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ORIGINAL PAPER

Vulnerability of tropical Indian cities to augmenting heat stress during summer and monsoon season months (1969–2015)

Amit G. Dhorde[1] · Manasi S. Desai[2] · Anargha A. Dhorde[3] · Mahendra S. Korade[4]

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Abstract
Human beings are adversely affected by climate extremes, pertinent to an increase in frequency and intensity of warm temperatures, eventually inducing warming on a global and regional scale. In a tropical nation like India, high summer temperature and increased moisture with the arrival of the southwest monsoon (hereafter referred to as monsoon) aggravate the sultriness of the ambient environment. Irrespective of global climate change, cities alter their climate due to urban materials' impervious surfaces and thermal properties, which upsurge moisture and temperature in urban settings. Thus, urban dwellers are peculiarly vulnerable to heat stress health hazards. Heat stress indices allow quantitative assessment of thermal stress to determine the safe limits of thermal exposure. In the present study, statistical trends in Heat Index were evaluated to analyze heat stress over 41 urban stations of southern peninsular India over the summer and monsoon season from 1969 to 2015. Results indicated that almost all stations registered a significant increase at 95% confidence level in heat stress except for an insignificant decrease at a few stations. Changepoint detection depicted an increase in heat stress initiated in the late 1990s and early years of the decade 2000 at most urban stations. Hierarchical cluster analysis partitioned data into seven spatial units. Accordingly, the highest magnitude of increase was observed over cities located in the northeastern part of the study area and the southern tip of peninsular India. The study demands attention to perilous health risks related to India's increasing heat stress casualties and the need for an indigenous thermal stress alerts system.

1 Introduction

The rhythm of a climate has been profoundly altered in the twenty-first century on a global and regional scale. Substantial scientific literature has reported an increase in daily temperature extremes and the number of extremely hot days. A considerable increase in the frequency and intensity of heatwaves has been successively reflected in the Intergovernmental Panel for Climate Change (IPCC) reports. IPCC (2013) affirms that the warming of the earth's climate system is unequivocal, and anomalies observed since 1950 are unparalleled over decades to millennia. An increase in the frequency of warm daily temperature extremes and decreases in cold extremes on a global scale was observed (IPCC 2012). The warming trend continuing over several decades has been linked to alteration of the large-scale hydrological cycle, such as increasing atmospheric water vapor content in certain areas with a simultaneous decrease in others (Bates et al. 2008). Recent decades have experienced overall moistening of the globe; both ground moisture content (Dai 2006; Willett et al. 2008) and atmospheric humidity aloft (Trenberth et al. 2005) depicted considerable increase. In scorching heat and muggy, humid weather, the human body's ability to cool itself is challenged. The human body responds to excess heat by draining off surplus body fluids through sweating to cool itself in hot ambient temperature, but the high loss of fluids increases the risk of heat-related illness. Besides the heat component, in the presence of high air humidity, perspiration cannot evaporate from human skin, and thus outer and core body temperature fails to maintain its ideal temperature range. Evaporation is a prominent

Responsible Editor: Emilia Kyung Jin.

✉ Amit G. Dhorde
amitdhorde@unipune.ac.in

1 Department of Geography, Savitribai Phule Pune University, Pune 411007, India

2 Department of Geography, Symbiosis College of Arts and Commerce, Pune 411004, India

3 Department of Geography, Nowrosjee Wadia College, Pune 411001, India

4 Department of Geography, Shri Shiv Chhatrapati College, Junnar 410502, India

cooling process that effectively reduces human body temperature. Therefore, a human being feels uncomfortable and stressed in hot and humid conditions. Kleerekoper et al. (2012) infer that global temperature rise combined with the microclimatic effect of Urban Heat Island (UHI) may result in unhealthy heat stress and even a significant increase in heat-related mortality. The urban microclimate determined by the modified urban landscape (Arnfield 2003) and attenuated meteorological conditions have severe implications for human thermal comfort (Unger 1999). India, a developing nation with a dense population and one of the fastest emerging economies globally is highly dependent on human resources. Substantial population is predicted to get concentrated in urban areas. The present rate of urbanization is unsustainable with insufficient urban resources. The socio-economic condition plays a vital role in elevating the risk of heat stress for a socially and economically vulnerable population. The study by Smoyer et al. (2000) highlights that demographic characteristics and socio-economic conditions threaten and impede the adaptive capacity of the population to deal with heat stress adversities. Thus, it is evident that adaptive capacity to deal with heat stress further deteriorates in developing and large population-sized tropical nations like India.

Dependency on heavy manual labor, large population size leading to the insufficient reach of public health measures, congested unplanned urban areas along with less individual awareness regarding heat-related illness leads to high heat stress casualties. The rise in heat stress has a considerable adverse impact on human health (Harlan et al. 2014; Kovats and Akhtar 2008; Michelozzi et al. 2009; Gosling et al. 2009). Heat stress impacts human activity (Maloney and Forbes 2011) leading to reduced labor productivity (Kjellstrom et al. 2009; Dunne et al. 2013; Zander et al. 2015). Another phenomenon worsening human thermal comfort during the summer season is heatwaves. Rohini et al. (2016) indicated a statistically significant increase in the frequency and duration of heatwaves over India. De et al. (2005) noticed a rise in heatwave-induced casualties over recent decades. Further, they advocated that a decrease in daily temperature range due to urbanization fails to neutralize high daytime temperatures during heatwave epochs leading to human discomfort.

Steadman originally proposed the Heat Index (Steadman 1979), and subsequent study published in 1984 (Steadman 1984) gained scientific attention towards its suitability for assessing heat stress. Steadman's indices evaluated thermal comfort using an iterative solution for multiple variables through multiple equations representing the body's temperature and moisture transfer, combining atmospheric air temperature and humidity. However, the complexity of the calculation of Steadman's (1979) equations necessitated modification, and a simpler version as a single approximated Heat Index (HI) equation was put forth by Rothfusz (Iheanacho 2014). The present computation of the heat index is a refinement of a result obtained by multiple regression analysis carried out by Lans P. Rothfusz and mathematically explained in 1990 National Weather Service-National Oceanic and Atmospheric Administration (NWS-NOAA), United States of America (USA) (Rothfusz 1990). HI is mathematically expressed as;

$$\begin{aligned} \mathrm{HI} = & -42.379 + (2.04901523 \times T) + (10.14333127 \times R) \\ & - (0.22475541 \times TR) - \left(6.83783 \times 10^{-3} \times T^2\right) \\ & - \left(5.481717 \times 10^{-2} \times R^2\right) + \left(1.22874 \times 10^{-3} \times T^2 R\right) \\ & + \left(8.5282 \times 10^{-4} \times TR^2\right) - \left(1.99 \times 10^{-6} \times T^2 R^2\right) \end{aligned}$$

where, HI is the heat Index (°Fahrenhiet), T is the Ambient dry bulb temperature in °F, RH is the relative humidity in %.

In the present study, HI was used by applying necessary adjustments as prescribed by NWS-NOAA (http://www.wpc.ncep.noaa.gov). HI is one of the most popular indices for environmental health research as a measure of thermal comfort. The index is used for studies related to outdoor temperature exposures and the development of synoptic scale heat warning systems (Anderson et al. 2013). Though the index was devised in the USA and used to evaluate thermal stress conditions for the USA (Robinson 2001; Glazer 2005), it has been applied worldwide (Michelozzi et al. 2009; Diffenbaugh et al. 2007; Zahid and Rasul 2012). In the tropical climate of India, the combined effect of temperature and moisture alters in tandem with a seasonal rhythm. In summer, the temperature over peninsular India frequently crosses 30 °C, seldom resulting in convective heating and precipitation at a local and regional scale. This characteristic of the tropics, though provides intermittent respite from the scorching heat, is a temporary phenomenon as the arrival of the monsoon towards the culmination of the summer season increases sultriness in the ambient environment. Thus, besides temperature, humidity contributes to the feeling of sultriness and forms an essential element to be considered while assessing thermal stress, especially for the tropical climate of India. The study by Hijioka et al. (2014) states that "The population of South Asia is specifically vulnerable to heat-related mortality; risk gets further magnified due to high rate of urbanization and lack of efficient adaptation strategies". The Heat Index (HI) adopted by NOAA is one such index that includes temperature and humidity components and thus devised for assessment of sultriness emblematic during summer and monsoon months in warm tropical climate in the cities of peninsular India. Rajib et al. (2011) used heat index to assess the impact of climate change on human thermal comfort. He advocated the applicability of HI for areas with a temperature of more than 26 °C and relative humidity usually above 39%. Thus HI is relevant for the tropical climate of India. Jaswal et al. (2017) applied HI to assess the long-term behavior of heat stress caused by increasing temperature and moisture over the Indian subcontinent for a vast spatial coverage by acquiring data for 283 meteorological stations over 1951–2010. In India, Mohan et al. (2014) applied HI to analyze thermal comfort conditions for five metropolitan cities. They provided a relative ranking of the cities based on thermal comfort (discomfort) conditions. Pai et al. (2013) evaluated trends in heatwaves for 103 stations over India and found that exacerbated conditions during heatwave incidences lead to heat stress and increased heat-related mortality, and suggested using a heat stress index to assess the impact of both temperature and humidity on human health. Recently HI index has been preferred by India Meteorological Department (IMD) on an experimental basis for issuing heatwave warnings to avoid human fatalities jointly with National Disaster Management Authority (NDMA). The suitability of HI is jointly analyzed by Heat Wave Warning services, IMD, Ministry of Earth Sciences, Govt. of India.

The present study may form crucial reference input to this endeavor. The other empirical and direct indices are devised for temperate climates and often not widely tested for India's tropical peninsular region. The conventional Thermo-Hygrometric Index (THI) endows extra weightage to temperature than humidity and thus may not form a suitable option for tropical monsoon muggy conditions. Wet Bulb Globe Temperature (WBGT) is primarily used to evaluate occupational heat stress. WBGT has several versions, while the standard version of WBGT for outdoor conditions requires an input of black globe temperature, for which long-term data is not available for India. The WBGT indoor version provided by Bernard and Pourmoghani (1999) underestimates tropical heat. The addition of 2–3 °C to the output obtained by Lemke and Kjellstrom (2012) appears subjective not widely accepted.

The present study attempts to analyze spatio-temporal trends in heat Index for 41 selected urban weather stations of southern peninsular India during summer (March to May) and monsoon/southwest monsoon (SWM) season months (June to September). Based on the absolute change in HI over the study period, cities were partitioned and grouped, applying hierarchical cluster analysis techniques to assess the spatial distribution of heat stress and identify regions of differential heat stress over peninsular India (Fig. 1). The Sequential Mann Kendall (SQ–MK) test was applied for change point detection to determine the approximate period of change in heat stress trends.

2 Materials and methods

2.1 Data obtained and study area

For the present study, daily dry bulb temperature and relative humidity data were obtained from the India Meteorological Department (IMD) for the summer and monsoon season months. The data was obtained for well-distributed 41 urban stations of southern peninsular India for 47 years (1969–2015). Southern peninsular India experiences a tropical monsoon climate. The wet period is confined to the monsoon season (June to September) for a majority of the peninsular region, while the southeastern region (Tamilnadu and Andhra Pradesh) experiences a wet season during the northeast monsoon (NEM) season (October to December). The central interior part of peninsular India receives meager rainfall, thus being subjected to a semi-arid climate. Summers are exceedingly hot over the interior peninsular region of India. During the summer months, mean monthly temperatures in the region hover around 35 °C, with daily maxima occasionally topping above 40 °C. Towards the southern tip, high temperature combined with humidity augments sultriness. Over the coastal part, temperature hovers around 32 °C, but proximity to the sea leads to high humidity. Transition months between summer and SWM season (May and June) are exceptionally stressful. During weeks before the monsoon, a decrease in temperature is not much prominent over the south and southeast region of the peninsula (NEM region), while the instigation of high humidity augments thermal discomfort. The SWM season over India has its distinct essence. SWM gradually progresses inland in stages. Though the monsoon burst gradually decreases scorching summer temperatures by 5–6 °C, from mid-July during intermittent breaks in monsoon, heat stress aggravates due to sultriness. The SWM season is characterized by warm tropical temperatures and frequent increase (decrease) of atmospheric moisture due to wet and dry spells.

2.2 Temporal trend analysis

For temporal trend analysis Linear regression model (LRM) was used. The test has been widely used for several climatological studies to assess long-term tendency in climatic parameters (De and Rao 2004; Dash et al. 2007). The magnitude of the trend was obtained from the slope (value of '*b*') of the regression line. The significance of trends was checked with Student's *t* test at 95% confidence level. Besides the parametric test, Mann Kendall Rank (MK) analysis was used to verify the results of temporal trends with the application of a non-parametric test. Gadgil and Dhorde (2005); Zarenistanak et al. (2014) had used the test

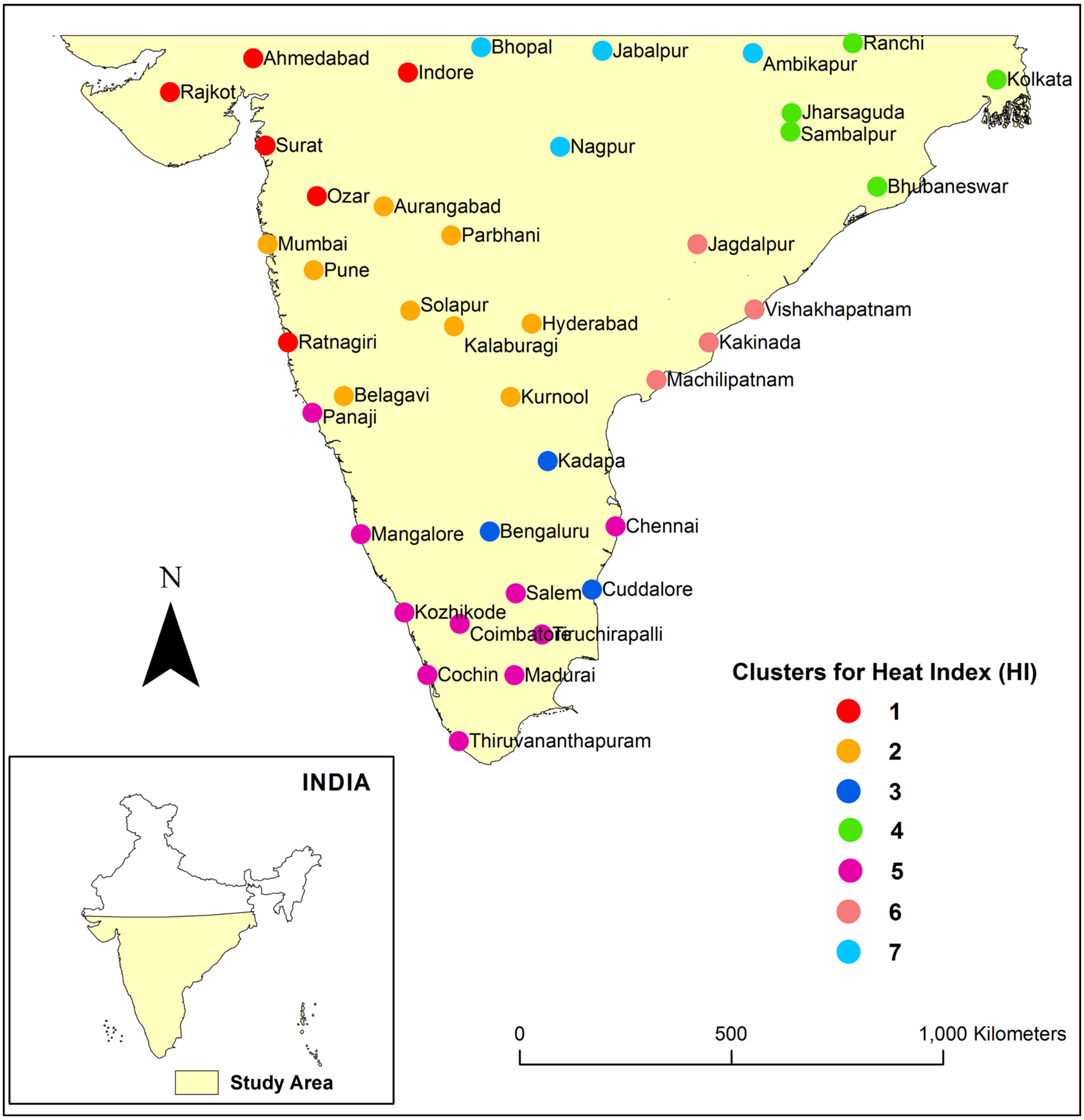

Fig. 1 Location of stations and clusters identified

for significant temporal trend detection for meteorological time series. Theil-Sen approach (TSA) was applied to assess slope magnitude in time series data (1969–2015). TSA is a robust statistical test compared to the least-squares method because of its relative insensitivity to extreme values and better performance for normally distributed data (Hirsch et al. 1982). TSA is a non-parametric method used to estimate the magnitude of climatological and hydrological time series data (Zhao et al. 2010; Chattopadhyay and Edwards 2016; Antonopoulos et al. 2001).

2.3 Change-point detection

Sneyers (1990) proposed a Sequential Mann–Kendall (SQ–MK) test. The method is used to test an assumption about the beginning of trend development within a sample (Partal and Kahya 2006). The test determines an approximate year for the initiation of a significant trend. If two series, progressive $U(t)$ and regressive $U'(t)$, converge and then diverge beyond a specific threshold value, the trend is considered statistically significant. The point at which forward and backward series converge determines the approximate year of the beginning of a movement. In the graphical representation of SQ–MK, upper and lower confidence limits are set at $+1.96$ and -1.96, respectively. The SQ–MK test is for change point detection in several meteorological and hydrological studies (Partal and Kahya 2006; Karpouzos et al. 2010; Safari 2012). Sneyers (1990) has explained the details of the test in the WMO technical note.

2.4 Cluster analysis

Cluster analysis (CA) is a multivariate statistical technique used for combining and segregating observations based on their similarity and dissimilarity (Gong and Richman 1995). CA thus involves the groupings of similar entities or observations that exhibit two properties external isolation and internal cohesion (Cormack 1971). Cluster analysis imposes a characteristic structure on data for exploratory purposes. The hierarchical clustering algorithm creates a nested sequence of partitions of the patterns from the dissimilarity matrix and proceeds through a series of either successive mergers or successive divisions (Gong and Richman 1995). In the present paper, for hierarchical cluster analysis Ward method was used by applying both the agglomerative schedule and proximity matrix. The squared Euclidean distance was used to measure dissimilarity (similarity) between elements of the cluster. Ward's approach does not successfully combine the two most similar objects; instead, the procedure chooses those whose merger decreases overall within-cluster variance to the slightest possible degree. Thus, sufficiently equally sized clusters and dataset results include fewer outliers (Mooi and Sarstedt 2011). Ward's method uses an analysis of variance approach to evaluate the distances between clusters. Thus, this method minimizes the sum of squares of any two clusters formed at each step.

3 Results

3.1 Hierarchical cluster analysis and temporal trends

In the present study, daily heat index values were calculated for each of the 47 years and summarized into monthly averages for summer (March to May) and SWM season months (June to September). The absolute change evaluated from slope value 'b' of LRM and TSA for the summer and monsoon months was given as an input for cluster analysis. Ward's method of cluster analysis applied grouped 41 urban stations in seven different clusters.

Cluster 1 comprises stations located in the northwestern part of the study area. The cluster includes six stations, namely Ahmedabad, Indore, Ozar, Rajkot, Ratnagiri, and Surat (Fig. 1). The absolute change in heat stress at these stations either shows a decreasing trend or a meager increase. During the summer season in March and April, all stations depicted a decreasing trend. However, a slight insignificant increase was noted in May at Rajkot, Surat, and Ozar (Fig. 2). A significant decrease in heat stress was observed only at Ratnagiri, which continued until August (Fig. 3). During the monsoon season (Fig. 3) statistically significant increase was observed in June at Rajkot, where the temperature remains high as the monsoon reaches there late, except Ratnagiri, which has a coastal location. All the cities north of Ratnagiri depict an increase in heat stress. However, as July heralds with monsoon rains, either decrease or an insignificant slight increase in thermal stress was observed. In August, Ahmedabad and Indore noted a substantial significant increase (Fig. 3). Following TSA absolute increase over the study period at these stations was 2.3 °C and 2.9 °C, respectively. A similar significant increasing trend sustained over Indore until the end of the monsoon season.

Cluster 2 includes cities located in the western part of peninsular India. This cluster also extends southward and inward from the coast towards semi-arid zones of peninsular India (Fig. 1). Mumbai is a prominent metropolitan city that has developed in multitude and sustains a substantial working urban population. The city noted a positive trend in heat stress during all summer and monsoon season months (Figs. 2 & 3). An increase in heat stress was not much prominent for March and April, but from May onwards till the end of the monsoon season significant rise in heat stress was observed as per the TSA test. During the summer season at Aurangabad, the city located in the semi-arid climate regime, an absolute increase in March was 2 °C, which elevated to more than 3 °C in April and reached up to 4 °C during May. During successive summer months, a similar increasing pattern was noticed at Kalaburagi, where an increase of 4.5 °C was witnessed in May, the highest absolute increase for this cluster during the summer season. In May, most of the stations in this cluster denoted a significant increase in heat stress (Fig. 2). In monsoon season invariably, all the stations in this cluster reflected a rising trend in heat stress, particularly cities within the semi-arid climatic zone, namely Aurangabad, Solapur, Parbhani, and Hyderabad, are vulnerable to heat stress adversities. A significant increase of more than 2 °C was noticed in these cities during almost all monsoon months (Fig. 3). At Mumbai and Pune, which experience tropical wet and dry climates, the end months of the monsoon season portrayed a significant increase in thermal discomfort. Overall, for this cluster, month of August was prone to significantly high heat stress.

Cluster 3 comprises of only three cities having triangular positioning over the southeastern part of the study area. These cities are; Bengaluru, Cuddalore, and Cuddapah (Fig. 1). The Cluster does not show a noticeable increase in heat stress trends during the summer season. Only Cuddalore registered a significant rise in March and May. However, the increase in heat stress was meager. This significant

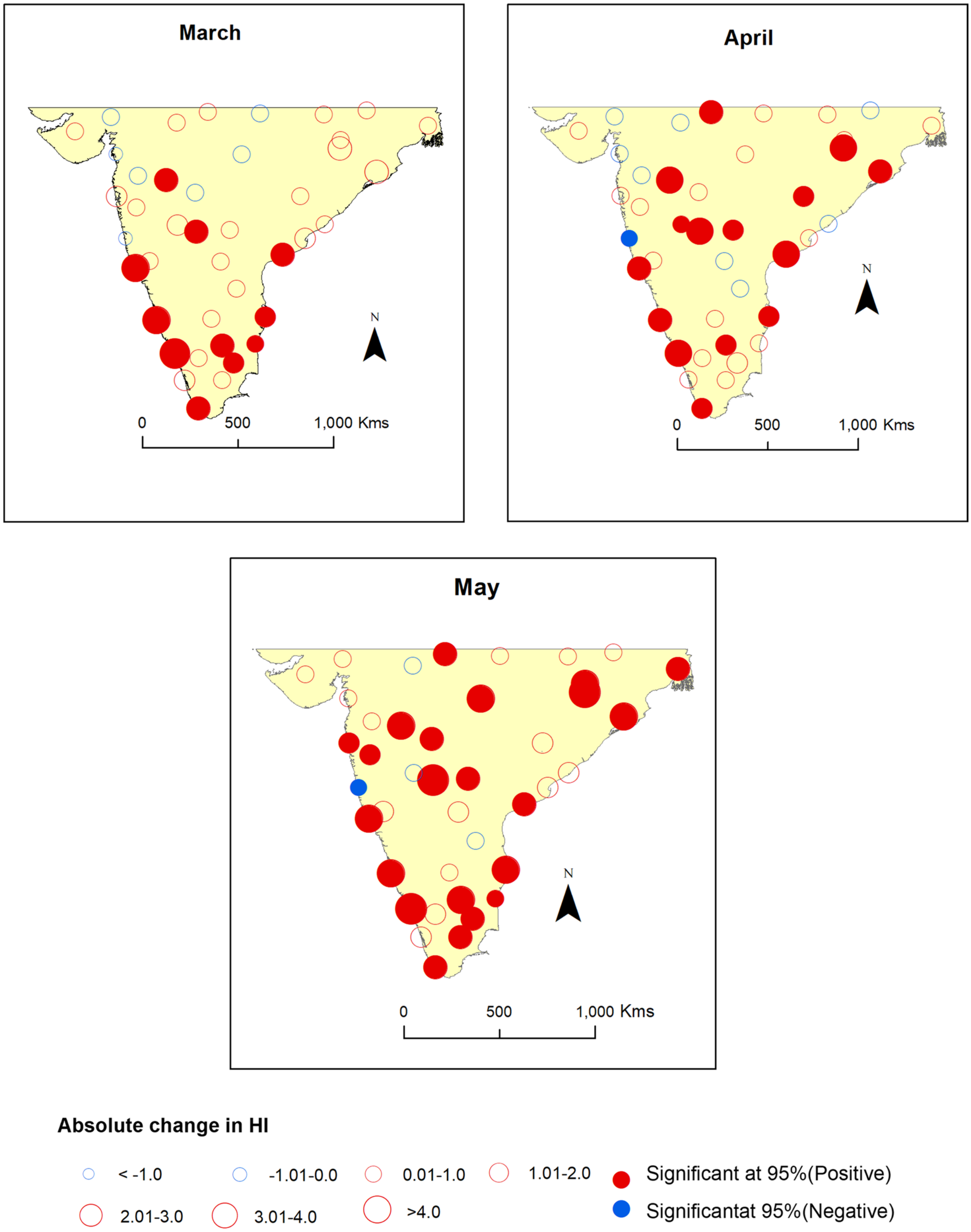

Fig. 2 Absolute change in HI (obtained by linear regression model) for summer season months during the period 1969–2015 (*HI values are in degree celsius*)

increasing trend continued during monsoon season months but remained fluctuating around 1 °C. Bengaluru, though depicted an increasing trend in thermal stress, the absolute rise was well within 1 °C. Cuddapah represented a significant decrease in heat stress from April onwards and towards the end months of (August and September) monsoon season.

The fourth cluster includes cities situated in the north-eastern part of the study area. The stations in this cluster

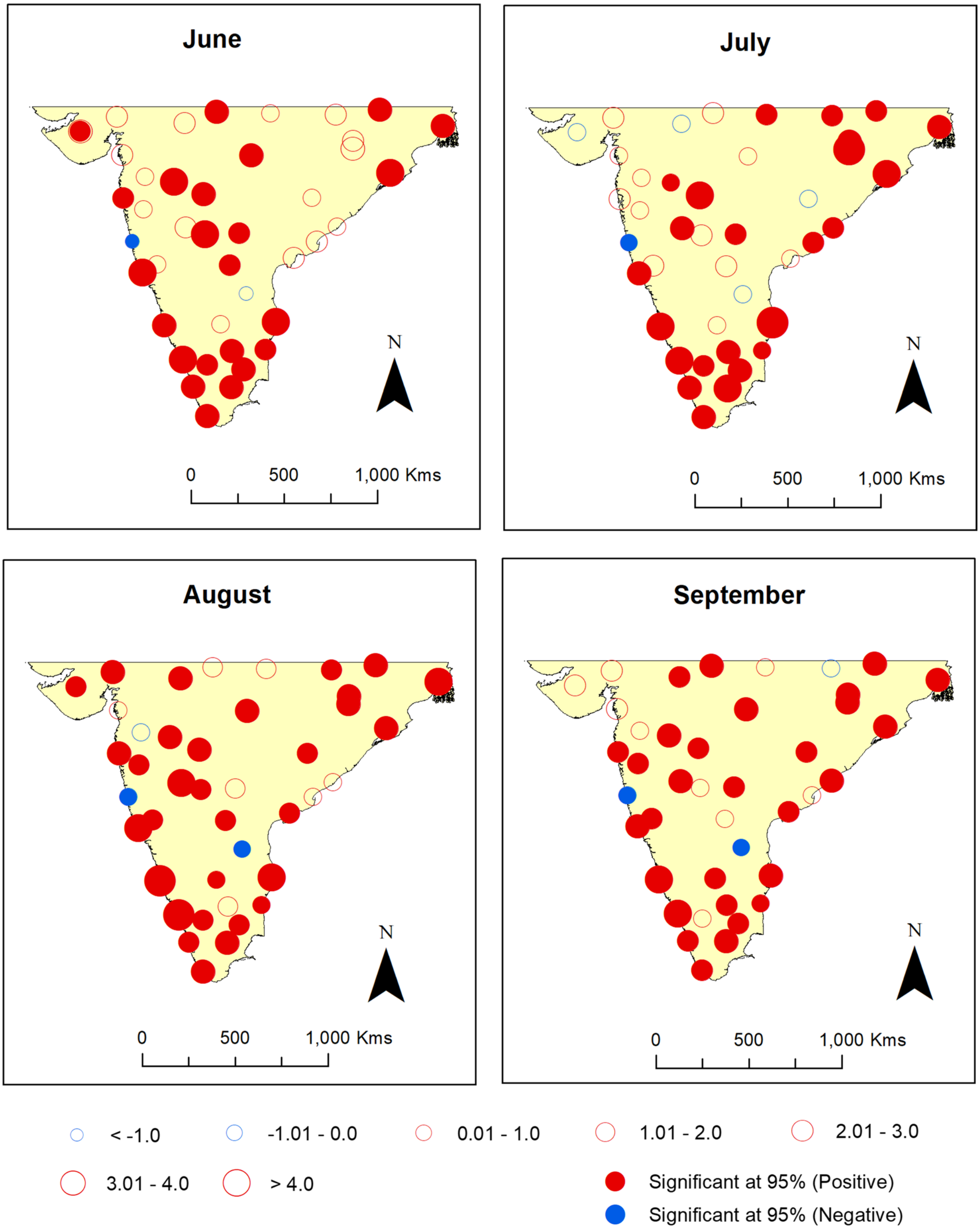

Fig. 3 Absolute change in HI (obtained by linear regression model) for monsoon season months during the period 1969–2015 (*HI values are in degree celsius*)

lie in dry sub-humid (Ranchi, Jharsaguda, and Sambalpur) to moist sub-humid climatic (Kolkata and Bhubaneswar) zone (Raju et al. 2013). From Figs. 2 and 3, it can be observed that the cluster depicts a marked increase in heat stress from May onwards until the end of the monsoon season. In contrast, Bhubaneswar and Sambalpur experienced a significant increase from April onwards till September. Absolute increase at Bhubaneswar was consistently above 2.5 °C and highest in May (3.7 °C), while at Sambalpur, summer heat stress had increased from 3.9 to 4.2 °C during April and May, respectively. In July, the marked absolute increase in heat stress reached up to 4 °C (TSA). At Kolkata,

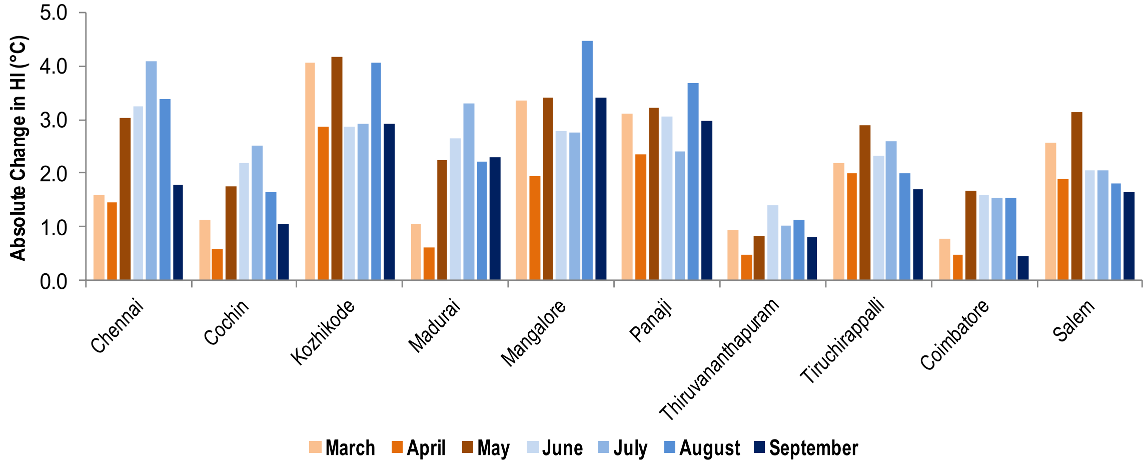

Fig. 4 Absolute increase in HI for the cluster 5 cities in accordance with Theil-Sen Approach

a significant increase was noticed from May onwards, while a meager significant increasing trend was detected in March and April. Ranchi and Jharsaguda do not depict a notable increase in heat stress during the summer season. Still, monsoon season months in these cities showed a significantly high increasing trend in heat stress. The cities in this cluster depict a noticeable increase in heat stress during monsoon season months.

Cluster 5 combines almost all the stations situated over the southern tip of peninsular India (Fig. 1). This cluster registered the highest significant increase in heat stress, particularly in the monsoon season. It includes cities along the west coast, namely Panaji, Mangalore, Cochin, Kozhikode, and Thiruvananthapuram, which experience a tropical monsoon climate. These cities receive most of their rainfall during the SWM season (June to September), while other cities within this cluster have tropical wet and dry climates: Chennai, Madurai, Tiruchirappalli Coimbatore, and Salem. These stations receive a majority of annual rainfall during the NEM season (September to December). Consequently, though summer high temperatures show a slight decrease from June to September, no interim relief from SWM showers is experienced at these cities and thus seldom provides relief from thermal discomfort conditions. Chennai and Salem, a metropolitan city and a major industrial hub, support a large working population. Both of these locations depict a significant increase in thermal stress during commencing months of the summer season. During April, a moderate increase was observed, while in May, already the hottest month, an absolute increase of about 3 °C was noticed at these two cities (Fig. 4). Madurai also depicted a significant increase in heat stress during May (2.3 °C). Tiruchirapalli, though consistently witnessed an increasing trend in heat stress, the highest increase was observed in May (2.7 °C). During all monsoon season months, Madurai experienced a significant increase in heat stress. However, at Salem and Coimbatore, a minor increase in monsoon season months was observed compared to the summer season. Southwestern coastal cities consistently depict a highly significant rise during all three months of the summer season (Fig. 2). The highest increase of more than 3.5 °C was noticed at Kozhikode, followed by Mangalore and Panaji (above 2 °C). The city of Thiruvananthapuram depicted a moderate but significant increase, less than 2 °C (Fig. 4). Cochin was the only city, which remained thermally comfortable during the summer season, but during the monsoon season, all the months depicted a significant increase in heat stress (Fig. 3). Though Kozhikode experienced the highest considerable increase in monsoon season, invariably, all the cities along the southwest coastline experienced a significant increase in thermal stress above 2 °C, seldom reaching 4 °C in mid monsoon months (Fig. 4). Among cities along the southeast coast, Chennai has experienced the highest increase in heat stress (above 3 °C). The highest absolute increase was observed in July (4.3 °C). Overall, cities in this cluster were highly vulnerable to the rise in thermal heat stress.

The cities towards the northeast of cluster 5 situated along the central part of the eastern coastline form cluster 6 (Fig. 1). These stations remained comparatively thermally comfortable over the study period. The trend analysis results do not depict a significant increase in the summer season except for Machilipatnam (more than 2 °C). The highest increase in this cluster for both seasons was also noticed at Machilipatnam in April (3.0 °C). During the monsoon season, Kakinada and Vishakhapatnam witnessed a significant increase in heat stress during July. Except for Kakinada, at the other three stations, the end months of the monsoon season showed a moderate but significant increase in heat stress (Fig. 3).

The cities located in the northern central part of the study area, namely Nagpur, Bhopal Jabalpur, and Ambikapur, had comfortable commencement of the summer season. March either registered a decreasing trend in heat stress or a slight unnoticeable increase (Fig. 2). But, at Bhopal, April and May depicted an absolute rise of more than 2 °C. Nagpur, a station near the tropic of cancer, had a conspicuous increase in May (3.9 °C) while March and April showed a decreasing trend and a slight meager increase. A significant increasing trend continued in both these cities during June, and later, thermal discomfort increased significantly during the end of the monsoon season. At Ambikapur, July and August showed a modest statistically significant increase in heat stress. This cluster of cities was most thermally comfortable among all the clusters identified during the analysis.

3.2 Change-point detection

The SQ–MK test was applied to detect the probable year of initiation or prominent change point in temporal trends. The result of the SQ–MK test further elaborates temporal patterns, as analysis identifies approximate years for commencement of significant trends. The results of the SQ–MK test are presented in Table 1.

In cluster 1, no prominent year of change was identified for the summer season, except at Ratnagiri significant decrease during May initiated later in 1989 and surpassed a negative significance level in 1999. During monsoon season, a change point was detected at Rajkot and Ahmedabad in 1981 June and 1977 August, respectively, surpassing a positive significance level in the late 1990s. In cluster 2, cities that depicted a significant increase in heat stress show the commencement of the trend during the late 1990s in the summer season (Table 1). Particularly at Aurangabad, a significant increasing trend initiated later in 1995. This pattern continued for the monsoon season, as the early 1990s marked the beginning of a substantial increase (Table 1). Though a significant increase in summer was observed during the 1990s, the month of May was an exception, with three large metropolitan cities, Mumbai, Pune, and Hyderabad depicted the early initiation of an increasing trend in the 1980s. In monsoon season during June, the early 1990s marked the beginning of a significant increasing trend. In Mumbai and Parbhani, rising heat stress was a recent phenomenon that commenced in 2009 and 2012. For July, the rising trend in thermal stress was triggered recently in the cities within this cluster (Table 1). End months of monsoon were peculiarly thermally uncomfortable for this cluster. Almost all the cities depicted the initiation of a significant trend in the latter halves of the 1990s. Still, in certain semi-arid cities, a rise in heat stress was a recent phenomenon during the August month, while in September, Mumbai and Pune depicted late commencement of heat stress trends (Table 1). At Cuddalore, a city located in cluster 3, from May onwards till July beginning of a significant increase, was identified recently. During the late monsoon $U(t)$ and $U'(t)$ series converge and mark the commencement of a significant trend in the late 1980s, while in other cities in this cluster late 1990s and the decade of 2000 marked the beginning of an increasing trend.

In cluster 4, cities located in the northeastern part of the study area, during the summer season, a significant rise in heat stress was triggered recently in the decade 2000 at Bhubaneswar. In May, cities in this cluster noticed the initiation of the significant increasing trend in the mid-1990s. For the monsoon season during June, a significant increase in heat stress was initiated recently. In July, the change point was identified at all the stations. However, the approximate period of significant increasing trend differs. For Bhubaneswar and Ranchi (mid-2000), Kolkata and Sambalpur marked an increase in the 1990s onwards, while at Jharsaguda, early commencement of heat stress was observed (1975).

Similarly, Sambalpur marked the early beginning of increasing heat stress during August and September (1986–1987). Cluster 5 is the largest group of cities situated over the southern tip of peninsular India. Among the cities over the southeastern coast of peninsular India, Chennai depicted an increasing trend in the 1990s during the summer months except for May. However, at Salem, a significant increase in heat stress was triggered during the late 1980s. In western coastal cities, heat stress increased in the late 1990s except for Panaji, wherein an increase in heat stress was a recent phenomenon (Table 1). Though in April, a positive significance level transversed recently at western coastal stations, but in May, rising heat stress triggered much earlier in the 1970s and 1980s in majority of the cases. During monsoon season, in most western coastal cities, increasing heat stress commenced in the late 1990s and early years of 2000. At Cochin, a moderate rise was observed in thermal stress, which invariably initiated in the decade of 2000 during all monsoon months except September. In June, a significant rise in thermal discomfort was triggered recently for the cities located along the east coast. For the rest of the monsoon months, heat stress invariably initiated in the 1990s (Table 1). The remaining cities of clusters 6 and 7 SQ–MK test identified significant trends in a few cities. Machillipatnam marked an increasing trend in the late 1990s and surpassed a significant level in the early years of 2000 in the summer season. For cluster 6 cities increase in heat stress was a recent phenomenon in July and August. However, in September for all the stations in this cluster, the late 1990s marked the beginning of a significant increase (Table 1). In cluster 7, during monsoon months, heat stress increased in the late 1980s except at Nagpur and Ambikapur, where initial months noted an increase over recent decades.

Table 1 Results of Sequential Mann Kendall (SQ–MK) test depicting cluster wise approximate year of the change point for the selected cities during summer and monsoon season months

Cities/clusters	Summer season			Monsoon season			
	March	April	May	June	July	August	September
Cluster 1							
Ahmedabad						1977, 2000	
Indore							
Ozar							
Rajkot				1981, 1990			
Ratnagiri			1989, 1999				
Surat							
Cluster 2							
Aurangabad	1995, 1999	1995	1996	1994	1992, 2002	1995	1993
Belagavi						1992, 2000	1995
Hyderabad		1999	1984, 2001	1992	2004	1992, 2001	1985, 2000
Mumbai			1980	2009		1998	2009
Pune			1978, 1991			2011	2008
Solapur					1995, 2009	1995	1999, 2002
Kalaburagi	1991, 2001	2001	1994	1991		2003	
Kurnool				1992		1995	
Parbhani				2012		2008	1984, 1986
Cluster 3							
Bengaluru						1994, 2005	1997, 2010
Cuddalore			2009	2008	2001	1986	1989
Cuddapah						2000	1997
Cluster 4							
Bhubaneswar		2010	2004	2010	2005		2000
Kolkata			1995	1995, 2002	1997	1998	2010
Ranchi				2011	2003	1993	2010
Jharsuguda			1994		1975	1997	2004
Sambalpur		1993, 1997	1997		1999	1986	1987
Cluster 5							
Chennai	1993, 1997	1997, 2011	2006	2005	1990	1992	2008
Cochin				2003	2001	2006	1997
Kozhikode	1997	2001	1989	1994	2000	1996	1998
Madurai			2009	1998	1996	2003	2004
Mangalore	1996	1989, 2003	1977, 1990	1997	2002	1995	1990
Panaji	2009	2002	1990	2003		1998	1994
Thiruvananthapuram	1997	1978, 2013	1979, 2010	2005	2001	1997	1992
Tiruchirappalli	1996		1994	1994, 2002	1998	1995	
Coimbatore				1995	1998	2002	
Salem	1988	1979, 1987	1987	1986, 2000	1997		1990, 1993
Cluster 6							
Kakinada					1996, 2006		
Visakhapatnam					2002		1998, 2001
Machilipatnam	1998	1999, 2003	1995, 2001			2004	1995
Jagdalpur		2009				2010	1986, 1995
Cluster 7							
Nagpur			2006	2006		1988	1986
Bhopal		2002	2001	1981, 1992			
Jabalpur							

Table 1 (continued)

Cities/clusters	Summer season			Monsoon season			
	March	April	May	June	July	August	September
Ambikapur					2010	1986, 1995	

Similarly, in summer at Bhopal, rising heat stress commenced over recent decades. Most cities in the last two clusters do not depict a consistent period of significant change in heat stress trends. Still, in a few prominent cities, the approximate period of transition was identified.

4 Discussion

The hierarchical cluster analysis technique applied to the monthly magnitude of trends has proved helpful in imposing a characteristic spatial structure by partitioning and grouping the cities within various clusters for distinctly identifying areas of variable trends in heat stress in selected cities. Accordingly, cities in cluster 4 located in the northeastern part of the study area and cluster 5 embracing cities situated over the southern tip of peninsular India depicted a marked significant increase in heat stress, particularly during monsoon season months. Most of the southeastern cities in cluster 5 receive most rainfall during NEM, while SWM provides scanty rainfall with prolonged intermittent breaks. Besides these two clusters, specific cluster 2 cities experiencing semi-arid climatic conditions are highly susceptible to building heat stress from May onwards until the end of the monsoon season. Spatio-temporal trends draw attention to steadily intensifying heat stress conditions over developing urban centers of India towards the culmination of the monsoon season. Increasing patterns were variable in magnitude; cities of the southern and northeastern parts of the study area are highly vulnerable with a consistent increase above 2 °C and seldom rise of more than 4 °C. In contrast, the magnitude of a significant increase in the rest of the cities was comparatively modest. The towns located in northwestern (cluster 1), north-central (cluster 7), and southeastern coast (cluster 6) do not depict a noteworthy increasing trend in heat stress. The result of change-point detection describes that the rising trend in heat stress is a recent phenomenon at most stations and initiated in a decade of the 1990s or during the early decade of 2000. Incidences of early initiation in heat stress (the 1980s) were peculiar to May and a few cities towards the end month of monsoon (September). Analysis ascertains that the month of August is highly vulnerable to building heat stress, the majority of cities depict a significant increase in this month, while in terms of the magnitude of the rise, both May and August were highly susceptible to rising thermal discomfort.

5 Conclusion

The present study infers that most of the prominent cities of southern India and the northeastern part of the study area depict increasing heat index trends during the summer and monsoon season months. These regions represented by clusters 4 and 5 comprise leading metropolitan cities sustaining considerably huge populations like Kolkata (cluster 4) and Chennai (cluster 5). It is crucial to note that, irrespective of cluster adherence, most of the emerging urban centers were experiencing a significant increase in heat stress during the study period. In these thriving urban centers, timely appraisal of increasing thermal discomfort can be resolved through appropriate urban planning for developing timely resilience to rising heat stress. It can be inferred that for the study period considered, heat stress conditions get worse in the transition period of summer and monsoon season and during the retreating monsoon phase over most parts of India. The change point detection marked the 1990s and 2000 for significant initiation of soaring heat stress. The heat index provides vulnerability mapping for the region concerned. However, it was observed that the heat index shows a marked increase in certain coastal cities due to high humidity, namely Mangalore, Panaji, Thiruvananthapuram, and Kozhikode on the western coast, and Kolkata, Machilipatnam, and Madurai in the east. This was observed to be a significant shortcoming of HI, that it inflates heat stress values for coastal areas. Thus, HI might have overstated heat stress conditions in the case of the above cities. The addition of ambient wind conditions to the HI as an input component may provide better results, particularly for coastal locations. Another major shortcoming of HI, which forms an essential determinant for the tropics, is radiative heat which has not been given due consideration in HI formulation. The radiative component can be incorporated by the input of black globe temperature for which long-term daily records are not available. An ambient object's radiation and heat emission are duly represented by mean radiant temperature (Tmrt). However, HI ignores this component. Thresholds for HI need to be reformulated for tropical regions as present thresholds are a mere adaptation used in temperate regions. Hence it has been almost essential to develop and set the threshold regionally, which demands an extensive region-specific meso, even microscale approach. While empirically tested and widely used heat stress indices, like 'heat index', provides a requisite alert for heat stress vulnerability mapping for regions with distinct climatic and geographical conditions. The impact of climate variability on human health cannot be ignored. Developing heat stress over recent years is a concern as it has an adverse impact on human health, occupational productive capacity, and growing cooling energy demand. The rise in human thermal discomfort is a clamant issue, and increasing heat stress must be dealt with regional mitigation strategies. Developing an indigenous thermal discomfort index for the tropical climate of India and its peculiar socio-economic conditions is essential. The present study is a modest attempt to depict the increasing vulnerability of India's urban population and demands the urgency for dealing with heat stress adversities.

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