Projected changes in heatwaves and its impact on human discomfort over India due to global warming under the CORDEX-CORE framework

Article

Published Version

It is advisable to refer to the publisher's version if you intend to cite from the work. See Guidance on citing.

To link to this article DOI: http://dx.doi.org/10.1007/s00704-023-04788-4

Publisher: Springer

RESEARCH

Projected changes in heatwaves and its impact on human discomfort over India due to global warming under the CORDEX-CORE framework

Pyarimohan Maharana[1,2] · Dhirendra Kumar[3] · Sushant Das[4,5,6] · P. R. Tiwari[5,6,7,8] · Marc Norgate[5,6,7] · Viswanathan Anantha Venkat Raman[9]

Abstract

Due to climate change, rapid warming and its further intensification over different parts of the globe have been recently reported. This has a direct impact on human health, agriculture, water availability, power generation, various ecosystems, and socioeconomic conditions of the exposed population. The current study thus investigates the frequency and duration of heatwaves, human discomfort, and exposure of the human population to these extremes using the high-resolution regional climate model experiments under two Representative Concentration Pathways (RCP2.6, RCP8.5) over India. We find that more than 90% of India will be exposed to uncomfortable warm nights by the end of the 21st century with the highest rise over western India, Madhya Pradesh (MP), Uttar Pradesh (UP), Punjab, and the Haryana region. States like Odisha, Chhattisgarh, eastern parts of MP and UP, and some parts of J&K will be the worst hit by the intense and frequent heatwaves and human discomfort followed by the densely populated Indo-Gangetic plains under RCP8.5. Strict enforcement of the stringent policies on stabilization of population growth, improvement of local adaptive capacities, and economic status of the vulnerable population along with enforcing effective measures to curb greenhouse gas emissions are important to reduce human exposure to future heat stress. We demonstrate that a proper mitigation-based development (RCP2.6) instead of a business-as-usual scenario (RCP8.5) may help to reduce 50–200 heatwave days, 3–10 heatwave spells, and 10–35% warm nights over the Indian region. Consequently, this can avoid the exposure of 135–143 million population to severe discomfort due to extreme heat conditions by the end of the 21st century.

✉ Dhirendra Kumar
   dhirendra.cub@gmail.com

[1] School of Ecology and Environment Studies, Nalanda University, Bihar, India

[2] Department of Environment Studies, DCAC, University of Delhi, Netaji Nagar, New Delhi, India

[3] National Centre for Atmospheric Sciences, University of Reading, Reading, UK

[4] Earth System Physics Section, The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy

[5] Department of Earth and Atmospheric Sciences, National Institute of Technology Rourkela, Rourkela, India

[6] Centre for Atmospheric and Climate Physics Research, University of Hertfordshire, Hertfordshire, UK

[7] Centre for Climate Change Research, University of Hertfordshire, Hertfordshire, UK

[8] Centre for Future Societies Research, University of Hertfordshire, Hertfordshire, UK

[9] Department of Geography, Shaheed Bhagat Singh College, University of Delhi, Delhi, India

1 Introduction

The frequency and intensity of extreme heat events are increasing all around the world, and these have both direct and indirect impacts on the comfort and health of living beings and various ecosystems (Luan et al. 2019; Nitschke et al. 2011; Russo et al. 2017; Zhang et al. 2017; Frich et al. 2002). One of the main reasons for the accelerated warming of the earth in recent times is attributed to the increase in concentrations of greenhouse gases (GHGs) from anthropogenic sources (Fischer et al. 2004). Extreme heat events are physical hazards that can cause health issues (Kent et al. 2014; Singh et al. 2021a) and also contribute to the earth's regional warming process (Pattnayak et al. 2017; Perkins-Kirkpatrick and Lewis 2020).

The rapid urbanization and the use of existing technologies are energy demanding, which is mostly obtained from fossil fuels. This further leads to heating of the atmosphere and manifests increase in the heatwaves and warm night which causes human discomfort (Koteswara Rao et al. 2020;

Mohan et al. 2020; Nageswararao et al. 2020) and adverse health effects (Fischer et al. 2004; Luan et al. 2019). Since the average temperature is constantly increasing since the last few decades, it results in the severe and frequent heatwave events. The extreme heat events have resulted in several casualties throughout the world (Fischer et al. 2004; Im et al. 2017; Zhao et al. 2019) with more severity over India in the recent times (Dhillon 2023). These increasing temperature extreme events may lead to a rise in mortality rates in the future (Mishra et al. 2017; Hu et al. 2019). Medical conditions caused by heatwaves can typically range from heat cramps and heat exhaustion due to dehydration and heatstroke and death in extreme cases. Further, the rising temperature increases the occurrence of the warm nights, which again leads to human discomfort due to the disruption in the sound sleep and sleeping hours.

Over India, heatwaves tend to occur during March to July, mostly in the pre-monsoon season (Nageswararao et al. 2020). It was found that the northern, northwestern, central, and northeastern peninsulas of India are worse affected by the heatwaves (Nageswararao et al. 2020; Pai et al. 2013; Singh et al. 2021b; Mukherjee and Mishra 2018). Areas likely to experience the most extreme heat episodes are the agricultural fields, where a large chunk of the population spends considerable time working outdoors, making them more vulnerable to extreme heat episodes (Im et al. 2017; Rohini et al. 2016; Sokhi et al. 2021). Humidity is an important variable to look at when assessing heat waves. The combined impact of temperature and humidity is measured using heat index (HI) and a high HI means the body struggles to release heat through evaporation, causing discomfort (Delworth et al. 1999; Koteswara Rao et al. 2020; Mishra et al. 2020; Nageswararao et al. 2020). Recent studies suggest that India already experiences extreme humid heat events based on the wet bulb temperatures (Im et al. 2017) and the heat wave conditions would continue to be common unless stringent measures are implemented (Perkins-Kirkpatrick and Lewis 2020; Saeed et al. 2021). A number of studies reported that the maximum temperature, heatwave duration, frequency, and intensities are projected to increase at the end of the century under higher GHG emission scenario and might engulf the regions which are unaffected from heatwaves at present (Murari et al. 2015; Koteswara Rao et al. 2020; Perkins-Kirkpatrick and Lewis 2020; Dubey et al. 2021; Das and Umamahesh 2022; Rohini et al. 2019). Koteswara Rao et al. (2020) found an increase of 20 to 30% of the extreme caution and danger category of the heat stress in the middle and end of the century, respectively. Mishra et al. (2017) found a projected increase of 30 times in the frequencies of the severe heatwave by the end of the century under RCP8.5, while the exposure of the population to the same increases from 15 to 92% by mid to end of the century. Similarly, an increase of the order of

one heatwave spell per decade has been also noticed in the last seven decades (Perkins-Kirkpatrick and Lewis 2020). The projected increase in the area impacted by extreme heat wave events ranges between 2 and 50% under various climate change scenarios (Das and Umamahesh 2022). Subsequently, Dubey et al. (2021) examined the heatwave characteristics and reported that the projected heatwave frequency will be twofold, while the duration will enhance by 8 to 12 days and the intensity will escalate by 2–3 °C at the end of the century. A few studies found regional variability in the high-temperature days, which increases in the recent time period over northern, western, and southern parts of India by 3%, 5%, and 18%, respectively (Jaswal et al. 2015; Pai et al. 2013). The heatwave projection over east Asian region reflects an increase of heatwave events from 5 to around 37%, while the magnitude is stronger by 1.4 to 9 times for different climate change scenarios (Kim et al. 2023). The northern Indian region is more prone to pre-monsoon heat stress days and its number may be as high as 30 days in the future. Rohini et al. (2019) found a projected rise of heatwave frequency (0.5 events) and duration (4–7 days) per decade over central and northern parts of India. Further, Singh et al. (2021a) used multiple model experiments to study the projected heatwaves over India and concluded that the bias-corrected downscaled regional climate models perform better than the model experiments without bias correction. With the available scientific studies, it is clear that although the heatwaves are projected to increase in numbers and intensify in terms of their persistence, there is a lot more uncertainty associated with their magnitude and how it might impact the large populated regions of India. The present work thus aims to investigate the projected changes in the temperature extremes and associated human discomfort (in terms of form of heatwaves and warm nights) in the future scenarios. A set of new-generation high-resolution climate model simulations from the Coordinated Regional Climate Downscaling Experiment-Coordinated Output for Regional Evaluations (CORDEX-CORE; Coppola et al. 2021) framework are employed here to understand the changes in the extreme heat and associated population exposure by the end of the century. Further, critical information regarding the impact on the projected population due to temperature extremes is also derived. The study also emphasized the role of climate policy formulation and their implementation in reducing the population exposure to the temperature extreme. The study fills the gap on the population exposure to the heat extremes under future using the state-of-the-art high-resolution model projections, which has not been carried out previously over the Indian region. The data and methodology are provided in the next section. Section 3 then discusses the results and conclusions are given in Section 4.

2 Data and methodology

We used the recently compiled CORDEX-CORE dataset for investigating the future (2074–2099) response of heatwave characteristics over India. The simulations are part of CORDEX-CORE South Asia domain. The lateral boundary conditions and prescribed sea surface temperature are taken from three different CMIP5 GCM models (i) MPI-ESM-MR, (ii) MIROC5, and (iii) NorESM1-M for driving the ICTP's regional climate model, RegCM4. For comparing the climate projections, we use two different greenhouse gas scenarios, namely, RCP2.6 and RCP8.5. The end of the century climate (2070–2099) for both the scenarios has been compared with the historical period (1976–2005) to assess the change.

In the CORDEX-CORE experiments (~25 km horizontal resolution), the RegCM4 main physics adopted the Tiedtke (Tiedtke 1989) over ocean and MIT (Emanuel 1991) convective schemes over land, SUBEX (Pal et al. 2000) for large-scale precipitation. The planetary boundary layer and radiation transfer scheme are represented through Grenier and Bretherton (2001) and Kiehl et al. (1996), respectively. The land model surface and biosphere interactions are taken care of by coupling RegCM4 with the community land surface model, CLM4.5 (Oleson et al. 2013). Over South Asia, the model has shown reasonably good performance in a wide variety of climate studies (Maharana et al. 2021; Shahi et al. 2021; Tiwari et al. 2017). The model output is utilized to prepare the annually averaged heatwave (duration and spells) and percentage of the warm nights following Expert Team on Climate Change Detection and Indices (ETCCDI: http://etccdi.pacificclimate.org/list_27_indices.shtml). In order to investigate the changes in the human discomfort, Thom's index is computed following the equation from Maftei and Buta (2017). The details and definitions are provided (Table 1).

$$DI = T - (0.55 - 0.0055 * RH)(T - 14.5) \tag{1}$$

where DI represents Thom's discomfort index, T is the mean monthly temperature in °C, and RH denotes the monthly

mean relative humidity of air (%). The heatwave spells, their duration, and the percentage of warm night indices for the historical climate and its projection at the end of the century are computed.

3 Results and discussion

We evaluate the RegCM4 experiments for their spatial representation of mean temperature over India against the ERA5 reanalysis dataset as shown in Fig. S1a–e. RegCM4 quite effectively captures the annual climatological temperature across India during the historical period in each model experiment. However, there exists a cold bias (~3°C) in the Himalayas, while the bias is much shallower over the mainland except for the MPI_RegCM4 experiment (Fig. S1f–i). The cold bias over the mountains could be attributed to excessive snow (Das et al. 2020) and improper representation of regional energy balance (Maharana and Dimri 2014). Further, the probability distribution function (PDF) of the spatially distributed temperature for the ERA5 reanalysis closely resembles the experiments in terms of mean and extremes over the Indian region during the historical period (Fig. S2). Further, the PDF of the maximum (minimum) temperature slightly overestimates (underestimates) as compared to the ERA5 reanalysis (Fig. S3, S4). The ensemble mean of the model experiments (ENS_Hist) is the closest of all, reflecting the confidence to use the ensembled temperature data for studying the heatwaves during the historical period and its future projections over India. Following the evaluation of model experiments and the ensemble, we investigate different extreme temperature indices under the future climate scenarios in the subsequent paragraphs.

3.1 Heatwaves

The occurrence of the heatwaves has been studied in terms of two different metrics (i.e., heatwave duration and frequency). From the climatological perspective, the model simulates at least 2–7 days of heatwaves per year across the

Table 1 The definition of extreme indices used in the study

Parameters	Definition
Heatwave (spells and duration)	A period during which the daily maximum temperature exceeds the normal maximum temperature by 5°C for more than 6 consecutive days, the "normal" period is defined as historical period (1980–2005) for the present study (World Meteorological Organization definition)
Warm night (percentage)	The percentage of times where the minimum temperature exceeds the 90th percentile of daily minimum temperatures for the historical period, which is used as a reference period for the present study
Thom's index	Indicator of thermal stress considering both temperature and relative humidity

Indo-Gangetic plains and eastern parts of the Indian landmass (Fig. 1a). A similar spatial pattern over most parts of the country is found at the end of the century under RCP2.6. However, Odisha, Chhattisgarh, the eastern parts of Madhya Pradesh (MP) and Uttar Pradesh (UP), and some parts of the Jammu and Kashmir (J&K) will experience 5–30 days of heatwave days (Fig. 1b). If no measures are taken to curb greenhouse gas (GHG) emissions (business as usual), then it projects a very pessimistic scenario represented by RCP8.5 with the maximum global to regional temperature rise. It is apparent that RCP8.5 projects a greater number of heatwave days at the end of the century throughout the Indian landmass (Fig. 1c). Interestingly, the model ensemble projects the lowest increase in the heatwave number over the southern Indian region (10–50 days/year). It gradually increases towards the north (100–150 days/year) over the western part of India, the Telangana region, and southern Odisha. The most populated states such as the UP, Bihar, along with Odisha, Chhattisgarh, and MP show around 150–200 days of heatwave days per year by the end of the century (Fig. 1c), which has been the hotspot of the heatwaves (Nageswararao et al. 2020). We further examined and compared the increase in the heatwave duration following both scenarios with respect to the historical period. At the end of the century, the heatwave duration is projected to increase by 1–10 days with the highest increase over Odisha and parts of Chhattisgarh and Madhya Pradesh along with J&K under RCP2.6, which is statistically significant at 0.05 level (Fig. 1d). However, under the RCP8.5 scenario, the amplified greenhouse effect increases the heatwave duration significantly throughout the country with a maximum increase over the populated north India and central to eastern states (~150–200 days) and relatively lesser over the southern parts of India (Fig. 1e). Interestingly, the difference of heatwave days between RCP8.5 and RCP2.6 at the end of the century ranges from 50 to 200 days across the country (Fig. 1f); and thus, better planning and adaptation measures may be required at the climate policy level to reduce the vulnerabilities under the future climate.

The Indian landmass experiences at least one heatwave spell in the model ensemble during the historical period (Fig. 2a). The rise in heatwave days leads to the increase in the heatwave spells (~2) over Odisha and eastern parts of MP and UP and some parts of the J&K under RCP2.6 (Fig. 2b) showing an almost similar spatial pattern as seen in Fig. 1. In contrast, there is a sharp rise in the frequency of heatwave spells across the country under RCP8.5 (Fig. 2c). Similar to the heatwave duration, there is a gradient in the rise of heatwave spells from south India (~1–5) to north India (~10) through the central Indian states (~8–9). There is a relatively smaller rise in the heatwave spells by the end of the century under RCP2.6, i.e., between 1 (over most parts of the country) and 3 (Odisha, Chhattisgarh, and J&K) as

seen in Fig. 2d. While there is a profound increase in heatwave spells across the country with a maximum ~8–10 over central and north India, the rest of India experience an average of 2–7 spells/year. Such findings corroborate the earlier studies where the frequency of heatwave spells across India is reported to increase in the future (Mishra et al. 2017; Koteswara Rao et al. 2020; Perkins-Kirkpatrick and Lewis 2020). The spatial patterns of the difference of heatwave spells between RCP8.5 and RCP2.6 follow an almost similar pattern with a statistically significant rise (at 0.05 level) of ~3–10 spells across the entire Indian landmass (Fig. 2f). Such a finding is consistent with the previous works of Mishra et al. (2017) where the rise in heatwave frequency under RCP8.5 is 2.5 times larger than RCP4.5. A consistent increase in the occurrence of heatwaves with a rate of one spell per decade in the last seven decades has been reported (Perkins-Kirkpatrick and Lewis 2020), while Koteswara Rao et al. (2020) identified the increasing summer time heat stress days by 40–60 under RCP4.5 and RCP8.5 scenarios, respectively.

3.2 Warm night percentage

Warm nights cause discomfort and hamper sound sleep and hence are a vital indicator of human discomfort. The east coast (e.g., Odisha, Andhra Pradesh), southeast (e.g., Tamil Nadu), and part of northeast India are highly vulnerable with almost 40–45% warm nights already in the historical period (Fig. 3a). This may be attributed to the proximity of these regions to the sea as well as the humid atmosphere attributed to the geographical locations, while the relatively arid/semi-arid regions like Rajasthan, Gujarat, Haryana, Delhi, Punjab, and J&K regions have warm night percentages ranging from 30 to 40% during the present climate. The relatively higher cooling in the desert and mountains leads to fewer numbers of warm nights. Interestingly, a significant rise in the percentage of warm nights is noticed by the end of RCP2.6 and has a N-S asymmetry with central and southern parts of India being projected to experience a higher number of warm nights (up to 70–80%). This also includes a strong rise in the percentage of warm nights over the southern, northeast, and coastal regions of India (Fig. 3b). Such asymmetry gives rise to a condition where central, southern, and northeast India experiences a higher percentage of warm nights (75–95 %) while over the northwestern and northern regions it may extend up to 40–70%.

Likewise, RCP8.5 forcing's led to an intense rise in air temperature, and hence, most parts of India will experience more than 90% warm nights per year (Fig. 3c). Interestingly, the rise of warm nights under RCP2.6 over eastern, central, northeast India along with western India Gujarat and most parts of Rajasthan and J&K is around 30–40% (Fig. 3d). The percentage rise in warm nights over
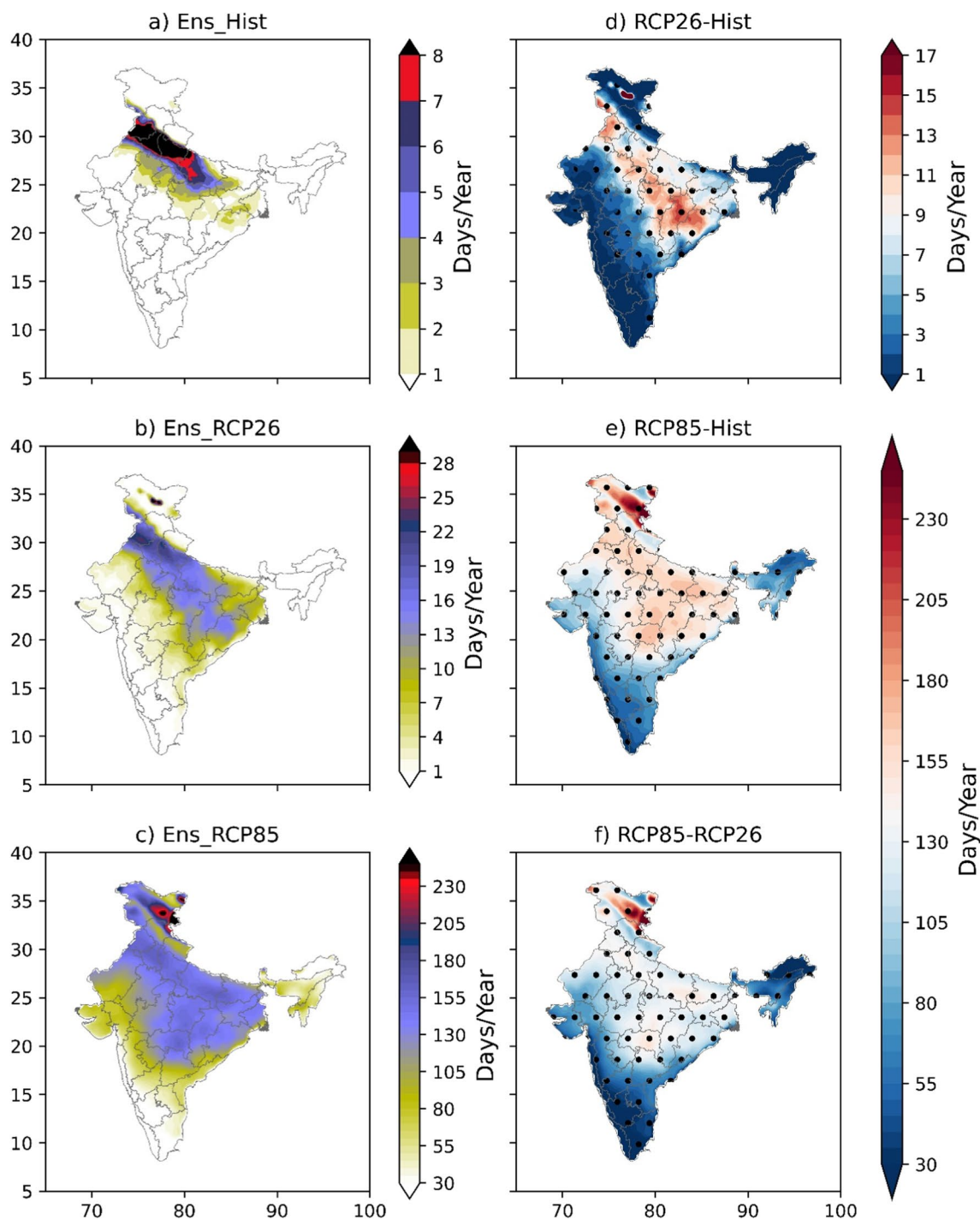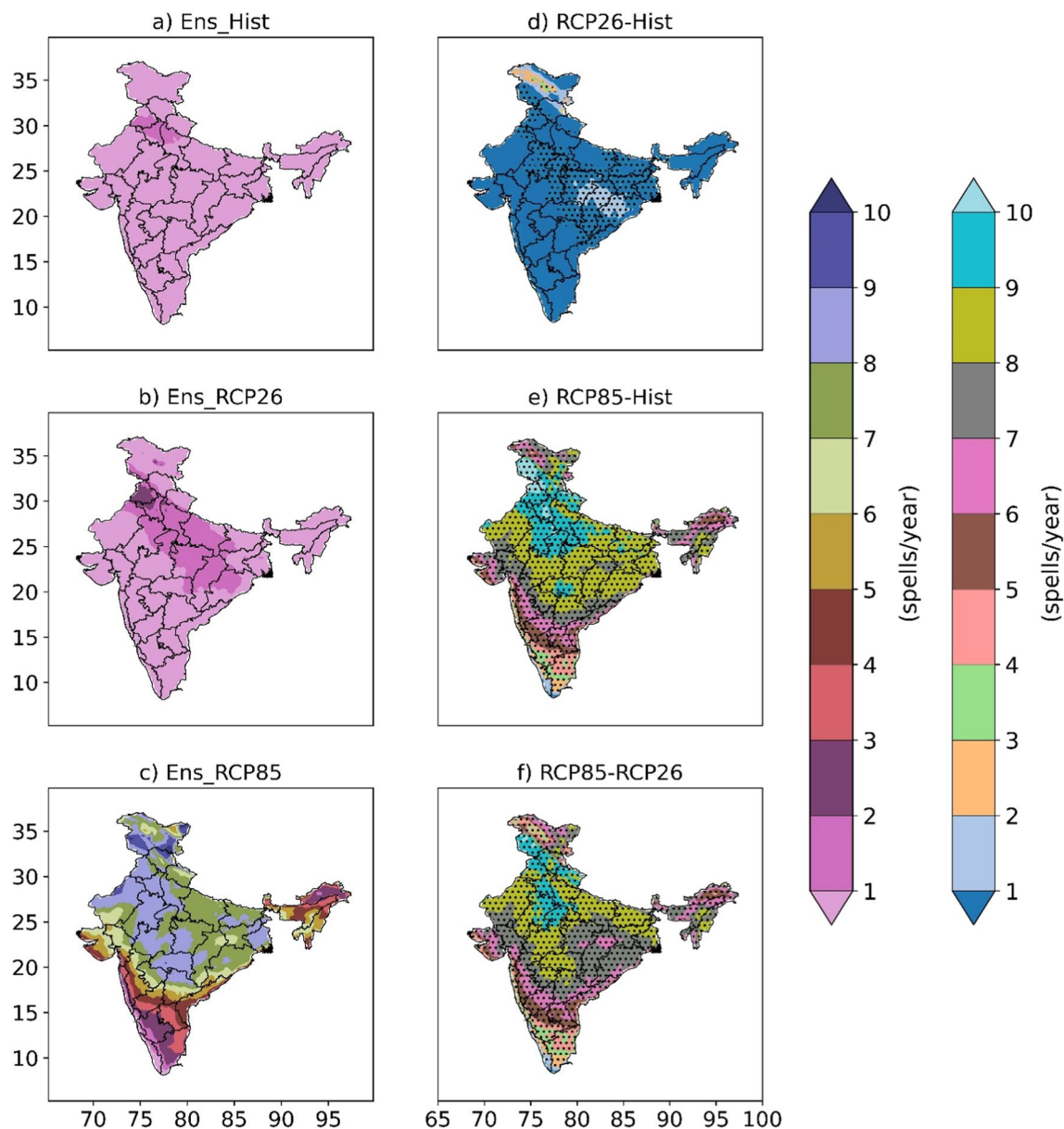
Fig. 1 Heatwave duration (days/year) for the model ensemble from **a** historical period and end of the century for **b** RCP2.6 and **c** RCP8.5 and **d**, **e** their differences. The dotted regions show change at 0.05 significance level

the western Rajasthan, Punjab, Haryana, and western UP ranges up to 25–30%. The largest rise is found over the western ghats regions and southern parts of India, which ranges between 40 and 45%. Although there is a higher number of warm nights in RCP8.5, the spatial pattern with respect to the historical period is exactly opposite to

RCP2.6. It shows that the rise in warm night percentage is the highest (>60%) over western India, western MP and UP, Punjab, and Haryana region (Fig. 3e), which is comparable (~70%) to the earlier finding (Sanjay et al. 2020). This is followed by the eastern Indo-Gangetic Plain (IGP), western parts of Odisha, Jharkhand, southern Maharashtra,

Fig. 2 Heatwave spells (spells/year) for the model ensemble at **a** historical period and end of the century for **b** RCP2.6 and **c** RCP8.5 and **d–f** their differences. The first color bar (close to the figure) represents **a–c** and the second color bar reflects the value of **d–f**. The dotted regions show change at 0.05 significance level

and Karnataka where it increases by 55–60%. The least percentage rise (~50–55%) is found over the east coast and southern northeast. The difference between the increase in the percentage of warm nights RCP8.5 and RCP2.6 reflects that the western regions of India will experience the highest increase (~30–35%) followed by central India (~20–30%). The least rise is projected (~10–20%) for the eastern coast, some parts of the northeast, and the southern Indian region (Fig. 3f); however, the results are not statistically significant at 0.05 level.

3.3 Thom's index

Thom's index is an expression of human discomfort, which takes into account both temperature and humidity (Delworth et al. 1999; Koteswara Rao et al. 2020; Nageswararao et al. 2020). Based on the numerical values, Thom's index is categorized into different types such as no discomfort (NDC < 21), under 50% of the population feels discomfort (U50 21–24), above 50% of the population feels discomfort (A50 25–27), most of the population suffers discomfort (MPD
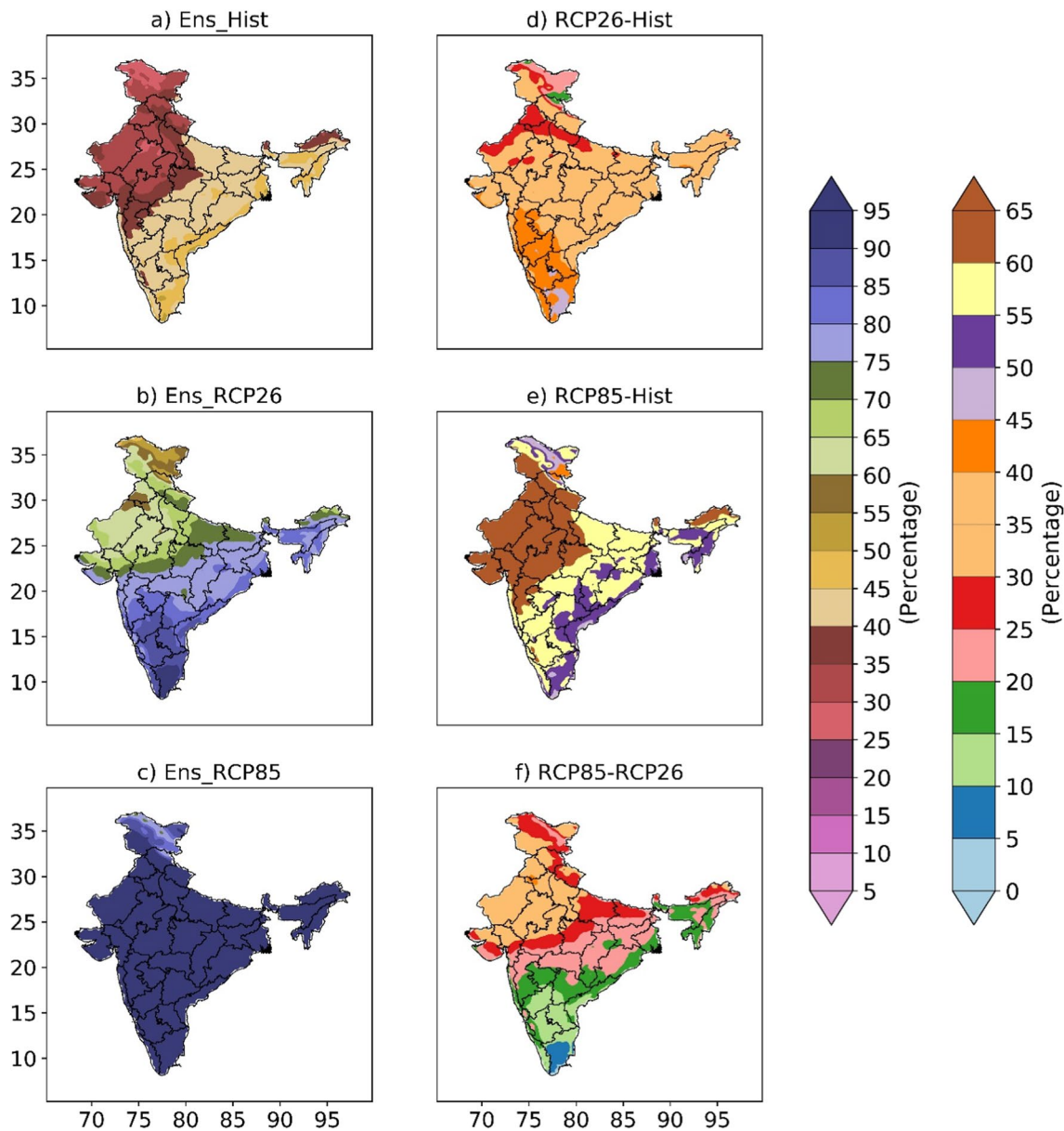
Fig. 3 Warm night percentage (%) for the model ensemble at **a** historical period and end of the century for **b** RCP2.6 and **c** RCP8.5 and **d**, **e** their differences. The first color bar (close to the figure) represents **a–c** and the second color bar reflects the value of **d–f**. The dotted regions show change at 0.05 significance level

28–29), everyone feels severe discomfort (SD 30–32), and state medical emergency (SME > 32). The spatial distribution of Thom's index over India shows that the mountainous regions mostly do not experience thermal discomfort in the historical period (Fig. 4a). The states of Rajasthan, Punjab, Haryana, western UP, MP, Jharkhand, and western coast are the regions with the discomfort range in the U50, while the eastern coast, Bihar, eastern UP, Telangana, and Gujarat have the discomfort in the A50 range. A similar analysis, at the end of the century, under RCP2.6 illustrates that the mountainous regions have not undergone any significant

changes in terms of thermal discomfort (Fig. 4b). Interestingly, most parts of the Indian mainland show an increase in thermal discomfort. For example, the states like Rajasthan, Punjab, Haryana, MP, and Chhattisgarh have migrated to A50 from U50, while the rest of the country remains in the discomfort range of U50. Under RCP8.5, Thom's index is still in the range of no discomfort over the mountainous regions (Fig. 4c). However, there is a drastic change in the discomfort projected across the country (e.g., the east coast, western UP, and a few parts of Gujarat that would experience the highest discomfort in the category of MPD, which
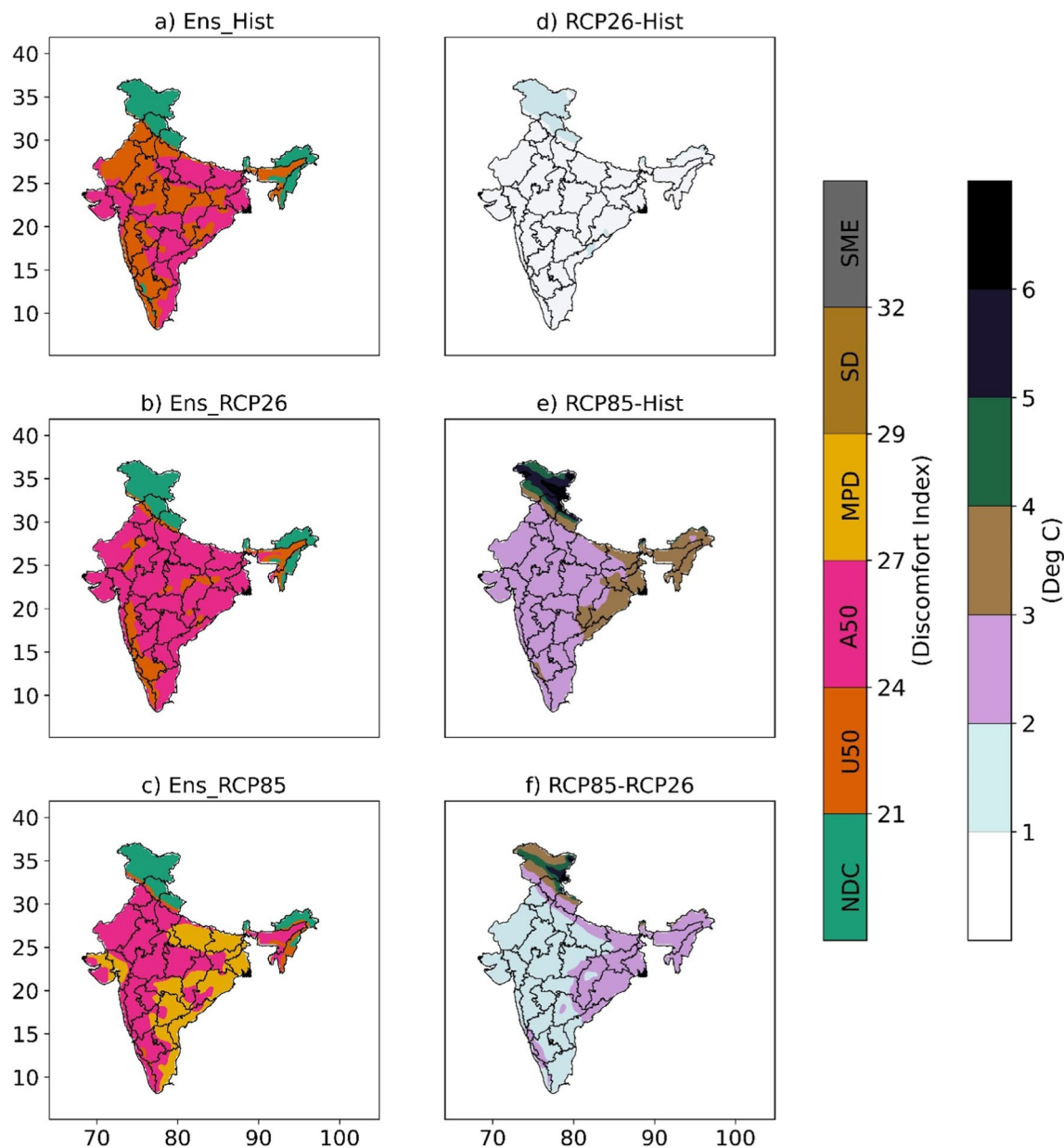
Fig. 4 The Thom index for the model ensemble at **a** historical period and end of the century for **b** RCP2.6 and **c** RCP8.5 and **d**, **e** their differences. The first color bar (close to the figure) represents **a–c** and the second color bar reflects the value of **d–f**. The dotted regions show change at 0.05 significant level

used to be in the A50). The rising temperature due to global warming increases evaporation and the water holding capacity of the atmosphere or humidity following the Clausius-Clapeyron relationship (Trenberth et al. 2003) which ultimately leads to an increase in moist heat events (Koteswara Rao et al. 2020). Apparent positive feedback between increasing temperature-evaporation-atmospheric moisture possibly leads to high moist heat events under a warming climate. The difference plots indicate that the severity of the index is going to be high in the future; however, the differences are not statistically significant (Fig. 4d–f).

3.4 Impact on the human population

The present study also examines the impact of thermal discomfort on the projected human population across the country under two shared socioeconomic pathways (SSPs) such as SSP1 and SSP5. There is an equivalence between RCPs and SSPs, where SSP1 has an equivalence with RCP2.6 and SSP5 has an equivalence with RCP8.5 (e.g. Meinshausen et al. 2020). The rural population is quite high across the Indian landmass during the historical period, while the urban population mostly lies across the IGP, some parts of

south India, and the Maharashtra region, and hence, it is also reflected in the total population (Fig. S5).

During the historical period, the population in the NDC range is around 10 million and this is projected to decrease with the temperature rise during RCP2.6 (~4 million) and RCP8.5 (~2 million). Similarly, the number of populations under U50 also declines from the historical period (~102 million) to ~46 and ~4 million under RCP2.6 and RCP8.5, respectively. On the other hand, the population in millions under A50 increases from 143 (historical) to 238 (RCP2.6) and 148 (RCP8.5). Around 135 million population will be exposed to MPD under RCP8.5 while the historical period and RCP2.6 will not have this extreme discomfort (Fig. 5a). The maximum population following RCP2.6 is under the A50 category compared to RCP8.5 implying proper mitigation of GHGs by following a sustainable path will reduce the extreme moist heatwave exposure to the population, especially for the A50 (143 million) and MPD (135 million) category. The human population around 142 million and 174 million are exposed to 20–40% and 40–60% warm nights, respectively, during the historical period. Even following RCP2.6, the percentage of warm night exposure to the population is still projected to increase and almost 10 million more will be exposed to ~40–60% of the warm nights. This further increases in most parts of the country, and around 182 million and 98 million will be exposed to 60–80% and 80–100% of the warm nights (Fig. 5b). However, the extreme

rise of temperature under the RCP8.5 has serious impacts on the human population and will increase the discomfort level, where almost 272 million of the population will be in the worst category of warm nights (80–100%) while the lower categories will not be experienced all across India. This indicates that controlling the GHG emission under the most conservative scenario (RCP2.6) can reduce the exposure of 174 million population to the extreme 80–100% category when compared against RCP8.5.

The population (248 million) across the Indian region currently experiences the heatwave duration in the category (<10 day per year) which would still be the case with RCP2.6 but an additional 34 million will experience higher heatwave duration in the range of ~10–30 per year. However, RCP8.5 will lead to a situation where the 7, 13, 22, 18, 29, and 66 million of the population will be exposed to <10, 10–30, 30–50, 50–70, 70–100, and 100–150 number of heatwaves days per year, respectively (Fig. 5c). Similarly, 248 and 282 million populations experience only less than 2 heatwave spells per year in the historical period and RCP2.6. During RCP8.5, 13, 26, 40, 57, 149, and 30 million of the population will be exposed to <2, 2–4, 4–6, 6–8, 8–10, and >10 heatwave spells, respectively (Fig. 5d).

As discussed earlier, the prolonged exposure to the heat stress has several negative impacts on the human health, agriculture, water availability, power generation, ecosystems, and socioeconomic conditions of the vulnerable
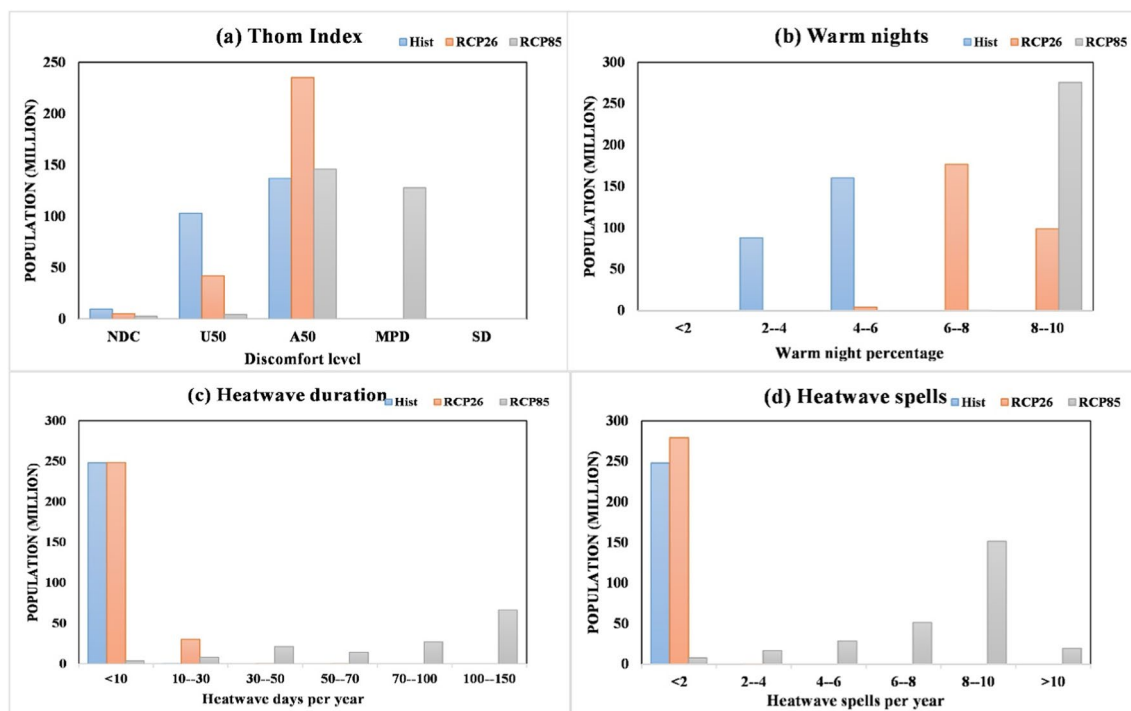

Fig. 5 The impacted projected population (in millions) at the end of the century at RCP2.6 and RCP8.5 for **a** Thom index, **b** warm night, **c** heatwave duration, and **d** heatwave spells

people (Jaswal et al. 2015; Rohini et al. 2019). These adverse consequences could be reduced through the provision and implementation of state-of-the-art and updated early warning system, the enhancement of healthcare professionals' capacity, raising public awareness, and conducting community outreach programs. The human exposure to this extreme heat stress can be managed through the policies with special focus on the stabilization or negative population growth, improving local adaptive capacities, improving economic status of the vulnerable population, taking effective measures to curb GHG emissions in order to limit the global temperature rise to 1.5 °C (Dubey et al. 2021; Mishra et al. 2017; Perkins-Kirkpatrick and Lewis 2020; Das and Umamahesh 2022). Therefore, the meaningful interaction and exchange of ideas become very important between various stakeholders (i.e., common citizens, scientists, local administrators, town planners, national and state level policymakers, and implementing agencies) involved in the adaptation and mitigation process to curb the human exposure to rising heat stress condition. The study illustrates that proper implementation of proper adaptation and mitigation strategies will reduce the exposure of almost 155 million people to the higher number of heatwave days and 195 million population to a higher number of heatwave spells (Fig. 5).

4 Conclusions

The present study focuses on the extreme heat indices such as the projected heatwave spells and their duration at end of the 21st century (2074–2099) under RCP2.6 and RCP8.5. It also includes the human discomfort in terms of the percentage rise in warm night indices and Thom's indices on the projected population. The study considered an ensemble from RegCM4 driven by three CMIP5 models at 25 km under the CORDEX-CORE framework over the South Asian region. The main conclusions are as follows:

1) The increase in heatwave durations (~150–200 days/year) and their spells (~2–10) will be more prominent in RCP8.5 compared to RCP2.6 by the end of the 21st century. The eastern coast (Odisha) will be the worst affected followed by the north (e.g., UP) and central parts (MP) of India whereas the least affected region could be south India.
2) Drastic changes (>90 %) in the warm nights are expected in RCP8.5 across all of India compared to (65–90%) in RCP2.6. More vulnerable regions include the western Indian states of Rajasthan, Punjab, parts of MP, and UP, whereas the least vulnerable region could be south India with ~5–20%.
3) Thom's index reflects that the mountainous regions will be mostly free from thermal discomfort. Most populations in eastern UP, Bihar, and the eastern coastal states

such as Odisha and Andhra Pradesh would experience severe discomfort.
4) Following a sustainable path (RCP2.6), the exposure of 135 million population to severe MPD and 143 million to A50 categories could be avoided. Overall, we show that the eastern parts of the Indian region, i.e., Odisha, Chhattisgarh, Jharkhand, and eastern Madhya Pradesh, are the most vulnerable areas under future heat extreme followed by the densely populated IGP.
5) To reduce the projected exposure of heat stress to the population, informed adaptation and mitigation measures with proactive approaches are inevitable.

For the future piece of studies, we aim to understand the compounding of these extremes and their drivers at different time scales over the Indian region. This will not only be useful to understand the processes leading to such changes in the heat extremes but will also provide a comprehensive assessment in order to translate the better adaptation and mitigation measures across a range of spatial and temporal scales.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication All the authors gave due consent to collaborate in the study.

References

Coppola E, Raffaele F, Giorgi F, Giuliani G, Xuejie G, Ciarlo JM, Sines TR, Torres-Alavez JA, Das S, di Sante F, Pichelli E (2021) Climate hazard indices projections based on CORDEX-CORE, CMIP5 and CMIP6 ensemble. Clim Dyn 57:1293–1383. https://doi.org/10.1007/s00382-021-05640-z

Das S, Giorgi F, Giuliani G (2020) Investigating the relative responses of regional monsoon dynamics to snow darkening and direct radiative effects of dust and carbonaceous aerosols over the Indian subcontinent. Clim Dyn. https://doi.org/10.1007/s00382-020-05307-1

Das J, Umamahesh NV (2022) Heat wave magnitude over India under changing climate: projections from CMIP5 and CMIP6 experiments. Int J Climatol 42(1):331–351. https://doi.org/10.1002/joc.7246

Delworth TL, Mahlman JD, Knutson TR (1999) Changes in heat index associated with CO_2-induced global warming. Clim Chang. https://doi.org/10.1023/A:1005463917086

Dhillon A (2023) India heatwave: 96 people dead reportedly from heat-aggravated conditions. The Guardian, 19 June 2023. https://www.theguardian.com/world/2023/jun/19/india-heatwave-scores-dead-warning-stay-indoors-during-day-heat-wave-uttar-pradesh-eastern-bihar

Dubey AK, Lal P, Kumar P, Kumar A, Dvornikov AY (2021) Present and future projections of heatwave hazard-risk over India: a regional earth system model assessment. Environ Res 201:111573. https://doi.org/10.1016/j.envres.2021.111573

Emanuel KA (1991) A scheme for representing cumulus convection in large-scale models. J Atmos Sci. https://doi.org/10.1175/1520-0469(1991)048%3c2313:asfrcc%3e2.0.co;2

Fischer PH, Brunekreef B, Lebret E (2004) Air pollution related deaths during the 2003 heat wave in the Netherlands. Atmos Environ. https://doi.org/10.1016/j.atmosenv.2003.11.010

Frich PALV, Alexander LV, Della-Marta P, Gleason B, Haylock M, Tank AK, Peterson T (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. Clim Res 19(3):193–212

Grenier H, Bretherton CS (2001) A moist PBL parameterization for large-scale models and its application to subtropical cloud-topped marine boundary layers. Mon Weather Rev. https://doi.org/10.1175/1520-0493(2001)129%3c0357:AMPPFL%3e2.0.CO;2

Hu K, Guo Y, Hochrainer-Stigler S et al (2019) Evidence for urban–rural disparity in temperature–mortality relationships in Zhejiang Province, China. Environ Health Perspect. https://doi.org/10.1289/EHP3556

Im ES, Pal JS, Eltahir EAB (2017) Deadly heat waves projected in the densely populated agricultural regions of South Asia. Sci Adv. https://doi.org/10.1126/sciadv.1603322

Jaswal AK, Rao PCS, Singh V (2015) Climatology and trends of summer high temperature days in India during 1969–2013. J Earth Syst Sci 124:1–15. https://doi.org/10.1007/s12040-014-0535-8

Kent ST, McClure LA, Zaitchik BF et al (2014) Heat waves and health outcomes in Alabama (USA): the importance of heat wave definition. Environ Health Perspect. https://doi.org/10.1289/ehp.1307262

Kiehl JT, Hack JJ, Bonan GB, et al (1996) Description of the NCAR community climate model (CCM3). NCAR Tech Note NCAR/TN-420+STR. https://doi.org/10.5065/D6FF3Q99

Kim YH, Ahn JB, Suh MS, Cha DH, Chang EC, Min SK, Byun YH, Kim JU (2023) Future changes in extreme heatwaves in terms of intensity and duration over the CORDEX-East Asia Phase Two domain using multi-GCM and multi-RCM chains. Environ Res Lett 18(3):034007

Koteswara Rao K, Lakshmi Kumar TV, Kulkarni A et al (2020) Projections of heat stress and associated work performance over India in response to global warming. Sci Rep. https://doi.org/10.1038/s41598-020-73245-3

Luan G, Yin P, Wang L, Zhou M (2019) Association between ambient temperature and chronic obstructive pulmonary disease: a population-based study of the years of life lost. Int J Environ Health Res. https://doi.org/10.1080/09603123.2018.1533533

Maftei C, Buta C (2017) Application of thermal discomfort indices for the coastal zone of Black Sea, in Dobrogea Region. Ovidius Univ Ann Constanta - Ser Civ Eng. https://doi.org/10.1515/ouacce-2017-0008

Maharana P, Dimri AP (2014) Study of seasonal climatology and inter-annual variability over India and its subregions using a regional climate model (RegCM3). J Earth Syst Sci. https://doi.org/10.1007/s12040-014-0447-7

Maharana P, Kumar D, Das S, Tiwari PR (2021) Present and future changes in precipitation characteristics during Indian summer monsoon in CORDEX-CORE simulations. Int J Climatol. https://doi.org/10.1002/joc.6951

Meinshausen M, Nicholls ZRJ, Lewis J et al (2020) The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci Model Dev. https://doi.org/10.5194/gmd-13-3571-2020

Mishra V, Ambika AK, Asoka A et al (2020) Moist heat stress extremes in India enhanced by irrigation. Nat Geosci. https://doi.org/10.1038/s41561-020-00650-8

Mishra V, Mukherjee S, Kumar R, Stone DA (2017) Heat wave exposure in India in current, 1.5 °c, and 2.0 °c worlds. Environ Res Lett. https://doi.org/10.1088/1748-9326/aa9388

Mohan M, Sati AP, Bhati S (2020) Urban sprawl during five decadal period over National Capital Region of India: impact on urban heat island and thermal comfort. Urban Clim. https://doi.org/10.1016/j.uclim.2020.100647

Mukherjee S, Mishra V (2018) A sixfold rise in concurrent day and night-time heatwaves in India under 2 C warming. Sci Rep 8(1):16922

Murari KK, Ghosh S, Patwardhan A, Daly E, Salvi K (2015) Intensification of future severe heat waves in India and their effect on heat stress and mortality. Reg Environ Chang 15:569–579. https://doi.org/10.1007/s10113-014-0660-6

Nageswararao MM, Sinha P, Mohanty UC, Mishra S (2020) Occurrence of more heat waves over the central east coast of India in the recent warming era. Pure Appl Geophys. https://doi.org/10.1007/s00024-019-02304-2

Nitschke M, Tucker GR, Hansen AL et al (2011) Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide.

South Australia: a case-series analysis Environ Heal A Glob Access Sci Source. https://doi.org/10.1186/1476-069X-10-42

Oleson K, Lawrence DM, Bonan GB, Drewniak B, Huang M, Koven CD, ... Yang Z-L (2013) Technical description of version 4.5 of the Community Land Model (CLM) (No. NCAR/TN-503+STR). https://doi.org/10.5065/D6RR1W7M

Pai DS, Nair SA, Ramanathan AN (2013) Long term climatology and trends of heat waves over India during the recent 50 years (1961-2010). Mausam 64(4):585–604

Pal JS, Small EE, Eltahir EAB (2000) Simulation of regional-scale water and energy budgets: representation of subgrid cloud and precipitation processes within RegCM. J Geophys Res Atmos 105:29579–29594. https://doi.org/10.1029/2000JD900415

Pattnayak KC, Kar SC, Dalal M, Pattnayak RK (2017) Projections of annual rainfall and surface temperature from CMIP5 models over the BIMSTEC countries. Glob Planet Chang. https://doi.org/10.1016/j.gloplacha.2017.03.005

Perkins-Kirkpatrick SE, Lewis SC (2020) Increasing trends in regional heatwaves. Nat Commun. https://doi.org/10.1038/s41467-020-16970-7

Rohini P, Rajeevan M, Mukhopadhay P (2019) Future projections of heat waves over India from CMIP5 models. Clim Dyn 53:975–988. https://doi.org/10.1007/s00382-019-04700-9

Rohini P, Rajeevan M, Srivastava AK (2016) On the variability and increasing trends of heat waves over India. Sci Rep. https://doi.org/10.1038/srep26153

Russo S, Sillmann J, Sterl A (2017) Humid heat waves at different warming levels. Sci Rep. https://doi.org/10.1038/s41598-017-07536-7

Saeed F, Schleussner CF, Ashfaq M (2021) Deadly heat stress to become commonplace across South Asia already at 1.5°C of global warming. Geophys Res Lett. https://doi.org/10.1029/2020GL091191

Sanjay J, Revadekar JV, Ramarao MVS, Borgaonkar H, Sengupta S, Kothawale DR, ... Ratnam JV (2020) Temperature changes in India. Assessment of climate change over the Indian region: a report of the Ministry of Earth Sciences (MoES), Government of India 21–45

Shahi NK, Das S, Ghosh S et al (2021) Projected changes in the mean and intra-seasonal variability of the Indian summer monsoon in the RegCM CORDEX-CORE simulations under higher warming conditions. Clim Dyn. https://doi.org/10.1007/s00382-021-05771-3

Singh S, Mall RK, Singh N (2021a) Changing spatio-temporal trends of heat wave and severe heat wave events over India: an emerging health hazard. Int J Climatol. https://doi.org/10.1002/joc.6814

Singh S, Mall RK, Dadich J, Verma S, Singh JV, Gupta A (2021b) Evaluation of CORDEX-South Asia regional climate models for heat wave simulations over India. Atmos Res 248:105228. https://doi.org/10.1016/j.atmosres.2020.105228

Sokhi RS, Tiwari PR, de Medeiros JSN (2021) Changes in extreme events over Asia for present and future climate conditions based on a modelling analysis of atmospheric circulation anomalies. Theor Appl Climatol. https://doi.org/10.1007/s00704-021-03742-6

Tiedtke M (1989) A comprehensive mass flux scheme for cumulus parameterization in large-scale models. Mon Weather Rev. https://doi.org/10.1175/1520-0493(1989)117%3c1779:ACMFSF%3e2.0.CO;2

Tiwari PR, Kar SC, Mohanty UC et al (2017) Sensitivity of the Himalayan orography representation in simulation of winter precipitation using Regional Climate Model (RegCM) nested in a GCM. Clim Dyn. https://doi.org/10.1007/s00382-017-3567-3

Trenberth KE, Dai A, Rasmussen RM, Parsons DB (2003) The changing character of precipitation. Bull Am Meteorol Soc 84(9):1205–1218

Zhang Y, Feng R, Wu R et al (2017) Global climate change: impact of heat waves under different definitions on daily mortality in Wuhan, China. Glob Heal Res Policy. https://doi.org/10.1186/s41256-017-0030-2

Zhao Q, Li S, Coelho MS, Saldiva PH, Hu K, Huxley RR, ... Guo Y (2019) The association between heatwaves and risk of hospitalization in Brazil: a nationwide time series study between 2000 and 2015. PLoS Med 16(2):e1002753