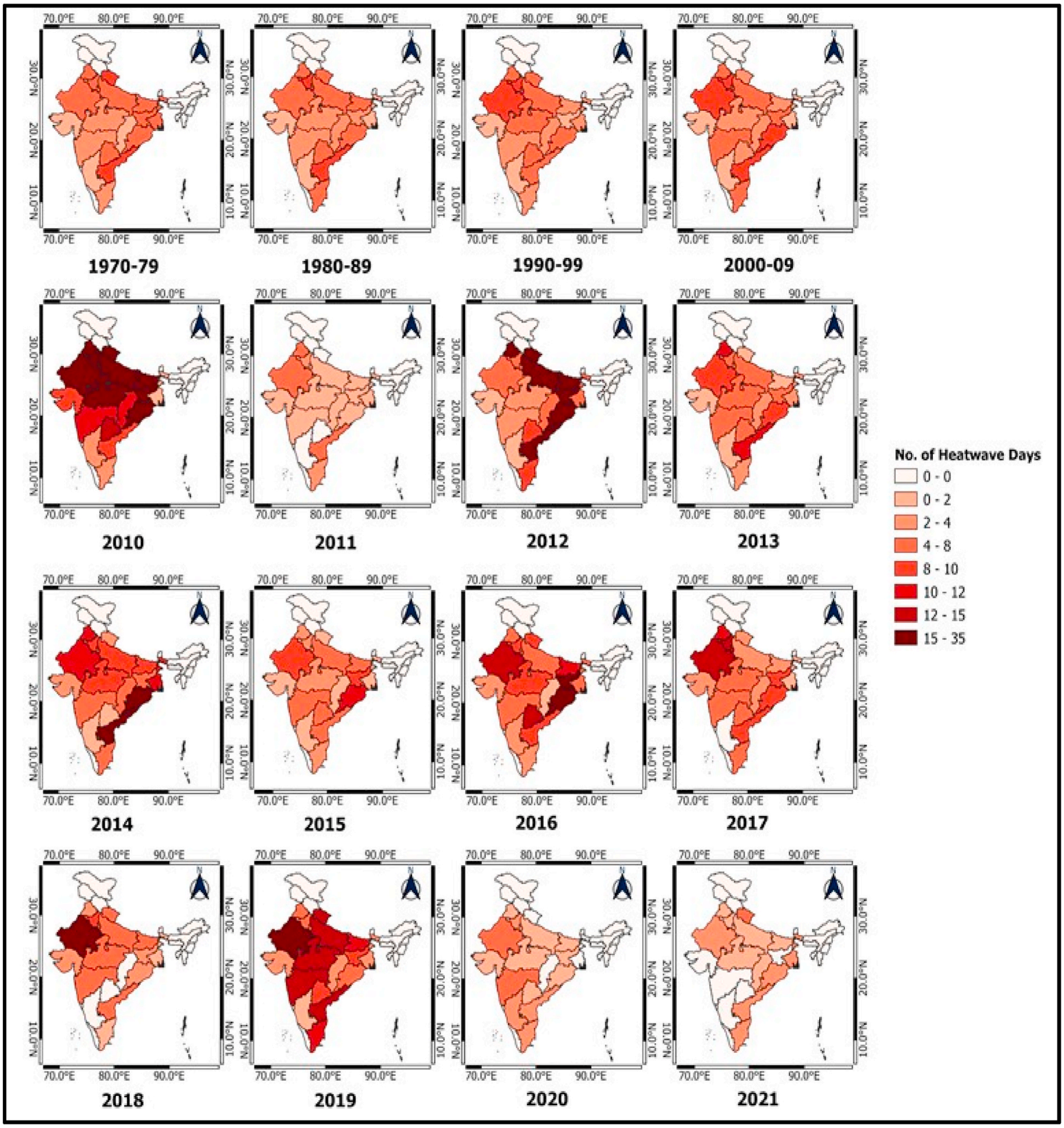

Fig. 3. State-wise heatwave days trend (1970–2021) in India.

under-explored.

3.1. Anti-cyclones in western India

The impact of the substantial circulation features over the Arabian Sea on the summer transition and onset of southwest monsoon-related rains along India's West Coast has been widely studied. However, recent findings suggest that rapid intensification of the sub-tropical anti-cyclone in the Arabian Sea, which repels monsoon flows, slows the monsoon's advance, significantly impacting Indian's heatwave and need to be further investigated [28]. A thorough analysis of anti-cyclone intensity and movement in the Arabian Sea could facilitate medium-range forecasting of the southwest monsoon onset, influencing the duration of heatwaves over the Indian subcontinent.

3.2. Rising temperatures in the Indian Ocean

The warming of the Indian Ocean has been substantial since the turn of the millennium [29]. The increased temperatures can lead to increased evaporation and transpiration from vegetation, resulting in elevated atmospheric moisture and oceanic precipitation. This increased precipitation can contribute to the water cycle and influence ocean currents, further affecting the ocean's temperature, salinity, and circulation patterns.

Researchers have found a possible link between El Niño events, Indian Ocean sea surface temperature (SST) anomalies and heatwaves in India [27]. There is a significant dependence between the Indian and Pacific Oceans. Warming of the tropical Indian Ocean and an increase in extreme El Niño events are likely to cause more frequent and long-lasting heatwaves in the Indian sub-continent. A multi-dimensional strategy, utilizing in-situ observations, numerical modeling, remote sensing, and palaeo-proxy networks at various spatial and temporal resolutions, are the critical requirements to understand the dynamics of Indian Ocean temperature.

3.3. Absence of periodic rainfall

The characteristics of the Indian summer monsoon using 33 CMIP5 (Coupled Model Intercomparison Project) models was investigated [30]. Since 1970, several regions of India have seen a significant decrease in precipitation [31]. The rainfall trend across 17 meteorological divisions was analyzed. It was found that 11 divisions recorded a notable decline in rainfall during the monsoon season, while a negligible negative trend was seen during the winter and pre-monsoon periods [32]. Western India experiences the greatest annual and seasonal rainfall fluctuation compared to the eastern and northern parts of India.

3.4. Soil moisture deficit

The land-atmosphere feedback drives the summer season temperature extremes and unleashes cumulative repercussions in India [33]. The areas of southwestern India experienced a substantially significant monsoon rainfall deficit and water storage losses in 2016, which were hit hard by the severe summer. This emphasized the significance and need for research into atmosphere-surface climate feedback-response analysis, which will further investigate the entire energy balance within the atmosphere-surface column and its role in amplifying the lethality of a heatwave.

3.5. Influence of absorbing aerosols on heatwaves

Anthropogenic aerosols, primarily composed of radiation-scattering sulfate, cause an overall cooling in most world areas, while greenhouse gas induced global warming exacerbates high-temperature extremes. In the Indian region, the aerosols are predominant in radiation-absorbing black carbon and dust mixtures, along with some radiation-scattering constituents. Recent evidence have revealed the influences of aerosols, particularly those of absorbing nature, on high-temperature extremes, on both climate and heatwave time scales over India [34–36].

Using long-term (1979–2013) satellite and ground-based observations, statistical tools (such as correlation and Granger causality) were applied to establish a causal relationship between absorbing aerosol index and daily maximum temperatures in northwest India, persisting on seasonal (MAMJ) and heatwave event scales [34]. Additionally, long-term (1981–2010) chemistry-coupled GCM simulations highlighted a relationship between absorbing aerosols (black carbon and dust) and high-temperature extremes in northern India, resulting from aerosol radiative heating of the surface layer (Mondal et al., 2021). Furthermore, GCM simulations from 1971 to 2010 indicated a substantial rise in surface air temperature in the Himalayas, with higher warming in parts of the Western and Central Himalayas (0.2–2 °C) [36]. Due to shifts in land-surface energy balance and abnormal rises in the atmospheric short-wave radiation flux, black carbon and dust cause increased snow melt.

3.6. Heatwave-associated mortality

Heatwaves pose a substantial risk to the existing population by reducing comfort levels, subsequently affecting the Quality Of Life (QOL). The four most common health consequences of prolonged heatwave exposure are-cramps, dehydration, fatigue and heatstroke. Further, rising temperatures significantly increase severe gastroenteritis and food poisoning cases due to spoilage and shelf-life reduction. Another heat connection is a surge in the instances of nervousness, palpitations, anxiety, chronic cardiovascular and respiratory diseases, and behavioral changes [20].

In recent years, the National Disaster Management Authority (NDMA) has recognized a trend of escalating heatwaves in India. These heatwave events have significantly affected various states, districts, and cities, as reflected by the upward trend in the number of heatwave days in India. In 2015, heatwaves were observed in 9 states, whereas in 2020, this number increased to 23 states. Not only this, but other states and Union Territories (UT) are also projected to experience severe heatwaves events. Rajasthan, Madhya Pradesh, Maharashtra, and Telangana are among the most heatwave-prone states in India, with mean maximum temperatures exceeding 40 °C during the summers. The frequency, duration, and intensity of heatwaves in these regions have increased in recent decades, in line with the global warming trend.

While most heatwave studies focus on temperature, multiple interacting meteorological parameters that govern physiological impacts should also be considered in combination. Solar radiation directly elevates heat gain, commonly experienced in northwest India's high insolation. Humidity offsets mitigating sea breezes along coastal regions, heightening heat index at lower temperatures. Rising night-time humidity impedes relief from high temperatures, which is critical for coping with extreme day heat and changes in wind flows like pre-monsoon low-level jets, which transport hot, dry air inland and deprive eastern regions of cooling ventilation. The development of heat indices for Indian conditions through biometeorological studies could better represent multi-parameter heat extremes for targeted heat actions attuned to local dynamics. An interdisciplinary approach is essential for a nuanced heatwave definition beyond just temperature cut-offs.

Indian states have established Heat Action Plans (HAPs), beginning with Ahmedabad in 2013, and various states have since adopted HAPs that involve measures like early warning systems, public awareness campaigns, capacity building of health professionals, and reducing heat exposure for vulnerable groups. These regions are also characterized by a semi-arid to arid climate with low rainfall and high evapotranspiration rates, exacerbating the impacts of heatwaves. Northern and Central India also experience intense heatwaves, as evidenced by studies from cities like Ahmedabad and Nagpur examining health impacts and excess mortalities associated with severe heat events. However, the eastern regions of Odisha, West Bengal, Kolkata, Bhubaneswar and Jharkhand still remain the primary focus due to high humidity and heatwave susceptibility [37]. Excess all-cause mortality during Ahmedabad in May 2010 when temperatures reached 46.8 °C was estimated to increase the deaths by 43% (1344 excess deaths) compared to May 2009–2011 averages [38]. The highest heatwave causalities were observed in Telangana, Orissa and Andhra Pradesh due to a combination of geographical, social, and economic factors such as high population density and lack of preparedness. In Uttar Pradesh, male heatstroke deaths climbed from 490 in 2001–2005 to 761 in 2011–2015, while female deaths climbed from 116 to 220 throughout the

Table 1
World temperature record from 2014 to 2021.

Temperature (°C)	Year
0.23	1990
0.22	1991
0.21	1992
0.24	1993
0.32	1994
0.44	1995
0.33	1996
0.47	1997
0.63	1998
0.41	1999
0.42	2000
0.54	2001
0.63	2002
0.62	2003
0.54	2004
0.68	2005
0.64	2006
0.66	2007
0.54	2008
0.64	2009
0.72	2010
0.61	2011
0.63	2012
0.65	2013
0.95	2014
1.1	2015
+1.23 Hottest year on record (tied)	2016
1.13	2017
1.06	2018
1.18	2019
+1.23 Hottest year on record (tied)	2020
1.05	2021

Source: [44].

same period. In 2010, there were 580–595 excess deaths during the May heatwave, a 30–31% increase over the previous year and there were 306–312 excess deaths in May–June 2014, a 14–15% increase in Nagpur [39]. Similarly, in Andhra Pradesh, the male mortality rate increased from 334 in 2001–2005 to 1284 in 2011–2015, and its female mortality rate climbed from an average of 49/year between 2001 and 2005 to 346/year between 2011 and 2015, making it the second highest mortality rate state. Currently, most studies rely on all-cause mortality data during heatwaves rather than mortality strictly attributable to heat stroke/heat stress. Heatwave deaths are likely underreported in official figures, as causes can be misclassified due to a lack of biometeorological evidence.

Further, a decreasing trend heatwaves events was seen in some states due to the combined efforts of NDMA coordinated with all stakeholders [40,41]. India currently lacks robust systematic data capture and interdisciplinary coordination to accurately quantify heat-attributable health impacts to inform evidence-based planning. This is evident from NDMA reports which suggest that lockdown measures resulted in only four deaths due to heatwaves in 2020. Whereas EnviStats-India, 2022 reported that 27 people died in 2020 from a heatwave and no death was reported in 2021. This data discrepancy between NDMA and EnviStats may be attributable to the fact that each organization uses a somewhat different “definition of death”, but it does cast doubt on the reliability of data. Death tolls attributed to heatwaves varied from 400 to 3000 between 1992 and 2015. However, it is believed that the actual death toll is likely to be much higher than the official count [42].

The heatwave is an extreme weather event that has caused a considerable rise in premature mortality. Therefore, the rising mortality toll related to heatwaves should serve as an early warning signal to health and disaster management authorities, urging them to increase their capabilities and readiness to face this hazard [43]. Heat-specific ICD codes are needed to accurately classify mortality causes. Improved coding will enable the analysis of heat-linked morbidities using health databases. Moreover, the proactive steps and preparedness must also involve sensitization, awareness campaigns, urban planning strategies and training of government and private sector health personnel.

4. Climate change and heatwave scenario over the Indian states

The world faces an unprecedented challenge as temperatures continue to be broken, and the previous eight years have consistently ranked among the warmest in recorded history, as shown in Table 1 [18]. In particular, 2021 has emerged as the 6th hottest year since reliable temperature records began. Table 1 represents the record from 1990 to 2021, where the average global temperature was at least 1.04 °C higher than the average of 1880–1900, subsequently increasing the land and ocean surface temperatures by +1.45 °C and +0.69 °C, respectively [19].

India has experienced considerable warming, with the 2021 annual mean temperature deviation being +0.44 °C above the 1981–2010 mean, marking it the 5th warmest year since 1901. While the top four warmest years were 2016 (+0.71 °C anomaly), 2009 (+0.55 °C), 2017 (+0.54 °C), and 2010 (+0.53 °C). Also, 11 of the 15 warmest years have been recorded within the last 15 years (2007–2021). This overall trend suggests a warming rate of 0.63 °C per 100 years, with maximum temperatures (0.99 °C per 100 years) increasing more rapidly than minimum temperatures (0.26 °C per 100 years). Therefore, the headline temperature readings may not reveal how challenging it is to deal with the ongoing period of extreme heat. No standard index applies for heatwaves, as it varies from place to place depending on the regional criteria/thresholds or as specified by the met offices. The 30 °C and 40 °C thresholds also do not account for differences in humidity levels across regions, exacerbating heat stress. Employing just two temperature cut-offs across India overlooks the varied climatology and acclimatization levels of different regions.

Climate change, driven primarily by greenhouse gas emissions, has led to an increase in the intensity, duration, and frequency of extreme heat events. While natural climate variability, such as changes in large-scale atmospheric patterns like the El Niño-Southern Oscillation and the North Atlantic Oscillation, can also result in heatwaves, those induced by human activities are generally more severe and widespread. Attribution studies employ climatic models like Global Climate Models (GCMs), which are crucial in determining the extent of human influence on observed climate changes and extreme weather events like heatwaves. GCMs capture large-scale climate change patterns, including global temperature, precipitation, and atmospheric circulation, and project the long-term impacts of human activities on the global climate system. These studies can help to explain heatwaves and other extreme weather phenomena by comparing simulations with and without humans.

Another essential aspect to consider is the Urban Heat Island (UHI) effect, which causes urban areas to experience higher temperatures than rural areas that are less developed or undeveloped. Various factors, such as anthropogenic heat, reduced greenery, land use, population density, and urban morphology, contribute to the magnitude of the UHI effect. The UHI, directly and indirectly, impacts the local climates, energy consumption, air quality, and public health. During pre-monsoon summer, UHI effects become prominent over central India, with nearly all locations exhibiting statistically significant positive Surface Urban Heat Island Intensity (SUHII). The reduction of evaporative cooling was discovered to be the primary contributor to UHI, and the increase in evapotranspiration in non-urban regions during the winter led to a positive SUHII. For UHI to be effectively addressed, a comprehensive national plan for harmonizing UHI-related measures is required, including urban planning, energy consumption policies, green building codes, and air pollution mitigation measures [45]. For example, Karnataka is likely to project an approximate temperature of 2.0 °C by 2030. The region is more susceptible to extreme heat events and requires an early heat health adaptation plan to minimize and mitigate the associated risks.

Over 706 heatwave episodes were reported in India between 1970 and 2019 [43]. In 50 years (1970–2019), extreme weather events killed 1,41,308 individuals, whereas 17,362 died due to heatwaves. The most considerable heatwave fatalities occurred in Andhra Pradesh, Orissa and Telangana. The Core Heatwave Zone (CHZ) is the most vulnerable region for severe heatwave (SHW) and heatwave (HW), with the maximum heat incidence occurrence in May month. The CHZ encompasses the states of Andhra Pradesh, Bihar, Chhattisgarh, Delhi, Gujarat, Haryana, Himachal Pradesh, Jharkhand, and Madhya Pradesh, Maharashtra, Punjab, Orissa, Rajasthan, Uttar Pradesh, Uttarakhand, Telangana and West Bengal. As the temperature continues to rise due to climate change, India has yet to recognize excessive heat as a major health problem. Heat vulnerability index (HVI) can be a way to map geographic variability in heatwave vulnerability across all districts in India, which can target adaptation efforts in a thermally diverse country [46].

State-level heat action and health promotion programs have recently been incorporated into official health policy. More comprehensive measures at the community level are required to mitigate future health hazards as there is still minimal awareness and discussion about the dangers that excessive heat can pose to an individual. In the context of ongoing climate change, it is crucial to comprehend the complexities of heatwaves and their effects on public health. Developing region-specific identification criteria for heatwaves, conducting attribution studies to determine the extent of human influence, and implementing comprehensive strategies to combat both climate change and UHI effects are essential steps in mitigating the risks associated with extreme heat events.

5. Advances in understanding temperature and heatwave projections

Since the Industrial Revolution, the global temperature has risen by more than 1.2 °C [47]. It is projected that even if all the commitments under the Paris Agreement (2015) are not met, global warming will exceed 3 °C by the end of the 21st century. While the average global temperature will rise, certain regions will experience more rapid warming than others. Global or regional climate models are necessary to understand the present and future climatic, particularly extreme events. There are various large-scale features that can be simulated using GCMs, but small-scale processes and extreme occurrences are still challenging to compute. Numerous studies were conducted using global climate models (Coupled Model Inter-comparison Project Phase 5 CMIP5) to predict the likelihood of future heatwaves over India [48], as shown in Table 2.

The existing studies have several limitations, including their focus on specific regions rather than pan-India, reliance on coarse global climate models unable to capture local heat dynamics, and use of varied emissions scenarios leading to a range of outcomes, and majorly emphasis solely on temperature without considering humidity. These limitations lead to uncertainties regarding localized projections, future pathways, human health and adaptation needs. There is a critical need for high-resolution modeling with rigorous validation, exploration of localized processes, interdisciplinary approaches incorporating vulnerability factors, and detailed impact studies to advance understanding of future heat risks across India, considering both climate and social dynamics.

Table 2
India's temperature projections studied by various researchers.

S. No	Model	Average Mean Maximum Temperature	Heat Wave	State/Region	References
1.	CMIP5 RCP8.5 (High emissions)	>1.5 °C for 2050 >2.5 °C for 2100	–	Delhi	[49]
2.	Global Earth System Model: REMO-OASIS-MPIOM (ROM)	0.5–2 °C (2020–2049) 2–4 °C: (2050–2079) 4–6.5 °C (2080–99)	–	East-central and northern regions	[3]
3.	CMIP5 RCP8.5	–	Projected to increase by 40 times at 2100	India	[48]
4.	RCP2.0	–	Projected to increase at 4-fold at 2100	India	
5.	CMIP5 multi-model simulations RCP2.6	1.8 K at 2100	Increasing warming trend till 2050 and thereafter decreases	India	[50]
6.	RCP4.5	2 K at 2100			
7.	RCP6.0	3.5 K at 2100			
8.	RCP8.5	5 K at 2100			
9.	Regional Climate Model Global Climate Model (HadCM3Q): 6 Models used: A1B scenarios (Projections w.r.t. baseline 1975–2005)	0.9 °C for 2020s 2.1 °C for 2050s 3.4 °C for 2080s	–	India	[51]
10.	CMIP5 (RCP8.5)	–	A sixfold rise in the concurrent day and night-time heatwaves	India	[52]
11.	Simulations of large EC-Earth model	Estimated the exceedance probability of the observed hottest summer in the present climate (2 °C and 3 °C warming worlds in India	Hottest summer rise >7 to 20-fold (as compared to present climate)	India	[53]
12.	RCP8.5	Under 2 °C warmer world in comparison to 1 °C warmer world	The frequency of exceptionally hot days to rise manifold is projected	Tropical region	[54]
13.	IMD daily gridded temperature data	Highest increasing trend of 1.28 °C	–	Jammu and Kashmir South peninsula	[55]

(CMIP5- Coupled Model Inter-Comparison Phase 5 models; GCM- General Circulation Models).

5.1. Future projections using global climatic models

The IPCC, Working Group 1 (WG1) presents the most updated and recent assessment of scientific understanding of the physical components of climate system and climate change based on the Shared Socio-economic Pathways (SSPs) to reflect multiple conceivable futures. In climate change research, SSPs are used to investigate the effects of different societal pathways on the climate system, human and environmental systems. Representative Concentration Pathways The (RCPs) are four scenarios of future radiative forcing levels used to evaluate the climatic implications of various future emission scenarios. The RCPs cover a broad range of radiative forcing levels (low-RCP 2.6 and high-RCP 8.5) and provide a framework for assessing the implications of various GHG emissions on the climate, human and natural systems [56]. Both SSPs and RCPs are complementary, presenting distinct but equally significant future visions. There is a close relationship between the SSPs and the RCPs, as the SSPs supply the assumptions about future GHG emissions and other change drivers to generate the RCPs.

The temperature trends from 1901 to 2020 and projected trends from 2050 to 2100 in selected cities, including Delhi were analyzed and an average mean maximum temperature increase of 1.5 °C since the 1980s and an additional increase of 1.5 °C for 2050 and 2.5 °C for 2100 in the RCP 8.5 (high emissions) scenarios was observed [49]. The likelihood of a heatwave over India has increased over the warmer decades of 2001–2010. The maximum temperature anomalies of 6–8 °C were noticed for Andhra Pradesh, indicating a highly vulnerable region to heatwaves [57]. Similarly, a considerable increase in the frequency of heatwaves from 1951 to 2015, with the most extreme heatwave events recorded in 1998, 1995, and 2012 in India [48].

The duration and frequency of severe heatwaves over India using CESM-CMIP5 projections showed an eight-fold increase in the low warming scenario (RCP2.0) by 2021–2050 and the same would rise 30 times at 2100 concerning 1986–2015 with RCP2.0. However, the RCP8.5 scenario predicts the frequency of severe heatwaves, which could increase 40 times by 2100 [48]. By the end of the 21st century, the average temperature rise expected under the RCP2.6, RCP4.5, RCP6.0 and RCP8.5 emission scenarios is projected to be 1.8 K, 2 K, 3.5 K, and 5 K, respectively (relative to 1901–1960) [50]. Hence, the observation shows the continuous increase in surface temperature under the RCP8.5 scenarios, whereas the long-term trend (2006–2099) showed a warming of approximately 0.2 K/decade across India.

Additionally, warming will accelerate by the end of the 21st century, peaking at around 0.4 K/decade. The Himalayan region is expected to face higher temperature extremes in overall scenarios. In contrast, under the RCP8.5 scenarios, India's Northeastern, Central and Northwestern regions might expect modest rises. The RCP4.5 emissions scenario indicated that the heatwave risks are expected to increase by a factor of ten at the end of 2100 [58]. Further, it is predicted that the heatwaves would influence more than 70% of land areas with a magnitude greater than 9. The worsened climate change impacts will be the precipitation deficit, and concurrent droughts and heatwaves are projected over India during the 2100 century.

The temperature forecast using the regional earth system model REMO-OASIS-MPIOM (ROM) for the early future (2020–2049), middle (2050–2079), and far (2080–99) future under the RCP8.5 emission scenario was computed [59]. The observance of accretion was in the range of 0.5–2 °C in 2020–2049, 2–4 °C in 2050–2079, and 4–6.5 °C in 2080–2099. This suggests a nationwide linear increase in temperature, with a significant increase in the far future than the near future. The highest growth in the temperature was observed above the east-central and northern parts of the country. Hence, the consistent increase in temperature is liable for the immediate increase in warmer days and heatwave actions and the associated increase in future hazards. By 2100, the average annual temperature in India could climb by 4 °C due to excessive greenhouse gas emissions [51].

According to Climate Impact Lab and the Tata Centre for Development at UChicago, the average number of extremely warm days around India will increase by more than eight times annually, from 5.1 in 2010 to 42.8 in 2019 [60]. Moreover, it predicts that by 2100, the Union Territories will have higher average temperatures than the warmest state of India, i.e., Punjab, which has an annual average temperature of below 32 °C (as of 2010) and is expected to reach approximately 36 °C. The largest increase in the frequency of warm days from 1.62 (2010) to 48.05 (2100) is predicted for Orrisa State. More than 1.5 million deaths are expected due to climate change in 2100; out of that, 64 % are concentrated in the regions mainly Bihar, Uttar Pradesh, Rajasthan, Madhya Pradesh, Andhra Pradesh, and Maharashtra. Researchers [61] investigated the future heatwave projection (duration and frequency) over India utilizing nine CMIP5 models. The RCP4.5 scenarios predict an increase of approximately two heatwaves and an increase of 12–18 days of heatwave duration in the period 2020–2064. Further, the findings show that climate change affects India's southern and coastal regions, which do not have a specific heatwave history.

The spatial trend analysis concludes that the frequency and duration of heatwaves in India's central and northwestern parts will rise significantly by 0.5 occurrences per decade and 4–7 days per decade, respectively. Daytime heatwaves across India were analyzed using the CMIP5. This revealed that human activities in India considerably boosted the frequency of concurrent hot day and hot night (CHDHN) episodes lasting 1–3 days [52]. In addition, under the high emission trajectory of RCP8.5, the frequency of 3-day CHDHN events is projected to increase 12-fold from the current level by the end of the 21st century and 4-fold by the middle of the 21st century. However, under the RCP2.6 low emission scenario, the increase in 3-day CHDHN events by the end of the 21st century can be kept to a mere 2-fold.

Changes in the occurrence of the warmest summers throughout observation (1951–2015) have been reported but not thoroughly explored [53]. The IMD discovered that between 1951 and 2015, the average maximum summer temperature in three of India's most significant meteorological seasons (arid, monsoon, and savannah) increased dramatically. According to the Climate of 20th Century Plus (C20C+) Detection and Attribution project, the hottest regional summer of 2010 can be attributable to anthropogenic warming. Under 2 °C and 3 °C warming scenarios, the study used the simulations of a large ensemble (2000 years) of the EC-Earth model to calculate the likelihood of India's current climate exceeding the probability of the reported hottest summer. Compared to the current climate, the exceedance likelihood of the observed warmest summers increases by more than a factor of seven in the 2 °C warmings world and by more than a factor of twenty in the 3 °C warmings world.

As a result, climate change will result in serious societal issues in the form of an anticipated rise in the frequency of hot summers and the number of days with related heatwaves. The analysis of maximum temperatures during the period 1951–2019, reported that the maximum temperatures are the highest during May and mainly prevail over Central India, whereas temperatures below 30 °C are noted in Jammu and Kashmir state of North India; West coast hilly region, and over Assam, Meghalaya and Nagaland of Northeast India [55]. Their trends analysis revealed that the region of Jammu and Kashmir and the South peninsula (both of which experience colder summers) have the highest growing trend of 1.28 °C, while East-central India has the lowest.

Since the 1960s, various studies have been conducted on heatwaves as temperature data from observatories have become available for a considerable period. First attempts were made for specific regions, such as Andhra Pradesh, Karnataka, Gujarat, etc., as case studies and later for North and South India and the entire India as the observations increased spatially and temporally. While most of the studies reported maximum temperatures to be over North India and during May, one study analyzed the severe heat of July 1966 that existed for ~10 days. It extended at least over 60% of India, which was shown to result from an unusually prolonged break monsoon condition [62].

Further, the previous works show that keeping the global mean temperature rise to less than 2 °C presents a formidable task that calls for negative emissions to be maintained over the long term and to implement continual mitigation measures [63]. Under the RCP 8.5 scenario, annual records are likely to establish new records for the foreseeable future for global temperature [64]. However, the frequency of hot days is predicted to multiply by a factor of several in a world that is 2 °C hotter than the current temperature [54]. Furthermore, under high emission scenarios, the tropics would continue to experience longer and more frequent heatwaves, in addition to the increased number of hot days and nights [65]. Therefore, climate change and accurate future heat forecasts are significant concerns and critical elements of mitigation and heat adaptation plans to safeguard vulnerable populations.

6. Recommendations

It is evident that a large number of people are at risk of illness and premature death subjected to extreme heat events and the situation is projected to worsen in the near future [48]. Currently, India lacks a comprehensive plan and strategy to mitigate the adverse effects of climate change, notably addressing heatwaves and related illnesses. According to NFHS-5, only 12% of the population have air conditioners (AC's), 8% have cars and four-wheelers and 55% still use two-wheelers. This limited penetration of air conditioning and prevalence of two-wheeler transport implies large vulnerable population segments in India lack the adaptive capacity to alleviate heat stress through technical interventions, potentially amplifying public health impacts. The relationship between temperature and health implications are neither predictable nor uniform. They are influenced by many complex and interrelated biological, social, medical, environmental, and geographical factors. Therefore, local temperature threshold estimation is essential for an effective heat-health warming system.

In light of this, the scientific community is making a concerted effort to lessen the vulnerability caused by heatwaves. The future projections studies were mainly computed using CMIP5 models under the RCP 8.5 Pathway. In order to solve urgent environmental issues like global warming and climate change, the focus needs to be given to reduce individual carbon footprints, as also highlighted in the Lifestyle for Environment (LiFE) initiative by the Indian Government. To promote climate-sensitive rural habitation, local eco-friendly architectural practices involving high heat capacity construction, such as thatched rooftops and shaded exterior living spaces, should be encouraged to maintain thermal homeostasis. Hydrological restoration of village water bodies alongside scaling up of irrigation infrastructure can minimize heat strain on agrarian communities. Expanding agroforestry and afforestation programs to increase tree cover and green spaces would aid in localized mitigation by providing evaporative cooling and radiation shading [66]. These emerging concepts for low-income countries like India to combat urban heat can reduce the air temperature by around 10%.

Early warning dissemination systems utilizing multiple communication channels can enhance lead time for proactive heat mitigation among vulnerable groups. Community health workers and rural healthcare system capacity building for identification, treatment, and emergency management of heat illnesses is imperative. For urban areas, mandatory cool roof provisioning for new buildings and retrofitting existing structures with high-albedo materials coupled with incentivizing bioclimatic architecture and passive cooling techniques can ameliorate heat stress. Scaling up urban greening schemes and augmenting shade-providing street infrastructure can aid mitigation efforts. Rescheduling high-risk outdoor occupational and educational activities along with community outreach for

Table 3
Policies linking SDG 13 and heat-health action in India.

Policy/Initiative	Description	References
National Disaster Management Plan (NDMP)	Provides a framework for heatwave mitigation under disaster management, including early warnings, capacity building, and inter-agency coordination.	[67]
National Action Plan on Climate Change (NAPCC)	Addresses adaptation under its "National Mission on Sustainable Agriculture" including managing heat stress on crops/livestock.	[68]
National Action Plan on Human Health and Climate Change	It aims to facilitate capacity building, surveillance, preparedness and awareness generation for climate-sensitive health risks, including heat stress.	[69]
Heat Action Plans	City-level plans were initiated after the Ahmedabad model to issue early heatwave warnings, minimize exposure of at-risk groups and boost health system preparedness.	[70,71]
National Disaster Management Policy	Mandates development of disaster-specific action plans, including for heatwaves, outlining prevention, preparedness and risk reduction.	[72]

vulnerable populations on preventative measures, including subsidized cooling devices and optimizing emergency readiness, can be the key to ensuring the goal of 'zero heatwave deaths'. This will also help to close the energy demand and supply gap and bring electricity to the country's unserved regions. Adapting renewable energy policies on a community level, incentivizing compliance, and leaping from 'Perform, Achieve, and Trade' model to a fully operational Energy Trading System. Additional barriers to enacting climate action plans include a lack of available skilled labor and the need for technological advancements.

By the end of 2050, the temperature could rise to ±1.2 °C to ±3.5 °C level, depending on the micro-climate of a particular area. In the wake of this, India has implemented various strategic policies and initiatives such as 'National Clean Air Programme (NCAP)', 'National Action Plan on Climate Change (NAPCC)', 'Nagar Van Scheme', 'Swachh Bharat Abhiyan', and 'A Green India for all' to reduce greenhouse gases and other air pollutants emissions. Various policies and initiatives have been launched by the Government of India aligned with SDG 13 targets to build adaptive capacity and resilience against rising heat risks. The NDMA has developed a National Disaster Management Plan and Policy, which provides frameworks for heatwave mitigation through early warnings, awareness generation, and coordination among agencies for emergency response. Table 3 highlights the policies linking SDG 13 and heat-health action in India.

More recently, a five-point agenda, i.e., the 'Panchmirt' was given by the Indian Prime Minister at the Conference of Parties 26 (COP26) to address climate change. The targets under the 'Panchmirt' initiative include 1) 500 MW non-fossil energy capacity, 2) 50% energy requirements from renewable energy, 3) reduction in one billion tonnes of carbon emissions, and 4] 45% reduction in the carbon-intensive economy to be achieved by 2030. The final goal is to reach a net-zero emissions economy by 2070. However, India needs adaptive planning to achieve these ambitious targets provided under these initiatives to reduce the temperature and severe impacts of heatwaves. Also, there is an immediate need to upgrade the medical infrastructure and facilities to reduce mortality from heatstroke [73]. This requires expanding access to healthcare facilities, investing in heat-specific emergency preparedness, and training medical professionals to recognize and treat heat-related conditions.

Moreover, the laws concerning occupational health must be amended appropriately to protect and safeguard individuals against extreme heat. Further, community engagement is very crucial to address such challenges. Education and awareness programs for capacity building that foster stakeholder learning and effective adaptation are required.

7. Conclusion

India is facing serious challenges due to the rising temperature and climate change. The rising temperature reported an increase in water scarcity, agricultural production, extreme weather events and other issues like a rise in heatstroke and mortality in some states of India. Therefore, the current review focused on anticipating rising heatwaves and future risk reduction and adaptation projections. While global climate change is well understood, regional climate shifts are not appropriately recognized due to a lack of local observational data and a lack of understanding of physical phenomena about particular places.

Yet, the study revealed that the likelihood of heatwaves would increase dramatically in the near future for all districts due to intensified global warming, affecting communities in the Eastern and Central Indo-Gangetic plains and Malabar region disproportionately. Therefore, adopting and establishing interventions for sustainable prevention, such as improving early warning systems to provide timely alerts and warnings of heatwaves and providing guidelines for protective measures to reduce the impact of heatwaves on public health and mitigation of heat-related mortality, is critical. Understanding current and predicted regional climate changes is essential for individuals and policymakers to plan effectively for disaster management and risk mitigation and to formulate relevant local adaptative strategies. There is an urgent need to develop a regional climate model to understand the dynamics of climatic shifts in a particular region. Along with scientific research, cross-disciplinary collaboration at the global level is required to design tailored solutions and promote sustainable development. The present study will provide significant insights for developing heatwave risk reduction techniques and future adaptive planning, addressing Sustainable Development Goal 13.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Ravindra Khaiwal: Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Sanjeev Bhardwaj:** Writing – review & editing, Formal analysis. **Chhotu Ram:** Writing – review & editing, Data curation. **Akshi Goyal:** Writing – review & editing. **Vikas Singh:** Writing – review & editing. **Chandra Venkataraman:** Writing – review & editing. **Subhash C. Bhan:** Writing – review & editing. **Ranjeet S. Sokhi:** Writing – review & editing. **Suman Mor:** Writing – review & editing, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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