Natural Hazards
https://doi.org/10.1007/s11069-024-06872-y

ORIGINAL PAPER

Impact of climate change induced heat stress on the people working in the coastal cities of India

T. V. Lakshmi Kumar[1,2] · **J. Bharath**[1,6] · **Walter Leal Filho**[3] · **Humberto Barbosa**[4] · **K. Koteswara Rao**[5]

Received: 12 November 2023 / Accepted: 7 August 2024

Abstract

Indian coastal cities are more vulnerable to heat stress in the context of climate change, with associated physiological stress in the working environment. The increase in heat stress obtained from the Steadman Heat Stress Index (SHSI) and its associated decline in work performance (DWP) are reported in this study using: (a) the reanalysis data sets of the Indian Monsoon Data Assimilation and Analysis (IMDAA) for the period 1981–2020; and (b) the high resolution, bias-corrected simulations of the Indian Institute of Tropical Meteorology (IITM)-Earth System Model (ESM) (source: NEX GDDP) for the period 1981–2014 (historical) and 2015–2050 (Shared Socioeconomic Pathway (SSP) 2.4.5 & 5.8.5) for the coastal cities of India. The SHSI values equivalent to the Wet Bulb Globe Temperature (WBGT), which recommend different rest/work ratios for all the study locations, have been estimated using the model data sets. The results show that the rising heat stress is mainly dependent on the changes in relative humidity in the cities of the west coast, while it is dependent on temperature changes in the cities of the east coast. The cities of Chennai, Nellore, Puducherry and Kochi showed a higher decline in work performance in the SSP2.4.5 scenario, while Mangalore and Thiruvananthapuram were added in the SSP5.8.5 scenario during the decade of 2041–2050. People working without thermal neutralities in Chennai, Nellore, Puducherry, and Kochi were recommended a further 25% increase of rest per hour in the light, medium, heavy, and very heavy work conditions in the future climate scenarios of 2021–2050.

✉ T. V. Lakshmi Kumar
lakshmikumar@jnu.ac.in

1 Centre for Atmospheric Sciences and Climate Studies, SRM Institute of Science and Technology, Chennai, India

2 School of Environmental Sciences, Jawaharlal Nehru University, New Delhi 110 067, India

3 Interdisciplinary Centre for Climate Change and Human Health, Hamburg University of Applied Sciences, Hamburg, Germany

4 Laboratório de Análise e Processamento de Imagens de Satélites-LAPIS, Universidade Federal de Alagoas, UFAL, Maceió, Brazil

5 Climate Section, National Center for Meteorology, Abu Dhabi, United Arab Emirates

6 Department of Physics and Nanotechnology, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu, India

Published online: 22 August 2024

Keywords Heat stress · IITM-ESM · IMDAA · Work-rest ratios

1 Introduction

Global climate change has its impacts in many sectors, including the living and working environments (IPCC 2007). Increasing heat extremes such as hot days and heat stress show great impact on human health and working performance. It has been reported that the increase in heat stress is going to affect work productivity in a manner equivalent to the loss of approximately 80 million jobs globally (ILO 2018). The UK Met Office reported that nearly one billion people of the world had experienced extreme heat stress, and that this increase in heat stress—which is estimated from the fatal combination of temperature and humidity—will be 15-fold, once the global temperature rise reaches 2 °C (www.metoffice. gov.uk). There will be an increase in the exposure to dangerous levels of heat stress of 50–100% across the tropical regions (Vargas et al. 2022a). An increment of 30–40% of daylight hours with excessive heat is observed across different areas of the globe, and this severely affects the physical activity of the labourer in outdoor work (Kjellstrom et al 2016). The estimated projections of the heat index, driven by anthropogenic CO_2 emissions show the global exposure to the category of dangerous environments (Zeppetello et al. 2022a, b). A study on projections of the temperature–humidity index calculated from the CMIP5 GCM simulations shows the adverse effect of increased heat stress on the socioeconomic conditions, with a more pronouncing effect on the poor and the people dependent on livestock in tropical regions (Carvajal et al 2021). Projections of the health heat index showed more frequent incidences of higher heat conditions over Africa, northern South America and large parts of India (Sun et al 2019). A review on the occupational heat stress-related economic burden revealed the substantial impact of climate change (Borg et al 2021). Cost estimates of 1.63 million USD in China from 2011 to 2012 (Ma et al 2019) and 6.2 billion USD in Australia from 2013 to 2014 (Zander et al 2015) were reported to be the economic burdens caused by increased heat stress due to climate change. In Australia, it is predicted that the exposure of the labourer handling the physical activity in the category of '*dangerous*' will be increased from one day per year to 15–16 days per year by the year 2070 (Maloney et al. 2011). In south Asia, the labour exposure for heat stress increased 2.2 times within the period of 2006–2015 (Saeed et al. 2021).

In India, the studies on heat stress are sparse. Heat stress has impacted 20% of the people in India, manifested in experiences from skin rashes to heat strokes (Patel et al. 2010). The coastal region plays an important role in India's economy, home to one third of its population. The peninsular coastal areas are witnessing rapid urbanisation amidst the environmental threats, such as the cyclones and frequent droughts on the east and west coasts (Sharma and Khan 2023). The coastal regions of India are most affected by the increased heat stress in present and future climate scenarios when analysed with the CMIP 5 simulations, and this heat stress will cause an approximate 35% decline in work performance among the labourers in open environments by the end of the century (Rao et al. 2020). A study on the heat extremes in the metropolitan cities of India revealed that the extreme heat stress causes heat strokes in the people living in the city of Chennai located on the east coast of India (Kumar et al 2022). The thermal heat stress estimates from the Universal Thermal Climate Index (UTCI) data sets for the period 1981 to 2019 revealed that the northwest region of India experiences the most heat stress amongst all the other regions of the country (Shukla et al 2022), and the thermal stress is going to increase every day per year in India (Schwingshackl et al. 2022). The rise in heat stress over eastern Asia, including India, is about 8 °C/11 °C and is much higher than the rise in temperature of 7 °C/10 °C for the CMIP5/CMIP6 data sets (Juzbasic et al. 2022). It has also been reported that the increased heat stress leads to a decline in work productivity and causes occupational illness and injuries if not enough breaks have been taken during the course of the work activity (Szewczyk et al. 2021).

Different indices—such as SHSI (Rothfusz 1990), UTCI (Blazejczyk et al. 2012), Normal Effective Temperature (Li and Chan 2000), etc.—have been used for the estimation of heat stress in India. All of the studies projected an increase in heat stress due to the changes in air temperature, relative humidity, and the varying strengths of the atmospheric background (Rao et al 2020). A large-scale connection in the quasi-resonant amplification effect has been reported to be linked to the deadly Indian heat waves, another form of heat extreme (Rao et al 2021). In our earlier study (Rao et al 2020), we reported the DWP in India using the CMIP 5 models' simulations. The projections of heat stress along with the DWP up to the end of the twenty-first century were presented in Rao et al. (2020) using the multi model mean of eighteen (18) global climate models for different pathways. In the present investigation, we report the heat stress and DWP particularly in the coastal cities of India, using the state-of-the-art NEX GDDP data set simulations of IITM-ESM for the study period up to the year 2050. Not limited to the DWP, we also present the work breaks required for the different capacities of light, medium, heavy and very heavy work conducted by the outdoor labourer for the present and future heat stress values under the different shared socioeconomic pathways of IIMT ESM.

2 Data and methods

Reanalysis data sets of the Indian Monsoon Data Assimilation and Analysis (IMDAA), developed jointly by the National Centre for Medium Range Weather Forecasting (NCMRWF) and the India Meteorological Department (IMD), and the UK Met Office are used to calculate the heat stress in different coastal cities of India (Indira Rani et al. 2021). These data sets are available in an hourly basis over a monthly scale and a daily basis with 12×12 km spatial resolution for the period of 1979–2020. The IMDAA data sets have been reported to be the best data sets with a high resolution in the Indian summer monsoon region (Ashrit et al 2020). These data have been widely used by several researchers, who have reported that they are in good agreement with the observational and other reanalysis data sets such as rainfall (Singh et al 2021) and temperature (Vishal et al. 2022). In the present study, we have used the temperature and relative humidity data sets for the period of 1981–2020, by extracting the data sets for the specific spatial co-ordinates of the study locations by using the nearest neighbourhood method. The cities considered for the study with their co-ordinates are provided in Fig. 1. The specific characteristics of these locations have been provided in Table 1. The entire study has been carried out for the months of April and May, which represent the summer months in India.

The high resolution ($0.25° \times 0.25°$), bias-corrected, and statistically downscaled simulations of the IITM-ESM, available under the umbrella of the NEX-GDDP data sets, were used in the present study. These simulations are originally part of the Coupled Model Intercomparison Project (CMIP) Phase 6 experiments. The availability of these data sets is from 1950 to 2100, in which the period 2015–2100 covers the different shared socioeconomic pathways. In the present work, the data sets pertaining to '*middle of the road*' (SSP2.4.5)

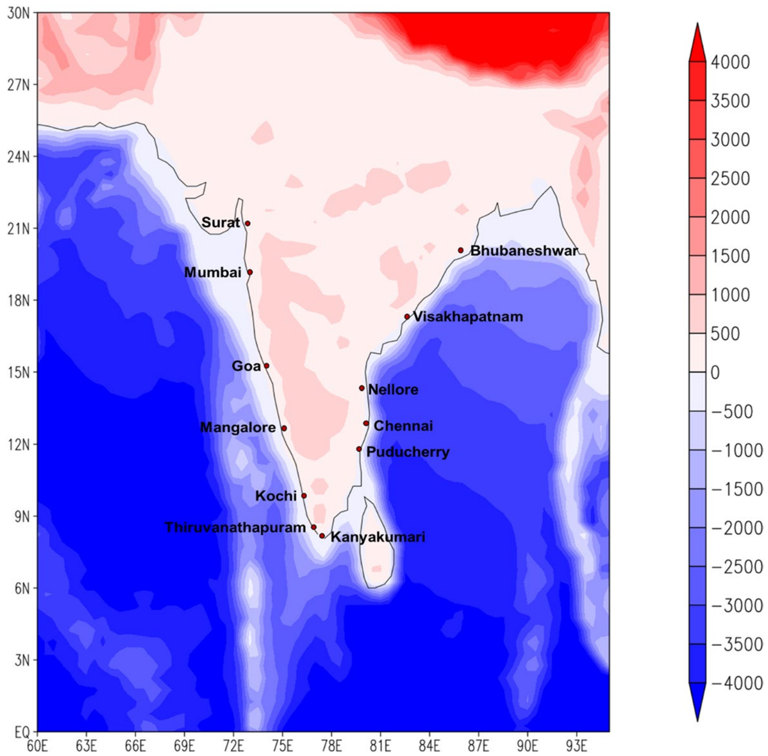

Fig. 1 Map showing the study locations (coastal cities) with topography in meters above the mean sea level

Table 1 Characteristics of the urban coastal locations, considered for the current study

Urban location	Region	Co-ordinates	Area (km^2)	Population (Census 2011)
Surat	West Coast	21.17°N, 72.8°E	326.5	44,67,797
Mumbai	West Coast	19.07°N, 72.8°E	603.4	1,24,42,373
Goa	West Coast	15.49°N, 73.8°E	36	14,58,545
Mangalore	West Coast	12.91°N, 74.8°E	132.45	4,99,486
Kochi	West Coast	09.93°N, 76.26°E	94.88	6,01,574
Thiruvananthapuram	West Coast	08.52°N, 76.93°E	214.86	9,57,730
Kanyakumari	East Coast	08.08°N, 77.53°E	26	15,39,802
Puducherry	East Coast	11.91°N, 79.81°E	19.54	2,41,773
Chennai	East Coast	13.06°N, 80.23°E	426	46,46,732
Nellore	East Coast	14.44°N, 79.98°E	149.14	6,00,869
Visakhapatnam	East Coast	17.68°N, 83.21°E	681.96	17,28,128
Bhubaneshwar	East Coast	20.29°N, 85.82°E	135	8,37,737

and '*full fossil fuel development*' (SSP5.8.5) have been used up to the year 2050. These NEX-GDDP datasets are mainly generated by using the bias-correction spatial disaggregation (BCSD) method (Wood et al. 2004; Thrasher et al. 2012). The retrospective run period was 1950–2014 for each experiment, and future projections from 2015 to 2100 (prospective run) were forced with SSP2.4.5 and SSP5.8.5 scenarios. The algorithm (BCSD) used for downscaling compares the GCM outputs with the corresponding observational climate variables to adjust the future climate simulations. The finer resolution grids in the NEX-GDDP data sets are obtained by making use of the algorithm with the spatial information of the observations. More details on these data sets are available at https://www.nccs.nasa.gov. The selection of IITM-ESM in the present study was mainly due to its capability to capture the Indian summer monsoon that predicts long-term climate change (Swapna et al 2015).

Here we used the Steadman's Heat Stress Index (Steadman, 1979) approach, which combines ambient air temperature and relative humidity to estimate the heat stress. Steadman's field observations and measurements have been converted to a table that represents the heat stress values for the corresponding risk categories. On the basis of the table generated by Steadman, Rothfusz (1990) developed the following equation for heat index:

$$\begin{aligned} \text{SHSI} =& -42.379 + 2.04901523 * \text{T} + 10.14333127 * \text{RH} - 0.22475541 * \text{T} * \text{RH} \\ & - \left(6.83783 \times 10^{-3} * \text{T}^2\right) \\ & - \left(5.481717 \times 10^{-2} * \text{RH}^2\right) + \left(1.22874 \times 10^{-3} * \text{T}^2 * \text{RH}\right) \\ & + \left(8.5282 \times 10^{-4}\text{T} * \text{RH}^2\right) - \left(1.99 \times 10^{-6}\text{T}^2 * \text{RH}^2\right) \end{aligned} \tag{1}$$

where T is ambient dry bulb temperature (°F) and RH is relative humidity in percentage.

This formula was obtained through a set of measurements, mathematically analysed by multiple regressions. The values of SHSI were then further converted into the Celsius scale and used in the present study. The categories of SHSI are classified as caution (27–32 °C), extreme caution (32–41 °C), danger (41–54 °C) and extreme danger (> 54 °C).

The DWP (in %) using the heat stress has been calculated using the formula adopted from Rao et al. (2020) and is given below:

$$\text{DWP } (\%) = 2 \text{ X } (\text{Heat stress, } ^\circ\text{C}) - 50 \tag{2}$$

The percentage bias was estimated between the SHSI calculated from IITM-ESM and IMDAA, using the standard formula of the percentage of ratio of the mean SHSI of IITM-ESM minus SHSI of IMDAA to the SHSI of IMDAA for the period of 1981–2014. Since the historical data of IITM-ESM is available up to 2014 (from the year 2015, the IITM-ESM data is simulated for different SSPs), we could only use the data until the year 2014 for estimating the bias.

The Wet Bulb Globe Temperature (WBGT) (Budd 2008) was calculated for all the study locations using the model data during the study period of 1981–2014 using the formula:

$$\text{WBGT} = 0.70 \text{ x } T_W + 0.20\text{x } T_G + 0.1 \text{ x } T_A \tag{3}$$

where T_W is Wet bulb temperature, T_G is Globe temperature and T_A is the air temperature.

T_G has been calculated from the data of solar radiation and relative humidity.

The values of SHSI and WBGT were subjected to the liner fit so as to get the SHSI values for the equivalent WBGT values for the study locations. These deduced values vary for each study location. Using the table of the WBGT for the recommended metabolic rate classes for different work categories as suggested in Kjellstrom et al. (2009) (Table 2), such

Table 2 Different rest levels recommended for different maximum WBGT with a light clothing (Kjellstrom et al. 2009)

Metabolic rate class (work intensity)	1 (light work) WBGT (°C)	2 (medium work) WBGT (°C)	3 (heavy work) WBGT (°C)	4 (very heavy work) WBGT (°C)
Continuous work, 0% rest/hour	31	28	27	25.5
25% rest/hour	31.5	29	27.5	26.5
50% rest/hour	32	30.5	29.5	28
75% rest/hour	32.5	32	31.5	31
No work at all (100% rest/hour)	39	37	36	34

as light, medium, heavy and very heavy work carried out by the labourers with light clothing, a similar table for the SHSI was prepared for all the study locations. Using these tabulated values of SHSI, the exposed levels for different metabolic rates were obtained for all the study locations in present and future scenarios (until the year 2050) of the shared socio-economic pathways of SSP2.4.5 and SSP5.8.5. As the WBGT calculation involves solar radiation data, the calculation of SHSI will be simpler than WBGT in the Indian context due to the availability of temperature and humidity data sets. Hence in the present study, we estimated the SHSI values equivalent to WBGT over Indian coastal cities. It is worth noting that the values of WBGT infer a general guideline for the adverse effects that are likely to occur. Errors in WBGT might arise in highly humid environments and need a careful evaluation in the context of people's clothing, activity etc., (Budd 2008). A similar context prevails for the SHSI's evaluation. The values of SHSI obtained from the WBGT in the present study provide a general assessment, and it needs to be compared with the measurement of individual elements from the people living in the environments without any thermal neutralities, so as to achieve the most comprehensive and reliable information. Furthermore, it has been reported that by the year 2050, nearly 70% of the world's population will be in urban areas. Also, an increase of 50% in greenhouse gas emissions by the year 2050 is estimated, if no new policies have been adapted. This will cause the warming of 3–6 °C above the preindustrial levels by the end of the century (The OECD Environmental Outlook to 2050). Hence, the current study underpins study period till 2050.

3 Results and discussion

3.1 Heat stress in the coastal cities of India

The heat stress exposure is above 40 °C during the forenoon hours for the cities of Chennai, Nellore, Puducherry, Bhubaneswar, and Mangalore, denoting the *extreme caution* and *danger* levels, while the afternoon values varied up to 40 °C, depicting the *extreme caution* levels of heat stress exposure (SFig. 1). The heat stress exposure does not have much variation from the forenoon to afternoon in the cities of Visakhapatnam, Thiruvananthapuram, Kochi, Kanyakumari, Goa, and Mumbai and is below the 40 °C level, depicting the *caution* and *extreme caution* levels of heat stress. The diurnal variations of heat stress might be due to the changes in anthropogenic latent and sensible heat fluxes that increase the moist entropy of the atmosphere, as studied over south and north China by Yang et al. (2021). As the rise in temperature causes more water-holding capacity, the perceived hot conditions play an important role in the changes of heat stress. SFig. 2a–d provides the mean (a) SHSI for the period of 1981–2020, the changes in (b) SHSI, (c) temperature, and (d) relative humidity from the decade 2011–2020 to 1981–1990 for all the study locations for the months of April and May together, for the time intervals of 08:30–12:30 h IST, 12:30–16:30 h IST, 16:30–20:30 h IST, and for the full day, i.e., 00:00–23:00 h IST. The cities of Chennai, Nellore, Puducherry, and Bhubaneswar have higher levels of heat stress (> ~ 42 °C) during the time interval of 12.30–1630 h IST, and these locations have higher heat stress even during the entire daytime, i.e., from 08:30 to 20:30 h IST. The increase in heat stress from the decade 1981–1990 to 2011–2020 is more pronounced in Surat, Mumbai, and Goa when compared to the other study locations. The increase in SHSI is beyond 4 °C in these locations. The other locations have a minimum increment of 2 °C during any of the intervals. These changes are mainly associated with the rise in air temperature (up to 2.5 °C) and humidity (up to 6%) (SFig. 2c–d). However, it is difficult to quantify the changes in air temperature and relative humidity that are contributing to heat stress. The evolution of SHSI, air temperature, and relative humidity during the study period of 1981–2020, with reference to the decade of 1981–1990, have been plotted with the 9-year running averages for all the study locations in Fig. 2a–l. In all the study locations, the changes in heat stress followed the changes in air temperature. In the cities of Goa, Mangalore, Kochi, Thiruvananthapuram, Kanyakumari, Puducherry, Nellore, Bhubaneswar, and Visakhapatnam, the distribution of heat stress followed the relative humidity also, during the decade of 2011–2020, which might be an indication of the increasing role of relative humidity in increasing heat stress levels in these cities. In most of the cities, the changes in relative humidity are in reverse with the increasing heat stress, except during the last decade. The grouping of cities on the east and west coasts and their changes in air temperature and relative humidity showed the role of air temperature and relative humidity. From Fig. 3a, b, it can be inferred that the changes in air temperature (28.04%) contributed less in the western coastal cities, while it contributed more (62.92%) in the eastern coastal cities. The RH changes are prominent in the western coastal cities (about 71.96%) when compared to the eastern coastal cities (about 28.04%). This means that the relative humidity is prominent in modulating the heat stress on the west coast when compared to the east coast. Please note that here we consider the data of temperature and RH during the maximum SHSI of a 4-h interval time during the day. This analysis disclosed the role of temperature and RH in the extreme exposure levels of heat stress during the study period.

The ocean to land contrast plays a key role in controlling the heat stress. The gradient of temperature between the ocean and peninsular India that is associated with the wind flow may provide a fair understanding of the increased heat stress. It was observed that mainly the westerlies at 950 hPa dominate during the summer in peninsular India (S.Fig. 3a, b). The temperature difference between the decades of 2011–2020 and 1981–1990 showed that the Arabian Sea's warming is more than that of the peninsular Indian temperatures (S.Fig. 4). It was also identified that the winds were slowed down during the decade of 2011–2020 when compared to the decade of 1981–1990 (S.Fig. 5). The temperature/wind gradients between the Arabian Sea and peninsular India is about 2 °C/0.9 m·sec^{-1} during the decade of 1981–2000 and were reduced to 1.7 °C/0.8 m·sec in the period of 2001–2020, which shows the trapping of wind within that region that leads to more heat and increased solar radiation, thus resulting in the increased heat stress levels in the study locations.

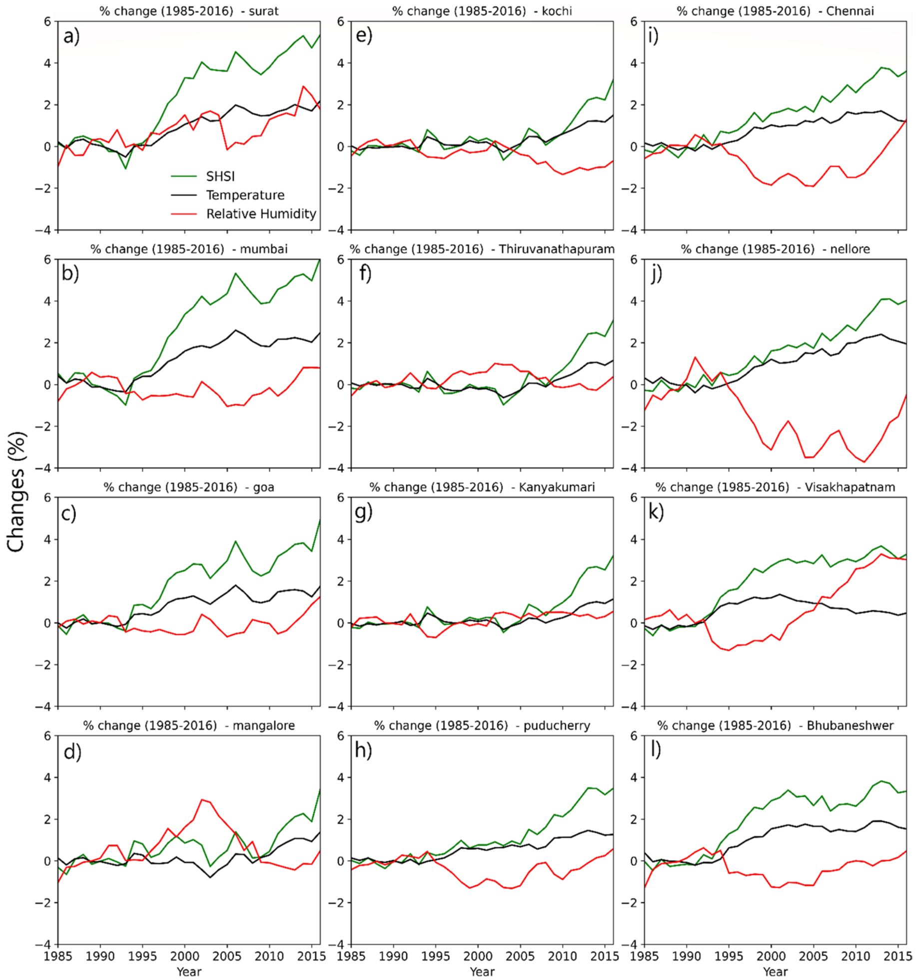

Fig. 2 Evolution of changes in SHSI, relative humidity, temperature in percentage. Here, changes are measured with reference to 1981–1990 period and moving average of 9 years was taken for various coastal cities a) Surat, b) Mumbai, c) Goa, d) Mangalore, e) Kochi, f) Thiruvananthapuram, g) Kanyakumari, h) Puducherry, i) Chennai, j) Nellore, and k) Visakhapatnam, and l) Bhubaneshwar obtained from IMDAA data sets

3.2 Decline in work performance and heat stress associated metabolic rates in the coastal cities of India

The spatial pattern of mean SHSI obtained from IMDAA, IITM-ESM for the period 1981–2014 and the percentage bias between them are shown in Fig. 4a–c. It can be noted that the SHSI is highest in the Himalayan region, the northeastern parts, followed by the east coast and west coast region, and the same is depicted by both data sets. The IITM-ESM underestimated the SHSI of IMDAA in the regions of the Himalaya, northeast and the Indo–Gangetic plains with the bias of −30%. The west coast region and southeast coast regions depict the percentage bias of ±10%. As our main focus is on the coastal cities of

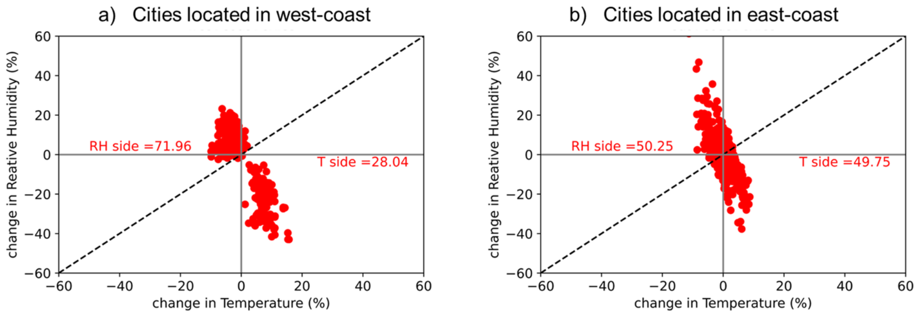

Fig. 3 Scatterplot of change in temperature vs change in relative humidity during high heat stress hours relative to daily average value obtained from IMDAA data sets

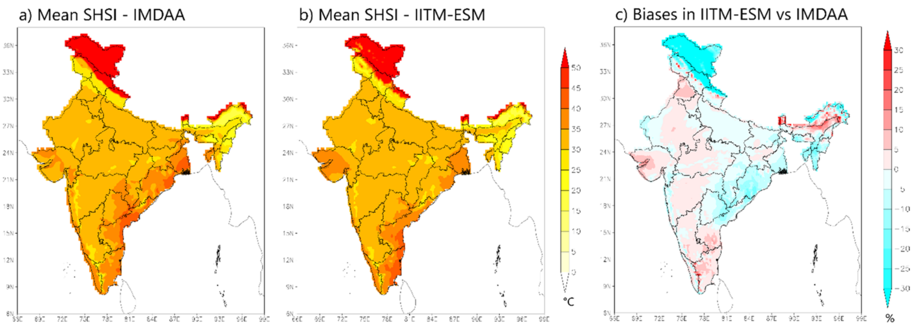

Fig. 4 Spatial mean summer (April and May) SHSI from **a** IMDAA in °C **b** IITM-ESM in °C and **c** spatial percent bias between the same in % for the study period 1981 to 2014

India, the low percentage bias with 90% confidence level in these locations substantiate to proceed for the estimation of future heat stress and decline in work performance (DWP) using the IITM-ESM simulations. The mean values of DWP for the decades 2021–2030, 2031–2040 and 2041–2050 for the SSP2.4.5 and SSP5.8.5 pathways in the study locations are given in Fig. 5a, b. It is conspicuous that the DWP is high in the SSP5.8.5 scenario when compared to that of SSP2.4.5. Cities such as Chennai, Nellore, and Puducherry have higher rates of DWP of 39%, 38%, and 36%, respectively, while cities such as Kanyakumari and Mumbai have lower rates of DWP of 18% and 20% in the SSP2.4.5 pathway. The decadal increment of DWP has increased to 40%, 40%, 39%, 38%, and 37% in the SSP5.8.5 pathway in Chennai, Nellore, Puducherry, Kochi, Thiruvananthapuram, and Goa, respectively.

The scatter plots along with the linear fits between the SHSI and WBGT for the different study locations for the period of 1981–2014 of the historical period (S.Fig. 6a–l), and for 1981 to 2050 by including the simulations from 2015 to 2050 of SSP2.4.5 (S.Fig. 7a–l) and SSP5.8.5 (S.Fig. 8a–l), facilitate the estimation of SHSI for the equivalent WBGT for all the study locations. Figure 6a–l shows the percentage of rest recommended for the people carrying out different levels of work such as light, medium, heavy, and very heavy work during the historical (1981–2014) and future (i.e., from 2021 to 2050) time periods in the SSP2.4.5 and SSP5.8.5 scenarios. The most affected cities are Chennai, Nellore, Puducherry, and Kochi, followed by Mangalore and Thiruvananthapuram. The values of a)

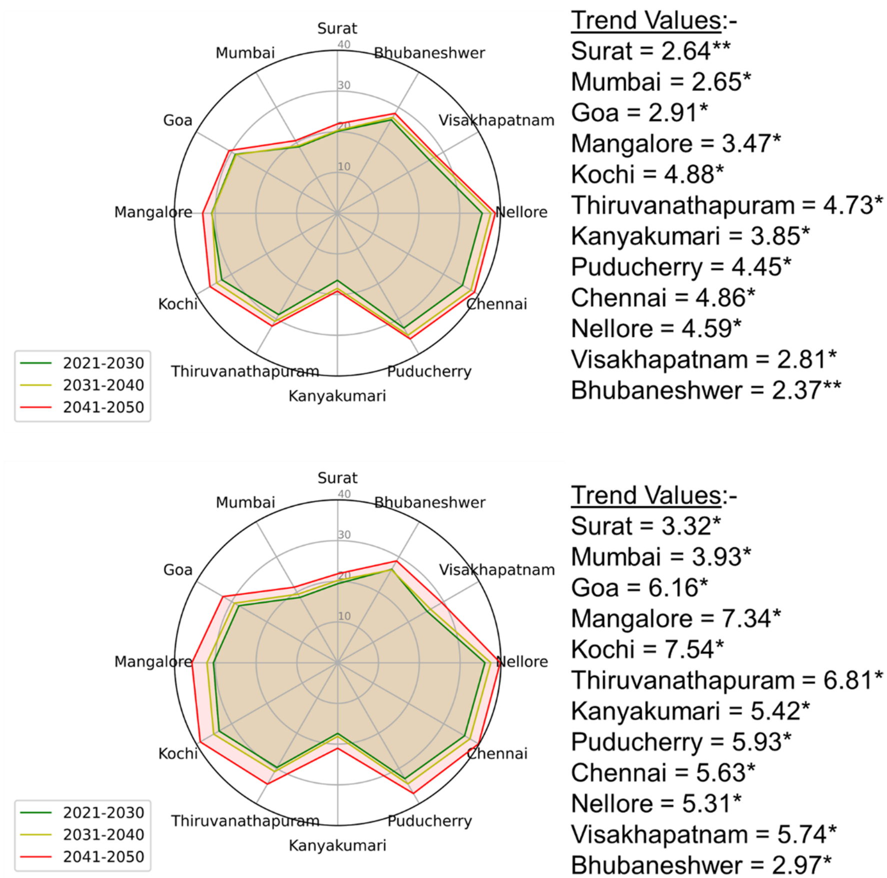

Fig. 5 Decline in work performance in future decades over the study locations obtained from IITM-ESM model **a** following SSP-245 pathway **b** following SSP-585 pathway along with trend values for 2021–2050 period in % and here * represents 0.05 significance level, ** represents 0.10 significance level

SHSI over Chennai, Nellore, Puducherry, and Kochi are 42 °C, 42 °C, 40 °C, and 40 °C, respectively, during the historical period, which infers that light work can be carried out without any rest per hour. However, the labourers should take 25%, 50% and 75% of rest per hour if they carry out medium, heavy, and very heavy works, respectively. The values of SHSI during SSP2.4.5 and SSP5.8.5 are 44 °C & 44 °C, 44 °C & 44 °C, 42 °C & 42 °C and 42 °C & 43 °C in Chennai, Nellore, Puducherry, and Kochi, respectively, for the period of 2021–2050, which suggests that the medium and heavy works need to be carried out with 50% and 75% of rest per hour. Thiruvananthapuram has a SHSI of 38 °C during the historical period that increased to 41 °C during the SSP2.4.5 and SSP5.8.5 scenarios, suggesting that the medium, heavy, and very heavy works require 25%, 50%, and 75% rest per hour, respectively. The conditions in Mangalore and Thiruvananthapuram are such that the labourers can carry out light and medium work without any rest. However, they are recommended to take 50% of rest per hour to carry out the heavy and very heavy work in the present scenario. During the future scenarios of SSP2.4.5 and SSP5.8.5, the SHSI values show 41 °C, 41 °C & 40 °C, 41 °C, which suggests that medium, heavy, and very heavy

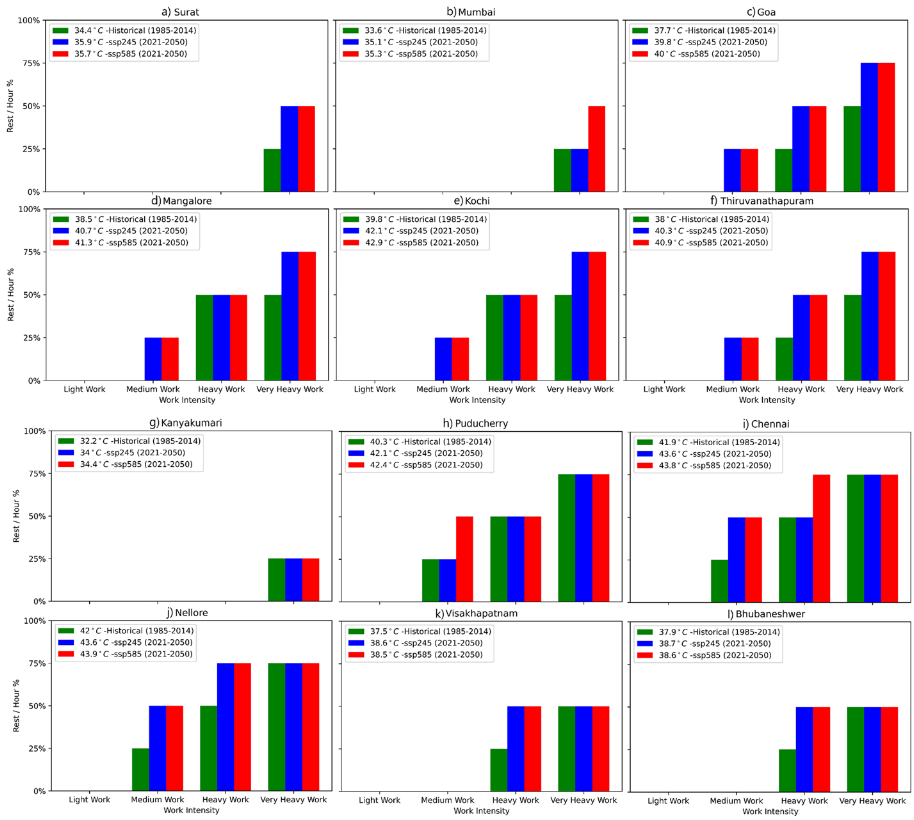

Fig. 6 a–l Recommendation of rest hours for different intensity of works over the study locations

work are to be carried out with 25%, 50%, and 75% of rest per hour. The SHSI value in Goa during the historical period is 38 °C, suggesting that the heavy and very heavy work requires 25% and 50% rest per hour. These values between 2021 and 2050 of the SSP2.4.5 and SSP5.8.5 are 40 °C and 40 °C, respectively, thereby recommending that the medium, heavy, and very heavy work need 25%, 50%, and 75% rest per hour. Kolkata, Bhubaneswar, and Visakhapatnam's SHSI recommends that the medium, heavy, and very works require 25%, 50%, and 75% rest per hour in future scenarios. Mumbai's SHSI is 34 °C, 35 °C, and 35 °C during the historical period, the SSP2.4.5 and the SSP5.8.5 scenarios of 2021– 2050, respectively, suggesting that the very heavy work requires 25% rest per hour. The other cities such as Kanyakumari and Surat did not show much implication during the future climate scenarios. The overall analysis suggests a strong shift towards more rest per hour in most of the cities during the future period of 2021–2050 when carrying out light, medium, heavy, and very heavy work.

Recent research on the study locations has revealed the significant impact of heat stress on the people working in open environments. The National Health Policy of India, 2017 has given more importance to the health care of agricultural workers affected by occupational injury. However, not enough importance is being given to the health care affected by the increased heat stress. A study on the people working in the construction site of the Metro Rail in Chennai reported that most of the work at the site is being carried out at the temperature range of 34–45 °C (Ajit and Srinivasan 2018). The study recommends reduced working hours for the workers and providing large quantities of ice at the workplace. Extreme heat stress resulted in illness among two thirds of the population in the cities of Bhubaneswar and Cuttack in eastern coastal India (Swain et al. 2019). The results of Zeppetello et al. (2022a, b) show higher heat stress levels in the eastern coastal region, which would increase drastically by the year 2050 when the 95th percentile of heat stress is considered. These results are analogous to our findings of the increased heat stress in the future. Also, they reported that the Indian subcontinent will face extremely dangerous heat stress by the year 2100. The study of Freychet et al. (2022) revealed that the excessive occurrences of threshold wet bulb temperatures of severe stress (27.5 °C) have been observed in tropical regions including India, and that these return values increase rapidly under the climate change scenario. Freychet et al. (2022) showed that more than 80%, 10%, and 3% of the Indian population will be exposed to severe, dangerous, and deadly heat stresses by the year 2100. The results of 300 micro surveys carried out by the Integrated Public Use Micro Data Service (IPUMS) showed that the ongoing climate conditions reduce the labour and work productivity due to the higher levels of heat stress. With an analysis based on the CMIP 5 simulations, Juzbasic et al. (2022) report that future climate change will reduce 18.6% of the labour in Asia under the low exposure of heat stress levels, and 25% under the high-level exposure of heat stress. Our results of the present study also project the increasing heat stress levels and associated work decline in the coastal cities of India. A global climate survey revealed the significant increase of web bulb temperature in south Asia at a level nearing and sometimes beyond human physiological tolerance. This increased heat stress in coastal areas is associated with the wind shifts that change the dew point temperature in the arid and semi-arid environments (Raymond et al. 2020). Heat stress studies in the Caribbean region found that the UTCI is positively correlated with air temperature and humidity, while it is negatively correlated with the wind speed (Napoli et al. 2022). Higher winds bring body temperature closer to the air temperature and reduce the heat stress. In our results, the reduced wind speeds over the coastal regions of peninsular India up to 0.4 m·sec^{-1} and the increase in temperatures of up to 0.8 °C in these regions from 2011 to 2020 when compared to 1981–1990 might have led to higher levels of heat stress and further work decline. However, the interior regions of peninsular India witnessed a decrease in air temperatures and much less decrease in wind speeds. It is also reported that the land–ocean warming contrast is linked to heat stress (Byrne and O'Gorman 2013). The decreased temperature gradient from ocean to land changes the circulation and further reduces the horizontal wind flow that may increase the heat stress risk with the associated increase in latent and sensible heat fluxes (Manning et al 2018). In the present work, the decreased gradients of temperature and wind between the Arabian Sea and the peninsular region for the periods of 2001–2021 and 1981–2000 show the alarming heat risks in the study locations.

4 Conclusions

Earlier reports highlight the vulnerability of people working in the coastal areas of India due to climate change. In the present study, we focused on the coastal cities of India by estimating the DWP and the rest required for different work categories. For this, we used the newly emerged reanalysis data sets of IMDAA and the high resolution, bias-corrected, and statistically downscaled simulations of IITM-ESM available at NEX GDDP. The following conclusions have been drawn from the results of the present work:

1. The heat stress over Chennai, Nellore, Puducherry, Bhubaneswar, and Mangalore is very high and is beyond 40 °C, showing extreme caution and danger categories during the period of 1981–2020. The increase in heat stress from the decade of 1981–1990 to 2011–2020 is more pronounced in Surat, Mumbai, and Goa when compared to the other cities.
2. Heat stress mainly followed the changes in temperature in the cities located on the east coast, while it followed the changes in relative humidity in the cities of the west coast.
3. The decline in work performance is very high in Chennai, Nellore, and Puducherry in the SSP2.4.5 scenario at about 35–39%, and Thiruvananthapuram, Kochi, and Mangalore have joined them by showing up to a 40% decline in work performance during the SSP5.8.5 scenario for the period of 2021 to 2050.
4. A clear shift towards enhanced rest is observed from the historical and future periods with regards to the recommendations of rest per hour for the people carrying out the light, medium, heavy, and very heavy work. The most affected cities are Chennai, Nellore, and Puducherry, followed by Kochi, Thiruvananthapuram, Mangalore, and Visakhapatnam, where workers are recommended to carry out medium, heavy, and very heavy works with 25%, 50%, and 75% rest per hour.

As there is limited literature available on the heat stress in India, the results of this study may be useful for policymakers in designing actions to mitigate the adverse effects of heat stress. Furthermore, these results may contribute to the development of new tools for optimised productivity in work environments. However, further research is very much required in the direction of designing heat absorbing shields, utilisation of tools that can reduce the physical strain, etc., for an effective mitigation of heat stress impacts.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11069-024-06872-y.

Author contributions T V Lakshmi Kumar—concept, interpretation of results and writing of the draft. Bharath J—data analysis and interpretation results. Walter Leal—interpretation of results and manuscript improvement. Humberto Barbosa—interpretation of results. Koteswara Rao K—manuscript improvement.

Funding The authors have not disclosed any funding.

Declarations

Conflict of interest The authors of this manuscript have no competing interests.

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