Meteorology and Atmospheric Physics (2022) 134:61
https://doi.org/10.1007/s00703-022-00897-3

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]

Received: 6 June 2020 / Accepted: 29 April 2022

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

Published online: 14 June 2022

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

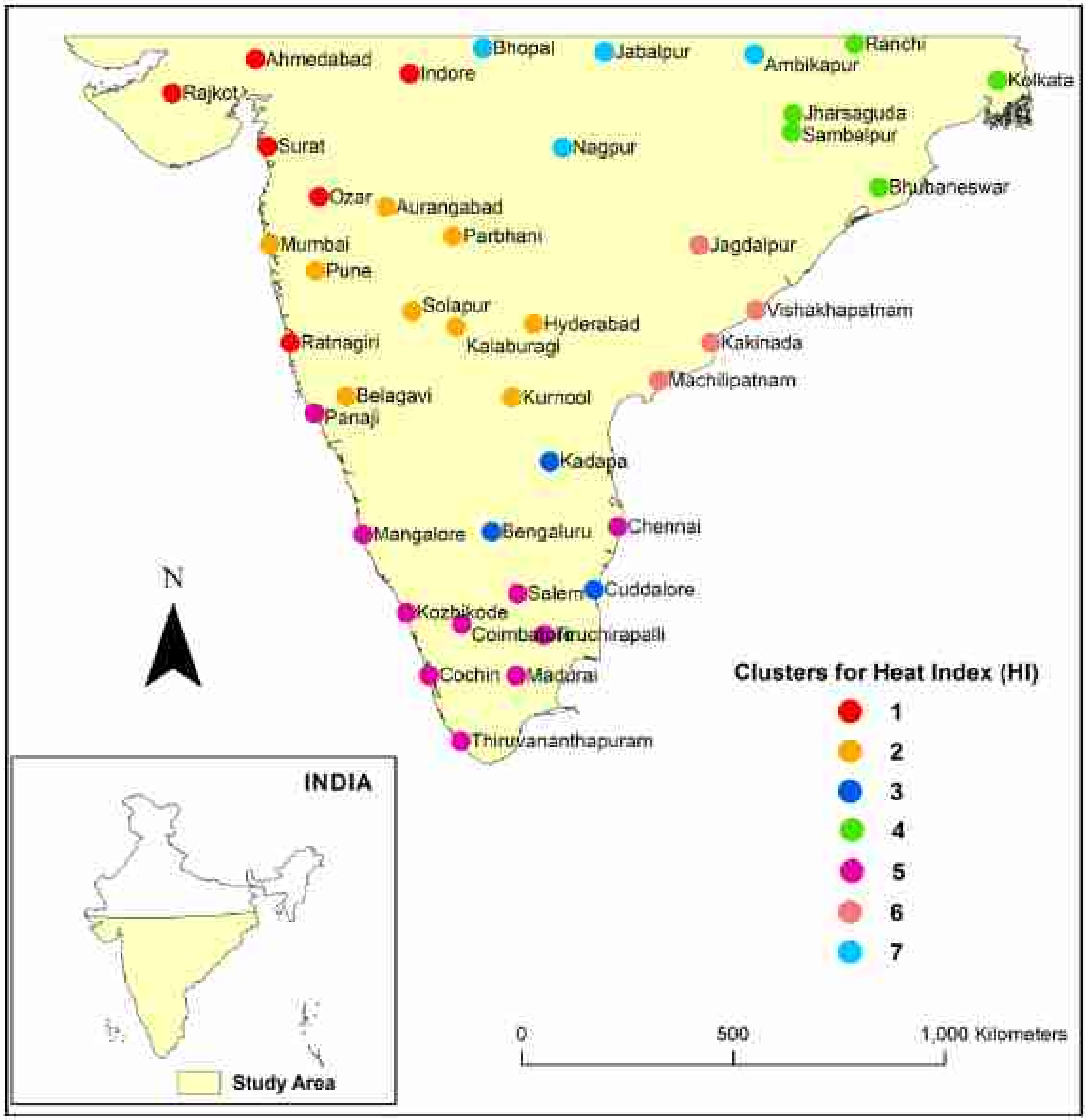


Fig. 1 Location of stations and clusters identified

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

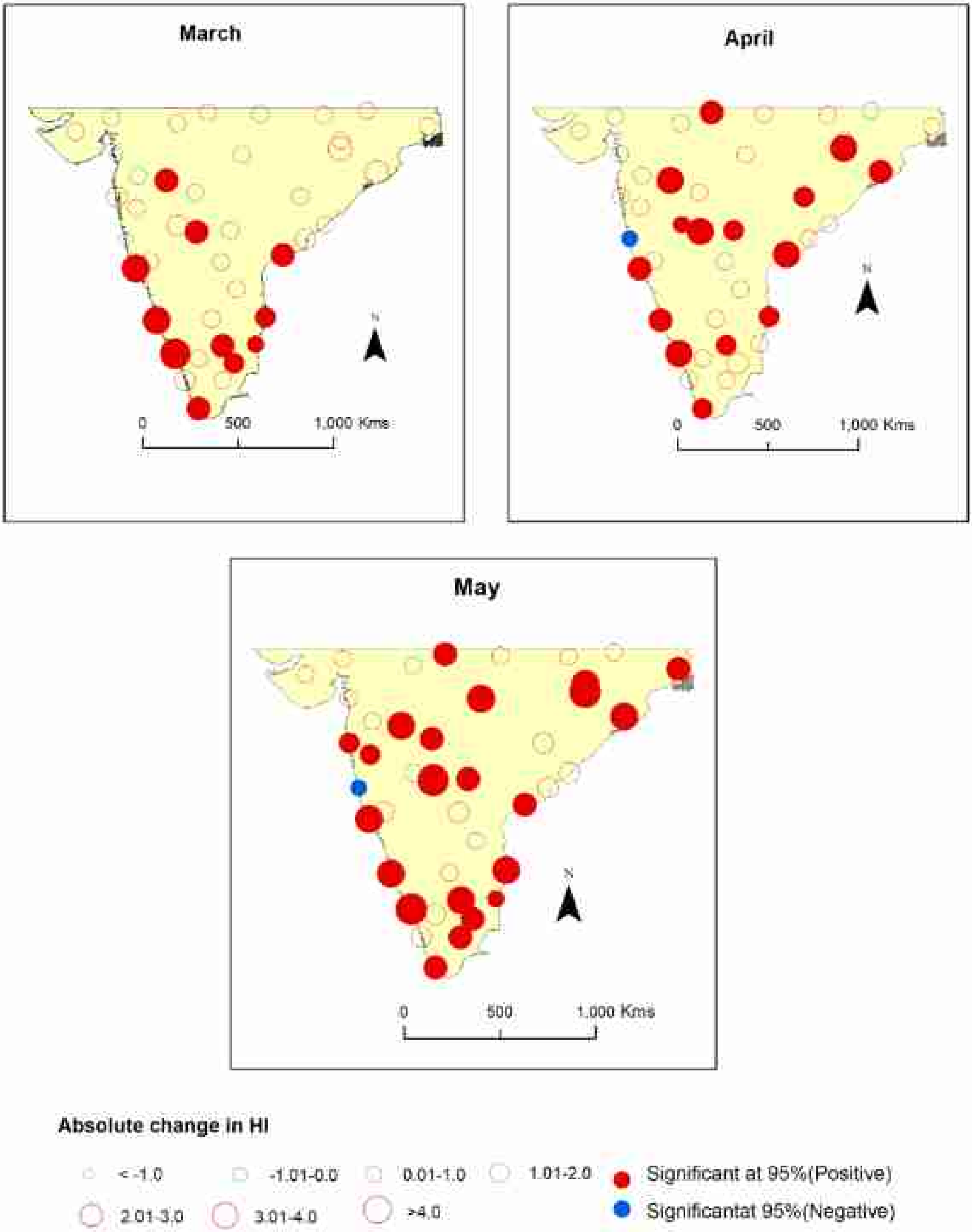


Fig. 2 Absolute change in HI (obtained by linear regression model) for summer season months during the period 1969–2015 (*HI values are in degree celsius*)

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

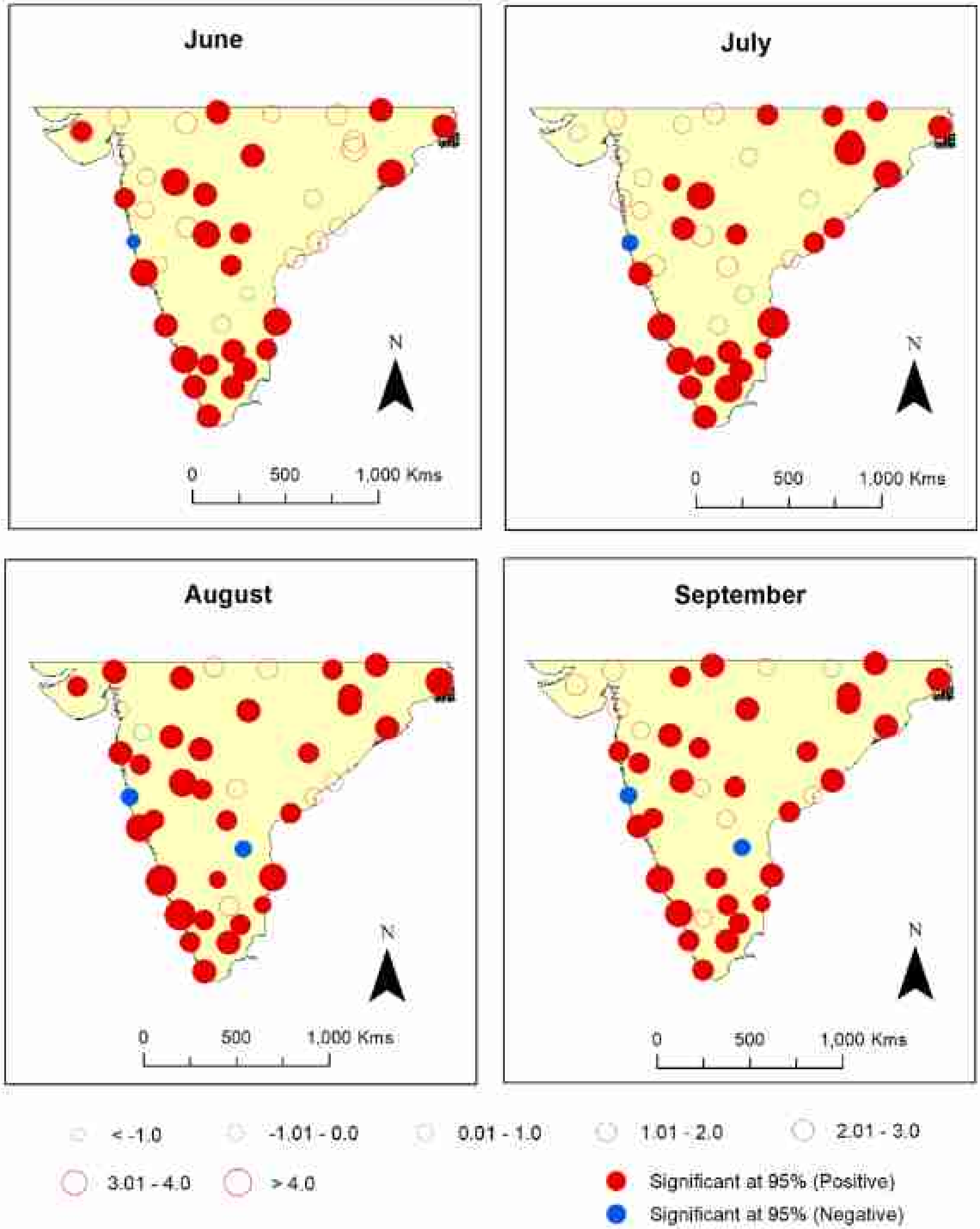


Fig. 3 Absolute change in HI (obtained by linear regression model) for monsoon season months during the period 1969–2015 (*HI values are in degree celsius*)

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,

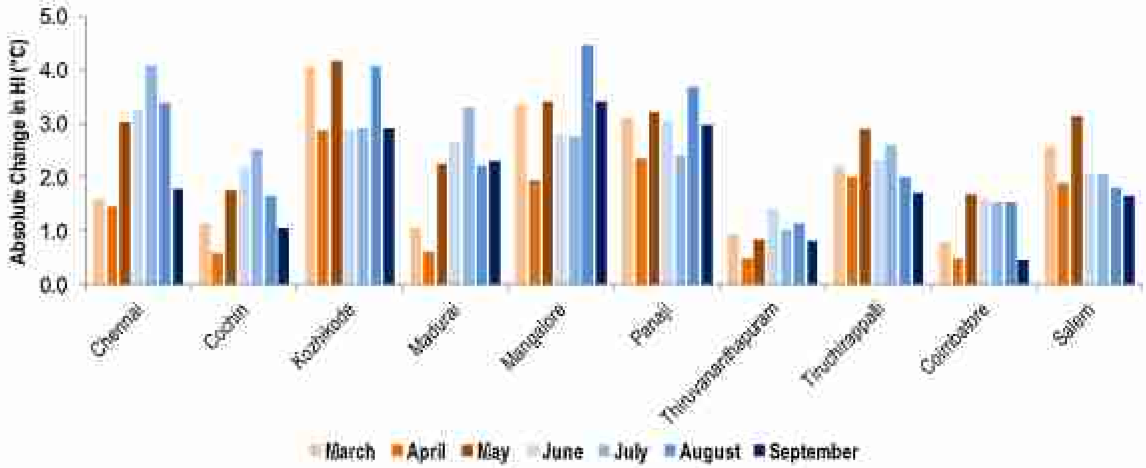


Fig. 4 Absolute increase in HI for the cluster 5 cities in accordance with Theil-Sen Approach

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.

Acknowledgements The research is funded by the Council of Scientific and Industrial Research (CSIR), New Delhi, India. The authors also express their gratitude towards the anonymous reviewers for their suggestions, which helped to improve this manuscript's quality.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

Anderson GB, Bell ML, Peng RD (2013) Methods to calculate the heat index as an exposure metric in environmental health research. Environ Health Perspect 121(10):1111–1119

Antonopoulos VZ, Papamichail DM, Mitsiou KA (2001) Statistical and trend analysis of water quality and quantity data for the Strymon River in Greece. Hydrol Earth Syst Sci 5(4):679–691

Arnfield JA (2003) Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. Int J Climatol 23(1):1–26. https://doi.org/10.1002/joc.859

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds) (2008) Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change (IPCC) Secretariat, Geneva, 210

Bernard TE, Pourmoghani M (1999) Prediction of workplace wet bulb global temperature. Appl Occup Environ Hyg 14:126–134. https://doi.org/10.1080/104732299303296

Chattopadhyay S, Edwards DR (2016) Long-term trend analysis of precipitation and air temperature for Kentucky, United States. Climate 4(10):1–15. https://doi.org/10.3390/cli4010010

Cormack RM (1971) A review of classification. J R Stat Soc 134(3):321–367

Dai A (2006) Recent climatology, variability, and trends in global surface humidity. J Clim 19:3589–3606. https://doi.org/10.1175/JCLI3816.1

Dash SK, Jenamani RK, Kalsi SR, Panda SK (2007) Some evidence of climate change in twentieth-century India. Clim Change 85:299–321. https://doi.org/10.1007/s10584-007-9305-9

De US, Rao GSP (2004) Urban climate trends—the Indian scenario. J Indian Geophys Union 8(3):199–203

De US, Dube RK, Rao GSP (2005) Extreme weather events over India in the last 100 years. J Indian Geophys Union 9(3):173–187

Diffenbaugh NS, Pal JS, Giorgi F, Gao X (2007) Heat stress intensification in the Mediterranean climate change hotspot. Geophys Res Lett 34:1–6. https://doi.org/10.1029/2007GL030000

Dunne JP, Stouffer RJ, John JG (2013) Reductions in labor capacity from heat stress under climate warming. Nat Clim Chang 3(4):1–4. https://doi.org/10.1038/nclimate1827

Gadgil A, Dhorde A (2005) Temperature trends in twentieth-century at Pune, India. Atmos Environ 39(35):6550–6556. https://doi.org/10.1016/j.AtmosEnviron.2005.07.032

Glazer JL (2005) Management of heatstroke and heat exhaustion. Am Fam Physician 71(11):2133–2142

Gong X, Richman MB (1995) On the application of cluster analysis to growing season precipitation data in North America east of the Rockies. J Clim 8:897–931

Gosling SN, Lowe JA, McGregor GR, Pelling M, Malamud BD (2009) Associations between elevated atmospheric temperature and human mortality: a critical review of the literature. Clim Change 92(3–4):299–341

Harlan SL, Chowell G, Yang S, Petitti DB, Butler EJM, Ruddell BL, Ruddell DM (2014) Heat-related deaths in hot cities: estimates of human tolerance to high-temperature thresholds. Int J Environ Res Public Health 11:3304–3326. https://doi.org/10.3390/ijerph110303304

Hijioka YE, Linn JJ, Pereira RT, Corlett X, Cui GE, Insarov RD, Lasco E, Lindgren, Surjan A (2014) Asia. In: Climate Change 2014: Impacts adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros VR, Field CB, DJ Dokken, MD Mastrandrea, KJ Mach, TE Bilir, M Chatterjee, KL Ebi, YO Estrada, RC Genova, B Girma, ES Kissel, AN Levy, S MacCracken, PR Mastrandrea, and LL White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA:1327–1370

Hirsch RM, Slack JR, Smith RA (1982) Techniques of trend analysis for monthly water quality data. Water Resour Res 18:107–121. https://doi.org/10.1029/WR018i001p00107

IPCC (2012) Managing the risk of extreme events and disasters to advance climate change adaptation. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner GK, Allen SK, Tignor M, Midgley PM (eds) A special report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 582

Iheanacho I (2014) Can the USA National Weather Service heat index substitute for Wet Bulb Globe Temperature for heat stress exposure assessment? Graduate thesis and dissertation. The University of South Florida. http://scholarcommons.usf.edu/etd/5244 Accessed 16 Aug 2017

IPCC (2013) Summary for policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Jaswal AK, Padmakumari B, Kumar N, Kore PA (2017) Increasing trend in temperature and moisture induced heat index and its effect on human health in climate change scenario over the Indian subcontinent. J Clim Change 3:11–25

Karpouzos DK, Kavalieratou S, Babajimopoulos C (2010) Trend analysis of precipitation data in Pieria Region (Greece). Eur Water 30:31–40

Kjellstrom T, Holmer I, Lemke B (2009) Workplace heat stress, health and productivity-an increasing challenge for low and middle-income countries during climate change. Glob Health Action 2:1–6. https://doi.org/10.3402/gha.v2i0.2047

Kleerekoper L, Van Esch M, Salcedo TB (2012) How to make a city climate-proof, addressing the urban heat island effect. Resour Conserv Recycl 64:30–38. https://doi.org/10.1016/j.resconrec.2011.06.004
Kovats S, Akhtar R (2008) Climate, climate change, and human health in Asian cities. Environ Urban 20(1):165–175. https://doi.org/10.1177/0956247808089154
Lemke B, Kjellstrom T (2012) Calculating workplace WBGT from meteorological data: a tool for climate change assessment. Ind Health 50:267–278. https://doi.org/10.2486/indhealth.MS1352
Maloney SK, Forbes CF (2011) What effect will a few degrees of climate change have on human heat balance? Implications for human activity. Int J Biometeorol 55:147–160. https://doi.org/10.1007/s00484-010-0320-6
Michelozzi P, Accetta G, De Sario M, D'Ippoliti D, Marino C, Baccini M, Biggeri A, Anderson HR, Katsouyanni K, Ballester F, Bisanti L, Cadum E, Forsberg B, Forastiere F, Goodman PG, Hojs A, Kirchmayer U, Medina S, Paldy A, Schindler C, Sunyer J, Perucci CA (2009) High temperature and hospitalizations for cardiovascular and respiratory causes in 12 European cities. Am J Respir Crit Care Med 179:383–389. https://doi.org/10.1164/rccm.200802-217OC
Mohan M, Gupta A, Bhati S (2014) A modified approach to analyze thermal comfort classification. Atmos Clim Sci 4:7–19
Mooi E, Sarstedt M (2011) A concise guide to market research. Springer-Verlag, Berlin. https://doi.org/10.1007/978-3-642-12541-6_9
Pai DS, Nair SA, Ramanathan AN (2013) Long-term climatology trends of heat waves over India during the recent 50 years (1961–2010). Mausam 64(4):585–604
Partal T, Kahya E (2006) Trend analysis in Turkish precipitation data. Hydrol Process 20:2011–2026
Rajib MA, Mortuza MR, Selmi S, Ankur AK, Rahman MM (2011) Increase of heat index over Bangladesh: Impact of climate change. World Acad Sci Technol 58:402–405
Raju BMK, Rao KV, Venkateswarlu B, Rao AVMS, Rama Rao CA, Rao VUM, Bapuji Rao B, Ravi Kumar N, Dhakar R, Swapna N, Latha P (2013) Revisiting climatic classification in India: a district-level analysis. Curr Sci 105(4):492–495
Robinson PJ (2001) On the definition of a heatwave. J Appl Meteorol 40:762–775
Rohini P, Rajeevan M, Srivastava AK (2016) On the variability and increasing trends of heat waves over India. Sci Rep 6:26153. https://doi.org/10.1038/srep26153
Rothfusz LP (1990) The heat index equation (or, more than you ever wanted to know about heat index). Technical Attachment SR/SSD 90-23 National weather Service Office S. Reg Headquarters, Forth Worth
Safari B (2012) Trend analysis of the mean annual temperature in Rwanda during the last fifty-two years. J Environ Protection 3:538–551
Smoyer KE, Rainham DGC, Hewko JN (2000) Heat-stress-related mortality in five cities in Southern Ontario:1980–1996. Int J Biometeorol 44:190–197
Sneyers S (1990) On the statistical analysis of series of observations. Technical note no. 143 WMO No. 725 415 Secretariat of the World Meteorological Organization Geneva 192
Steadman RG (1979) The assessment of sultriness. Part I: a temperature-humidity index based on human physiology and clothing science. J Appl Meteorol 18:861–873
Steadman RG (1984) A universal scale of apparent temperature. J Clim Appl Meteorol 23:1674–1687
Trenberth KE, Fasullo J, Smith L (2005) Trends and variability in column-integrated atmospheric water vapor. Clim Dyn 24:741–758. https://doi.org/10.1007/s00382-005-0017-4
Unger J (1999) Comparisons of urban and rural bioclimatological conditions in the case of a central-European city. Int J Biometeorol 43:139–144. https://doi.org/10.1007/s004840050129
Willett KM, Jones PD, Gillett NP, Thorne PW (2008) Recent changes in surface humidity: development of the HadCRUH dataset. J Clim 21:5364–5383. https://doi.org/10.1175/2008JCLI2274.1
Zahid M, Rasul G (2012) Rise in summer heat index over Pakistan. Pakistan J Meteorol 6(12):85–96
Zander KK, Botzen WJ, Oppermann E, Kjellstrom T, Garnett ST (2015) Heat stress causes substantial labor productivity loss in Australia. Nat Clim Chang 5(7):647–651
Zarenistanak M, Dhorde AG, Kripalani RH (2014) Trend analysis and change point detection of annual and seasonal precipitation and temperature series over southwest Iran. J Earth Syst Sci 123(2):281–295
Zhao G, Hörmann G, Fohrer N, Zhang Z, Zhai J (2010) Streamflow trends and climate variability impacts in Poyang lake basin, China. Water Resour Manag 24:689–706. https://doi.org/10.1007/s11269-009-9465-7

MAUSAM, **72**, 4 (October 2021), 915-934

551.524 : 551.584.5 (540)

Evolution of Heat Index (HI) and Physiological Equivalent Temperature (PET) Index at Mumbai and Pune Cities, India

MANASI DESAI, ASHISH NAVALE* and AMIT G. DHORDE*

Department of Geography, Symbiosis College of Arts and Commerce, Pune – 411 004, India

**Department of Geography, Savitribai Phule Pune University, Pune – 411 007, India*

(*Received 27 September 2019, Accepted 23 August 2021*)

e mail : amitdhorde@unipune.ac.in

सार – वर्तमान अध्ययन में, अनुभवजन्य रूप से व्युत्पन्न हीट इंडेक्स (एचआई) और तर्कसंगत गर्मी संतुलन आधारित शारीरिक समकक्ष के आवेदन के साथ 1969 से 2015 तक 47 वर्षों की अवधि के लिए दो शहरों, पुणे और मुंबई के लिए गर्मी और मानसून के मौसम के महीनों के दौरान गर्मी के तनाव के रुझानों का आकलन किया गया था। तापमान (पीईटी) सूचकांक। गर्मी के तनाव की घटनाओं में बदलाव के लिए जिम्मेदार मौसम संबंधी मापदंडों के योगदान को निर्धारित करने के लिए एक चरणबद्ध बहु प्रतिगमन विश्लेषण लागू किया गया था। अध्ययन से पता चलता है कि पुणे शहर की तुलना में मुंबई में गर्मी के महीनों के दौरान गर्मी के तनाव में काफी वृद्धि हुई है। इसी तरह, मानसून के मौसम के अंतिम महीनों के दौरान, सांख्यिकीय रूप से महत्वपूर्ण बढ़ती प्रवृत्तियों के साथ, दोनों शहरों में थर्मल असुविधा की स्थिति बढ़ जाती है। हीट इंडेक्स के अनुसार अध्ययन अवधि के दौरान थर्मली असुविधाजनक दिनों की वास्तविक पहचान और वर्गीकरण मध्यम था। वे गर्मियों के दौरान पुणे में लगातार बने रहे, हालांकि, मानसून में, गर्मी के तनाव की घटनाएं कम थीं। जबकि मुंबई में 'उच्च' और 'बहुत अधिक' के साथ, हाल के वर्षों में गर्मी के तनाव में वृद्धि हुई है। पीईटी सूचकांक के अनुसार वर्गीकरण ने पुणे में 'मजबूत' और 'अत्यधिक गर्मी के तनाव' की विशिष्ट उपस्थिति को दर्शाया, जबकि मुंबई में, 'गर्म' और 'गर्म' दिनों में मामूली वृद्धि को दर्शाया गया। मौसम संबंधी मापदंडों के आकलन ने दर्शाया कि बढ़ी हुई आर्द्रता और तापमान मुंबई में गर्मी के बढ़ते दबाव के लिए मुख्य चिंता का विषय है। इसके विपरीत, औसत उज्ज्वल तापमान, प्रतिबंधित हवा की गति के साथ परिवेशी वायु तापमान, जिससे उच्च संवेदनशील गर्मी होती है, पीईटी में महत्वपूर्ण वृद्धि की प्रवृत्ति के लिए जिम्मेदार हो सकती है। अध्ययन से पता चलता है कि दोनों शहर बढ़ते गर्मी के तनाव की चपेट में हैं और शहरवासियों के स्वास्थ्य पर प्रतिकूल प्रभाव पड़ सकता है।

ABSTRACT. In the present study, trends in heat stress during summer and monsoon season months were assessed for two cities, Pune and Mumbai, for the period of 47 years from 1969 to2015 with the application of empirically derived Heat Index (HI) and rational heat balance based Physiological Equivalent Temperature (PET) index. A stepwise multiple regression analysis was applied to determine contributing meteorological parameters responsible for changes in heat stress incidences. The study reveals a considerable increase in heat stress during the summer months over Mumbai compared to Pune city. Similarly, during the end months of monsoon season, thermal discomfort conditions aggravate over both the cities, with statistically significant rising trends. The actual identification and categorization of thermally discomfortable days during the study period in accordance with the Heat Index were moderate. They remained consistent in Pune during summer, however, in monsoon, heat stress incidences were meager. While at Mumbai days with 'High' and 'Very High,' heat stress have increased towards recent years. Categorization according to PET index depicted conspicuous presence of 'Strong' and 'Extreme heat stress' at Pune, while at Mumbai, 'Warm' and 'Hot' days portrayeda slight increase. The assessment of meteorological parameters depicted that increased humidity and temperature were the main concern for the increase in heat stress over Mumbai. In contrast, mean radiant temperature, ambient air temperature with restricted wind speed leading to high sensible heat may be responsible for the significant increasing trend in PET. The study infers that both the cities are vulnerable to escalating heat stress and may have adverse implications on the health of city dwellers.

Key words – Heat Index, Physiological Equivalent Temperature, Thermal discomfort, Temporal trends, Mumbai, Pune.

1. Introduction

The period from 1983 to 2012 was the warmest 30-year period of the last 1400 years for the Northern Hemisphere (IPCC, 2014a). On global scale, both frequency and magnitude of warm daily temperature extremes have increased with an apparent decrease in cold extremes. Similarly, the length of warm spells or heat waves has increased since the middle of the 20^{th} century. According to IPCC's Fifth Assessment Report: for South Asia (IPCC, 2014b), the number of warm days and nights have increased since 1950 in Asia, and the heatwave frequency has increased since the middle of the 20^{th} century in large part of Asia. In India, several studies reported temperature variability during the last century (Pai *et al*., 2004; De *et al*., 2005; Kothawale and Rupa Kumar 2005; Rao *et al*., 2004; Kothawale *et al*., 2010; Pai *et al*., 2013; Jaswal *et al*., 2015). It was observed that all India mean annual temperature has increased in recent decades (1971-2003), thus denoting substantial acceleration in the warming trend (Kothawale and Rupa Kumar, 2005). Pai *et al*. (2004) studied the increase in frequency, persistency, and spatial coverage of high-frequency temperature extreme events like heat waves.

Rohini *et al*. (2016) signify that extreme temperatures during summers reduce latent heat transfer to the atmosphere and increase sensible heat transfer inducing positive feedback and thus enhancing surface warming. In aggregate, hot weather extremes and recurring heatwaves lead to severe societal hazards and have distinct adverse implications on human health and comfort (Kothawale *et al*., 2010). The observations made by Kothawale *et al*. (2010) for well spread 40 stations of India showed that heatwave incidences are more frequent in May than June, while they are relatively sparse in March and April. Further, spatial analysis shows that over the western coastal region and interior peninsular region, there is a significant increasing trend in hot days. Simultaneously frequency of cold days depicted a significant decreasing trend. Kothawale *et al*. (2016) revealed that urbanization has a vital role in rising temperatures in major cities during the recent period (1971-2013). The study further noted a significant increase in annual mean temperature after 1985. De *et al*. (2005) observed that the diurnal range of temperature has decreased due to urbanization, which fails to neutralize high day-time temperatures during heat epochs leading to human discomfort. Changes in climatic conditions towards successive warming have implications on human health in numerous ways. One of the crucial impacts is in terms of thermal adjustment and adaptability to changing climatic conditions.

The cities are characterized by a peculiar urban microclimatic condition that outwardly augments heat stress risk than their rural counterparts. Thus, irrespective of global climate change, cities alter their climate pertaining to impervious surfaces. In microclimate modified by urban landscape (Arnfield, 2003), attenuated meteorological parameters have higher implications on human thermal comfort (Unger, 1999). Although the advent of urbanization and industrialization led to comfortable urban living conditions, cities create unique microclimatic conditions leading to issues of human adjustment. The rapid growth of industrialization and increase in synthetic materials has led to rise in the temperature of urban regions (Memon *et al*., 2008). Higher atmospheric and surface temperatures in urban areas than in the surrounding rural areas are termedthe urban heat island (UHI) effect (Voogt and Oke, 2003). Urban heat island is characterized by the large expanse of impervious materials, which has a consequent increase in sensible heat flux (Oke, 1982; Owen *et al*., 1998). The UHI effect intensifies due to anthropogenic heat generated by traffic, industry, and congested building structures, which tends to affect energy exchange and conductivity levels (Yuan and Bauer, 2007).

Moreover, the urban areas have sparse vegetation due to its typical land use, exacerbated further by solar radiation stored in urban areas due to massive construction material (Memon *et al*., 2008). A human being is exposed to his surrounding thermal environment directly or indirectly. Climate and weather conditions are determinants of environmental heat stress, affecting efficiency and productivity and may even threaten survival (Epstein and Moran, 2006). Very high or shallow temperatures induce the experience of thermal discomfort as human beings need to maintain thermo homeostasis equilibrium, that is core body temperature needs to be regulated around 37 °C (Auliciems and Szokolay, 2007). The interaction between surrounding thermal environment with the human metabolic processes leads to continuous exchange of bodily heat through conduction, convection, and mainly through perspiration; this helps to preserve body core and skin temperature within sustainable limits. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines; 'Thermal Comfort as the state of mind, which expresses satisfaction with the thermal environment (ASHRAE, 2004)'. The definition emphasizes on subjectivity of thermal sensation unique to every human being, however, to provide generalized effect of thermal sensation on human population several outdoor thermal indices have been devised. The outdoor thermal discomfort indices are broadly categorized as thermal stress model based indices, which study effect of excessive heat on human body in relation to meteorological parameters, while other group comprises of more comprehensive heat budget model of human biometeorology, which takes into account all the mechanisms of heat exchange (Tahbaz and Beheshti, 2010). In tropical hot and humid climate, combined effect of high temperature and sudden increase in moisture with arrival of monsoon, towards culmination of summer season increases sultriness in ambient environment. Warming over several decades has been linked to alteration in the large-scale hydrological cycle such as increase in atmospheric water vapor content in certain areas with simultaneous decrease in others (Bates *et al.*, 2008). Thus, besides temperature, humidity contributes to the feeling of sultriness and essential element to be considered while assessing thermal stress. The population of South Asia is highly vulnerable to heat related mortality; risk further magnifies due to high rate of urbanization and lack of efficient adaptation strategies (Hijioka *et al.*, 2014). Heat stress index allows quantitative assessment of thermal stress and used to determine limit of thermal exposure. The Heat Index (HI) adopted by NOAA is one such index that includes temperature and humidity component, and therefore, is advised for assessment of sultriness emblematic during summer and monsoon months in tropical warm climate at the cities of peninsular India. The heat index is a refinement of a result obtained by multiple regression analysis carried out by Lans P. Rothfusz and described in a 1990 National Weather Service-National Oceanic and Atmospheric Administration (NWS-NOAA), United States of America (USA) (Rothfusz, 1990). In the present study, HI is used by applying necessary adjustments as described by NOAA-NWS (2014). HI is one of the most popular indices for environmental health research as a measure of thermal comfort. It is used for studies related to outdoor temperature exposures and development of synoptic scale heat warning systems (Anderson *et al.*, 2013). Though the index was devised in USA and had been used to evaluate thermal stress conditions for USA (Robinson, 2000; Glazer, 2005) it has been widely applied worldwide (Michelozzi *et al.*, 2009; Diffenbaugh *et al.*, 2007). Zahid and Rasul (2012) used HI for identifying regions in Pakistan vulnerable to heat stroke during summer season. Therefore HI had been applied earlier to assess heat stress conditions in Indian subcontinent region. For India Mohan *et al.* (2014) with the application of HI, studied thermal comfort conditions of five metropolitan cities and provided relative ranking of the cities on the basis of thermal comfort experienced in each of the five cities. Rajib *et al.* (2011) used heat index for assessing impact of climate change on human thermal comfort, he advocated applicability of HI for the areas having temperature of more than 26 °C and relative humidity usually above 39%. Jaswal *et al.* (2017) applied HI for assessing long-term behaviour of heat stress caused by increasing temperature and moisture over Indian subcontinent for a vast spatial coverage by acquiring data for 283 meteorological stations over the period from 1951 to 2010. The HI index has been recently chosen by India Meteorological Department (IMD) jointly with National Disaster Management Authority (NDMA) on experiment-tal basis for issuing heat wave warning to avoid human fatalities.

However, the complete assessment of outdoor thermal bioclimate considering environmental and human physiological characteristics is possible only through rational indices. The rational indices are based on human heat balance and thus provide comprehensive understanding of thermal stress (Epstein and Moran, 2006; Blazejczyk *et al.*, 2012). The inherent complex nature of urban areas creates unique microclimate conditions. The urban geometry, urban morphological characteristics, street orientation and positioning of buildings as well as urban materials attenuates meteorological parameters (Ahmed, 2003; Steeneveld *et al.*, 2011; Goggins *et al.*, 2012; Alvarez, 2013; Amirtham *et al.*, 2014; Lindberg *et al.*, 2016). Overall high temperature, higher radiation due to high emissivity of urban structures, slower wind speed as a result of high-rise buildings, modified humidity quotient as well as artificial combustion heat are some of the prime effects of urban form on meteorological parameters (Jones *et al.*, 1999; Stone and Rodgers, 2001; Matzarakis *et al.*, 2010). However, there are several difficulties involved in using rational approach of evaluating thermal bioclimate. The initial intricacy arises due to complicated calculation of these indices involving several input elements, such impediments are resolved by progress in computing techniques corresponding to human energy balance assessment required for determining thermal bioclimate by analytical (rational) approach (Hoppe, 1999). The Physiological Equivalent Temperature (PET) is one such rational index that is most widely applied for several climatic conditions as well as serving varied practical thermal bioclimatic assessment needs (Matzarakis *et al.*, 2010). PET has an added advantage because it is obtained in the widely known unit, degree Celsius, which makes it easier to comprehend for urban and regional planners (Matzarakis *et al.*, 1999). PET index is based on the Munich Energy-balance Model for Individuals (MEMI) that describes the thermal bioclimatic conditions in a physiological relevant way (Nastos and Matzarakis, 2013). PET index assessment scale is derived by evaluating Fanger's PMV (Predicted Mean Vote) equations (Van Hoof, 2008) for varying air temperatures with reference to ambient environment for human physiological conditions for a person having following characteristics; height : 1.75m, weight: 75 kg, age: 35 years and sex male with 80 W of light metabolic activity and heat resistance of clothing 0.9 clo (Hoppe, 1999). Gomez *et al.*, (2013) explain that, assumptions of constant values for clothing and metabolic activity for PET index is necessary to keep index independent of any subjectivity arising out of individual behaviour. PET index can be conveniently evaluated through the use of thermal bioclimate computing model, RayMan (Matzarakis *et al.*, 2007). The RayMan model enables the calculation of mean radiant temperature (T_{mrt}) which accounts for short and long wave radiation fluxes and most difficult parameter to compute. The PET is a universal index and evaluates thermal conditions in physiologically significant manner (Matzarakis *et al.*, 1999). PET index considers the outdoor thermal environment in totality accompanying environmental configuration elements such as sky view factor (SVF), vegetation cover, H/W (height/width) ratio in the urban scenario, etc. It is thus widely used in urban micro bio-climate studies (Tsiros *et al.*, 2012).

Presently Universal Thermal Comfort Index (UTCI) has been put forth by a group of over 40 scientists from 23 countries collaborating within COST (European Union program promoting Cooperation in Science and Technology) Action 730 (Brode *et al.*, 2013). The UTCI represents a universal solution to the problem of characterizing the human thermal environment based on the advanced multimode model of human thermoregulation (Morabito *et al.*, 2014). UTCI has universal nature and represents varied bioclimatic conditions (Blazejczyk *et al.*, 2012). However the UTCI index has not been widely used for assessment of heat stress over various climatic regions of the world, thus practical applicability of the index in yet to be validated for tropical climate as well. Pantavou *et al.* (2018) tested thermal sensation threshold for both PET and UTCI in varied climates and showed that average increase in threshold was significant only for PET index. The study by Zare *et al.* (2018) inferred that UTCI has highest correlation coefficient with PET, thus in the present study among both the rational indices PET and UTCI, PET has been used due to its wide applicability over various climates and efficient calculation tool made available through RayMan model. The objective of the present study is to evaluate temporal trends in thermal discomfort by applying Heat Index (HI), which is thermal stress model based index and Physiological Equivalent Temperature (PET) which is heat budget model index. The PET takes into consideration all the relevant meteorological parameters affecting heat exchange between human body and environment. The present research aims at analyzing temporal trends in HI and PET index for Mumbai and Pune for the period of 47 years (1969-2015) during summer and monsoon season. The summer season is characterised by scorching hot weather over the tropical lands. As monsoon approaches, humid hot conditions lead to oppressive muggy climate. These conditions create high thermal discomfort and related heat stress.

1.1. *Study area*

The cities selected for the present study are Mumbai and Pune (Fig. 1), located in Maharashtra, India. Mumbai is a western coastal city known as the economic capital of India, and it is one of the most populated cities of the country (census, 2011). Pune, situated 150 km southeast of Mumbai, acts as a counter magnet for Mumbai city, attracting commercial activities and a working population.

Fig. 1. Location of Mumbai and Pune Cities

According to the 2011 census, the growth rate of Pune is 30.34%. Both the cities have different climatological conditions due to their distinctive geographic location. Mumbai being a coastal city, has a hot and humid climate, while Pune experiences a semi-arid climate due to its continental location.

2. Data and methodology

2.1. *Data procurement*

Daily data for weather parameters, namely dry bulb temperature (DBT), wet bulb temperature (WBT), relative humidity (RH), wind speed (WS) and global radiation (GR), were obtained from IMD for the period 1969 to 2015 for Mumbai (Santacruz) and Pune. Mumbai's (Santacruz) global radiation data has a high number of missing values. Thus, for evaluation of thermal comfort using the PET index, the analysis for Mumbai needed to be limited up to 2010. The data homogeneity of parameters selected was evaluated with robust Standard Normal Homogeneity Test (SNHT) (Alexandersson and Moberg, 1997).

One of the inputs needed for calculating the PET index was sky view photographs. For fulfilling this purpose fish eyelens was used to obtain 180 degrees of sky view for both the meteorological stations of Pune and Mumbai. The camera used was Nikon D5500 and the fish-eye lens used was sigma 8 mm. The camera was mounted on a tripod at the height of 1 meter. The lens captures a 180° view of the entire area. The sky view photographs obtained by fish-eye lens were used to identify radiation conditions when objects such as vegetation canopies or buildings obscure the sky. With this, direct and diffuse solar radiation at a particular point can be calculated by plotting solar path on photographs along with global radiation received at that specific point (Blennow, 1995).

2.2. *Thermal discomfort Indices*

2.2.1. *Heat Index (HI)*

Steadman originally developed the Heat Index (HI), which was later modified by U.S. National Oceanographic and Atmospheric Administration (NOAA) (Rothfusz, 1990). In this index, air temperature and relative humidity are combined to determine actual human perceived temperature, commonly known as apparent temperature. The Heat Index assumes an ideal condition where a person 5'7" tall and weighs 67 kg wearing long trousers and short sleeved shirt with internal body temperature at 37 °C, walking outdoor at the speed of 3.1 mph in light wind of 6 mph (Rothfusz, 1990). The Heat Index is the product of extensive bio-meteorological studies. The parameters used in the equation are expressed in terms of magnitude to simplify and comprehend the model. Thus, the model is reduced to the relationship between DBT and skin's resistance to heat and moisture (Rothfusz, 1990). HI quantifies sultriness and is used as the heat counterpart for the windchill index (Yan & Oliver, 1996). In India, the HI has been applied by Mohan *et al.* (2014) for relative ranking of five metropolitan cities of India and has determined the threshold level for tropical cities of India, which has been used in the present study to determine level of heat stress. Heat Index is mathematically expressed as:

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

where,

HI = Heat Index (°Fahrenhiet)

T = Ambient dry bulb temperature in °F

RH = Relative Humidity in %

In the present study, this index was converted from Fahrenheit to Celsius since Celsius is the standard unit used in India.

2.2.2. *Physiological Equivalent Temperature (PET)*

PET is defined as Physiological Equivalent Temperature at any given place (outdoor or indoor) and is equivalent to the air temperature at which, in a typical indoor setting condition of the heat balance of the human body (work metabolism 80 W of light activity, added to basic metabolism; heat resistance of clothing 0.9 clo) is maintained with core and skin temperatures equal to those under the conditions being assessed (Höppe, 1999). Compared to other indices like Predicted Mean Vote (PMV), PET has an added advantage because it is obtained in the widely known unit degree Celsius, making it easier to comprehend for urban and regional planners (Matzarakis *et al.*, 1999). PET index has been derived from the Munich energy balance model for individuals (MEMI) and enables a thermo-physiological relevant assessment of human thermal conditions. The PET combines the meteorological parameters of the thermal environment with physiological components of the human body such as activity level, age, clothing, etc. (Hoppe, 1999; Muthers *et al.*, 2010). In the present study, PET was evaluated for a standard person (male, age 35 years, body weight 75 kg) engaged in metabolic activity of 80 W (standing person) with clo (clothing) factor of 0.90. The PET index was calculated using RayMan 2.1 version software.

The RayMan model aims to calculate radiation flux densities, sunshine duration, shadow spaces, and thermo-physiologically relevant assessment indices using only a limited number of meteorological and other input data (Matzarakis *et al.*, 2010). In the present study, daily input data feed in RayMan model for calculating PET index were: dry-bulb air temperature (DBT), vapor pressure (VP), relative humidity (RH), wind speed (WS), and global radiation (GR) obtained from IMD for 47 years from 1969 to 2015. The GR for the period considered was uniformly converted in watts per meter square, along with actual meteorological station site locations for Pune and Mumbai (Santacruz) in the form of fish eye photographs to calculate sky view factor (SVF). The GR and SVF were utilized to calculate mean radiant temperature (T_{mrt}), a prerequisite and crucial input parameter for obtaining PET. T_{mrt} is defined as the uniform temperature of a surrounding surface giving off black body radiation, which results in the same radiation energy gain of the human body in prevailing radiation fluxes that usually vary under open space conditions (Matzarakis *et al.*, 2010). The RayMan model simulates short, and long-wave radiation flux densities using GR

TABLE 1

Categories of HI

S. No.	Category	Heat Index
1	Low risk	< 33
2	Moderate risk	33 to 39
3	High risk	39 to 46
4	Very high risk	> 46

TABLE 2

Categories of PET

S. No.	Category	Physiological Equivalent Temperature	Grade of physiological stress
1	Slightly warm	23 to 29	Slight heat stress
2	Warm	29 to 35	Moderate heat stress
3	Hot	35 to 41	Strong heat stress
4	Very hot	> 41	Extreme heat stress

and three-dimensional surroundings in simple and complex environments by calculating SVF from fish-eye images supplied to enumerate T_{mrt}. T_{mrt} is the most significant meteorological input for evalating human energy balance in tropical intense summer conditions. RayMan allows modifications in cloud cover, urban topography and morphologies (Matzarakis *et al.*, 2010), thus considering most of the related components for better evaluation of T_{mrt}. The radiation input in T_{mrt} and those mentioned above meteorological and physiological parameters form vital information for the PET index. The PET is a universal thermal index for characterizing human bioclimate and thus is extensively used for outdoor thermal comfort assessment (Hoppe 1999; Matzarakis *et al.*, 1999; Matzarakis *et al.*, 2007, Matzarakis *et al.*, 2010; Muthers *et al.*, 2010; Kruger *et al.*, 2013; Erell *et al.*, 2014).

2.3. *Statistical techniques*

The daily HI and PET indices calculated were averaged to obtain mean monthly HI and PET for summer season months from March to May and monsoon season months from June to September. Over the mean monthly HI and PET values for each of the seven months, the period of 47 years, a linear regression model for trend analysis was applied to detect a temporal change in thermal discomfort. The magnitude of the trend was determined from the 'b' (slope of the regression line) value, while Student's *t*-test was used to determine the statistical significance.

To determine days with substantial heat stress over the 47 years daily dataset, summer and monsoon season days were categorized according to Table 1 for HI and Table 2 for PET. These categories represent an actual number of heat stress days for each of the 47 years during summer and monsoon seasons. While assessing thermal discomfort for tropical cities in the hot regime, the heat Index categories from moderate to very high risk were considered. In contrast, summer and monsoon season days were categorized from slightly warm to very hot for the PET index. The results obtained were represented through stacked diagrams.

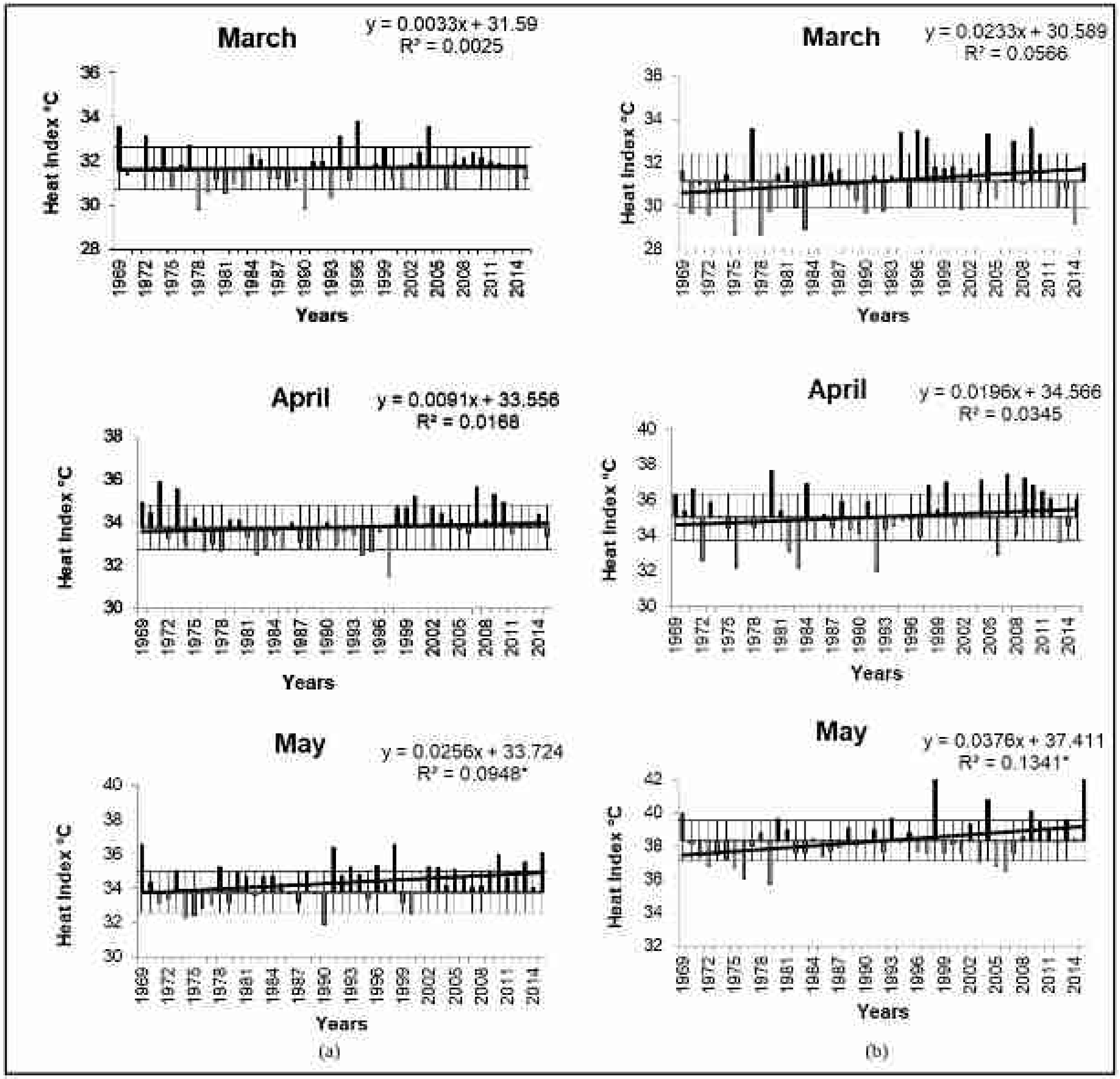
Stepwise multiple regression was applied to evaluate which of the meteorological parameters were closely associated with changes in HI and PET index during summer and monsoon seasons. In the stepwise multiple regression model, HI and PET were dependent variables while DBT, WBT, RH, VP, WS and mean radiant temperature (T_{mrt}) derived from GR were independent variables. Multiple linear regression is an extension of simple linear regression that considers the role of several independent variables in assessing variance in a single dependent variable (Nathans *et al.*, 2012). The stepwise multiple regression was calculated in SPSS 22. The main objective was to identify relevant regressors from the number of possible ones. In stepwise multiple regression, each variable is entered in sequence, and its value is assessed. If the variable added contributes to the model, then it is retained, but all other variables in the model are re-tested to see if they are still contributing to the model's success. If the variables no longer contribute significantly, then they are removed. Thus, this method ensures to end up with the smallest possible relevant predictors (variables). In the present study, relevant meteorological variables responsible for modification in HI and PET during summer and monsoon were identified with the help of multiple stepwise regression.

3. Results and discussion

3.1. *Temporal Trends in Heat Index (HI)*

3.1.1. *Monthly trends in HI during summer and monsoon season*

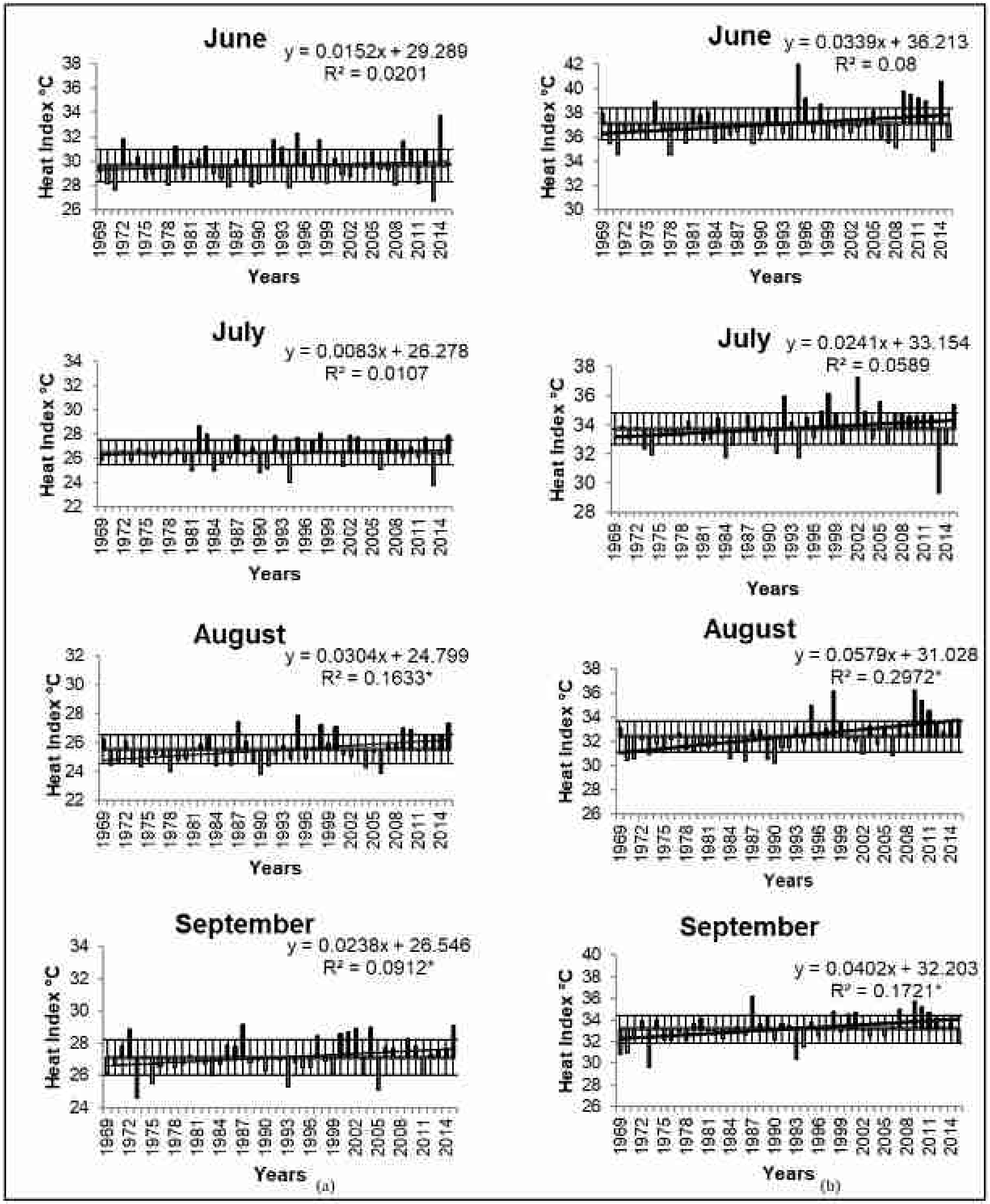
A linear trend was analyzed for 47 years of Heat Index values for summer (March to May) and monsoon (June to September) season months at Pune and Mumbai. For Pune city, in the month of March, the heat stress was near or above the mean for most of the years after 1990. During 1994, 1996 and 2004, the heat stress surpassed +1 standard deviation level [Fig. 2(a)]. In April, which is the hottest month for Pune city, unanimous increasing



Figs. 2(a&b). HI trends during summer at Pune (a) and Mumbai (b). Horizontal lines above and below the mean line represent +1 and -1 standard deviation. Significant trends are and marked with '*.'

tendency above mean was observed later to 1998 except for 2005, 2006 and 2011 to 2013, during which heat stress was below the mean. Fig. 2(a) shows that during May, the heat stress level was above the mean for almost all years from 2002 onwards. The years 1969, 1991, 1998, 2010 and 2015 distinctly stand out with positive anomaly above one standard deviation increase in heat stress. All these years were weak to strong El Nino years and warmest years on the record (NOAA). During the summer months, Pune city registered an increase in heat stress trend during the study period, but only in May, heat stress was statistically significant.

Similarly, in Mumbai significant increasing trend was observed in May [Fig. 2(b)]. At Mumbai, the mean heat stress level for March, April, and May was 31 °C, 35 °C and 38 °C, respectively. According to HI categories (Table 1), moderate heat stress risk initiates at 33 °C, thus during April and May, years portraying heat stress above mean level is undoubtedly vulnerable, as heat stress risk worsened during these years. The year 2010 was particularly susceptible in this sense since it depicted heat stress above the mean level during the whole of the summer season. The year 2010 was also recorded as the fourth warmest year on record (NOAA). During April



Figs. 3(a&b). HI trends during monsoon at Pune (a) and Mumbai (b). Horizontal lines above and below the mean line represent +1 and -1 standard deviation. Significant trends are and marked with '*.'

from 2007 to 2012 except 2008 and 2015 noticed episodes of unusually high heat stress levels, while discrete episodes of high heat stress were observed in the years 1980, 1984, 1998 and 2000.

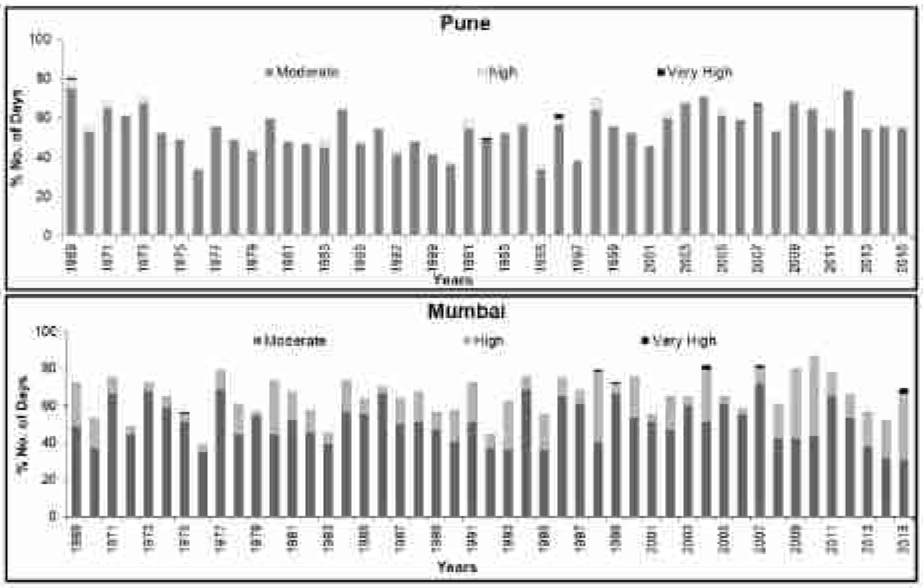


Fig. 4. Number of heat stress days in summer at Pune and Mumbai

Similarly, in May, the above mean pattern was observed, consequent for the year 2000 till 2015, unusually high heat stress incidences in this month were experienced during 1998, 2004 and 2015. Kothawale and Rupa Kumar (2005) had noted an abnormal surge in warming trends over recent decades. This continued warming has been reflected in high heat stress incidences over recent years.

Monsoon heralds intermittent relief from high summer-time temperatures. However, only a few degrees drop in mercury is noticed. Increased air moisture leads to muggy weather conditions. High daytime temperatures contribute to high sensible heat, particularly in urban areas. At the same time, a rise in ambient humidity further augments sultriness due to the restricted dissipation of heat from the human body by suppressing sweat evaporation that acts as an effective cooling mechanism. This phenomenon particularly proves true for Mumbai city owing to its coastal location. While at Pune, though weather conditions become quite amiable in monsoon season, the extended breaks in monsoon with accumulated air moisture and high temperature may increase heat stress. At the continental location of Pune, for transition months between summer to the monsoon season of June experienced mean HI level drop to 27 °C from approximately 34 °C in May. However, in the coastal city of Mumbai, June's mean HI level still remained between 36 °C to 40 °C for May. It can be observed from Fig. 3(b) that in June, high heat stress incidences were quite common over recent years. The month of June has more or less similar heat stress tendency observed during summer season months, especially in Mumbai city. The July HI graph depicts frequent incidences of high above mean heat stress conditions at Mumbai, noticeably from 2002 to 2012, with a conspicuous sharp drop in 2013 and 2014; a similar below mean sharp decrease in HI can be observed at Pune city [Fig. 3(a)]. Since 2009, August is marked with an increased risk of heat stress over Mumbai, while at Pune, HI values are confined between 24 °C and 28 °C with thermally comfortable conditions. In September, mean HI at Mumbai reached up to 34 °C following a similar pattern of high HI values during recent years, likewise in August, while a slight insignificant increase from mean HI level was observed at Pune. At Mumbai, extended above mean pattern over recent years may have contributed positively to a significantly increasing trend during retreating monsoon season months.

3.1.2. *Heat stress intensity categorization and per annum percentage distribution (Heat Index)*

The daily HI values calculated for summer and monsoon season were categorized according to heat stress thresholds defined by NOAA from moderate risk (33 °C to 39 °C) to very high risk (above 46 °C) for both the cities, Pune and Mumbai. This exercise proved beneficial to understand the percentage distribution of heat stress days in each category (moderate risk, high risk, and very high risk) during each of the 47 years of the study period (1969-2015). At Pune city, it was observed that during the summer season in the year 1969, 75% of days were experiencing moderate risk, there onwards moderate risk days vary between 45% to 60%, but later to 2002 again sudden increase in the percentage of moderate risk

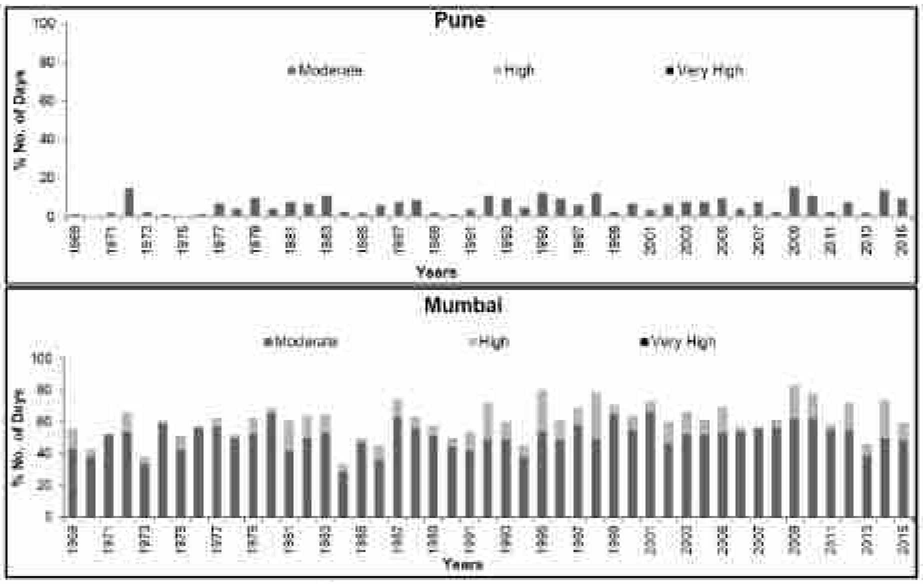


Fig. 5. Number of heat stress days in monsoon at Pune and Mumbai

days was observed (60% and above) which persisted till 2010. Further, from 2013 to 2015, more than 50% of days were under moderate heat stress risk (Fig. 4). High-risk days had non-frequent random distribution and were observed to coincide with warmest years or El Nino years on record like the years 1969, 1992, 1998, 2002, 2005, etc. Very high-risk days were observed only in 1996. Compared to Pune, the percentage of high-risk days in each of the 47 years were frequent over Mumbai. For most of the years after 2001, high-risk days varied from 8% to 15% and reached a whopping 40% in 2010. The moderate risk days fluctuate around 40% to 60% (Fig. 4) for 47 years. Very high-risk days for Mumbai were observed in 1975, 1998, 1999, 2004, 2007 and 2015. The summer season at both of these tropical cities was thermally discomfortable towards the last decade and precautions for heavy long exposure outdoor activities are needed.

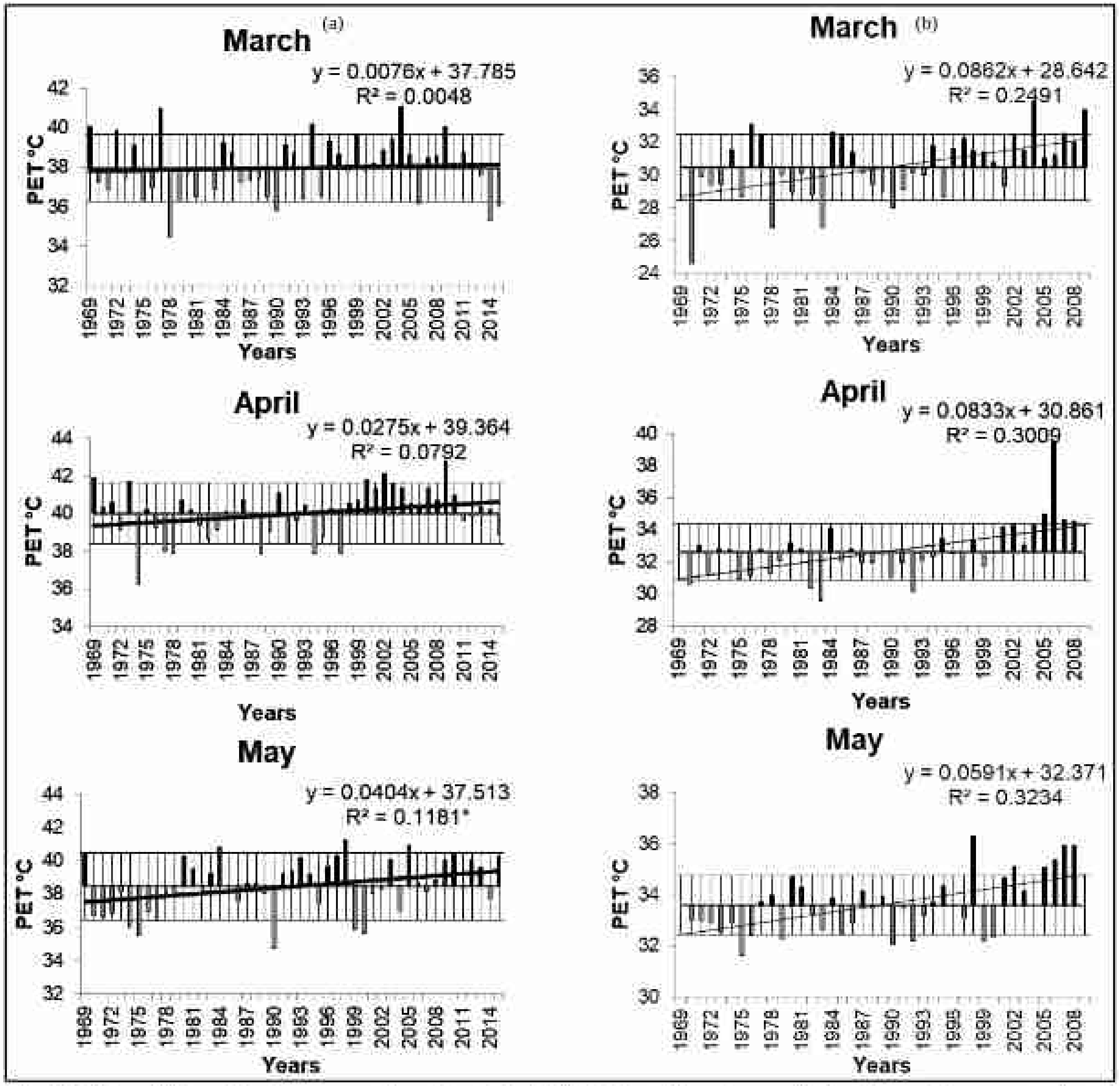
During monsoon season at Pune city, moderate risk days were less than 20% (Fig. 5). Thus for the rest of the monsoon season days, at Pune, there was low risk of heat stress, or days were thermally comfortable. While at Mumbai, due to the high humidity, percentage of days with moderate risk was well above 50% for all the 47 years (Fig. 5). After 1991 the rate of moderate risk days had increased to 65%. Also, the percentage of high-risk days increased during 1995, 1998, 2010 and 2014which had high-risk days of about 20%. For the rest of the years, high-risk days were well above 7%. Thus, according to the HI index, high humidity was a crucial contributing factor for high thermal discomfort during the study period in Mumbai.

3.2. *Temporal trends in Physiologically Equivalent Temperature (PET) Index*

3.2.1. *Monthly trend in PET during summer and monsoon seasons*

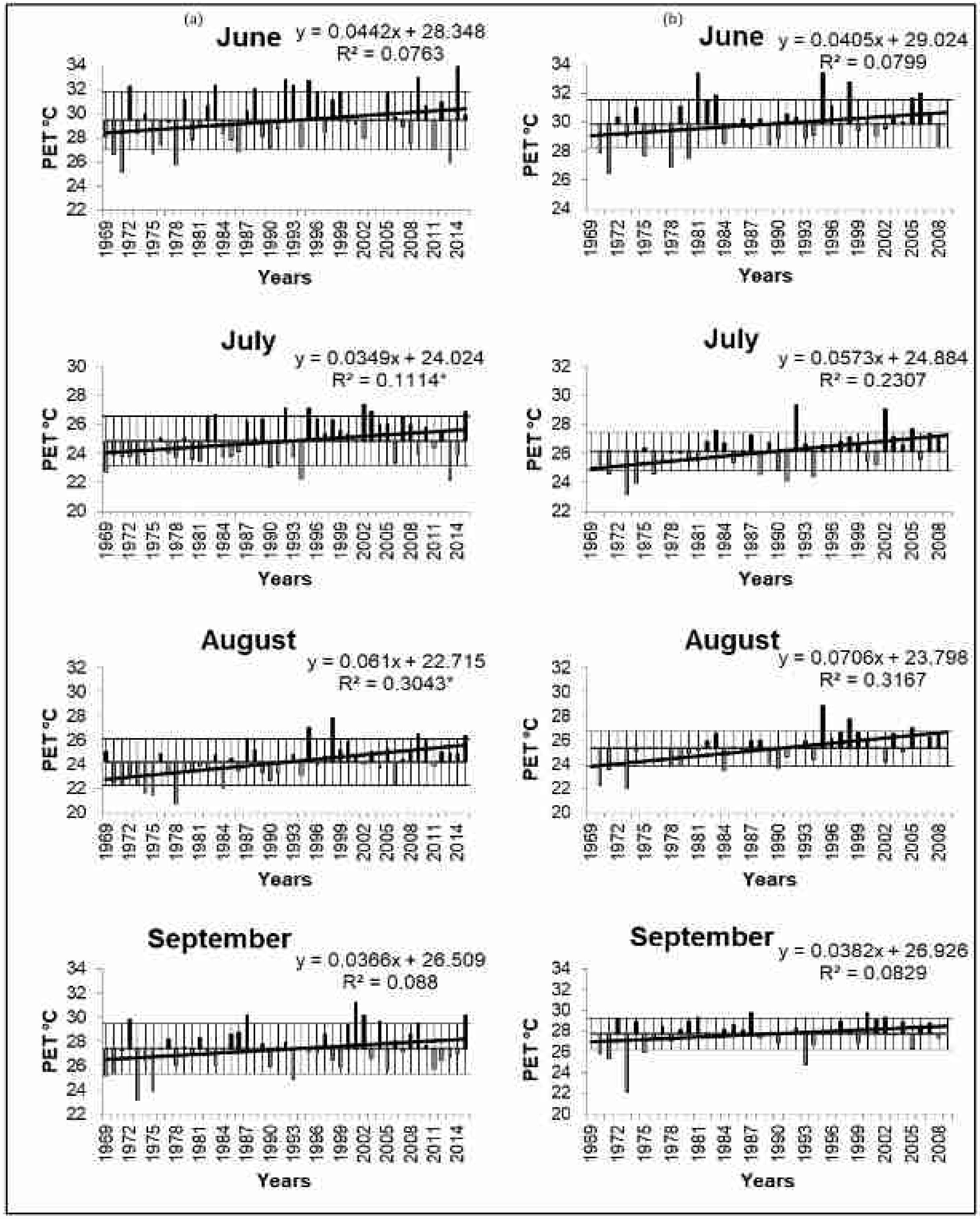
PET is the most rational and comprehensive index for human biometeorological assessment. The index is based on heat exchange between metabolic heat energy generated by the human body and environmental heat energy. For the present study, PET was calculated through the RayMan model. The output yield by the model is Mean Radiant Temperature (T_{mrt}) and Physiological equivalent Temperature (PET). Daily PET values were averaged to obtain mean monthly PET values for each of the seven months of summer and monsoon seasons.

Over Pune city, there was significant increase in PET in May. Though the increasing trend in March was not statistically substantial, above average (41 °C), PET was consistent from 1996 onwards till 2013, except for the year 2006 [Fig. 6(a)]. During the same month, notable changes can be observed during 1977-1978, wherein 1977 PET increased by 2 °C above the mean. Contradictory to this, PET showed a decrease of 2 °C in 1978. The absolute increase during April was 1.3 °C. PET values in this month were consistently above the mean and near to one standard deviation from 1998 till 2014. During May from 1996 to 1998 and from 2008 to 2015, PET was above the mean value of 41 °C. In May absolute increase in PET was 1.9 °C.



Figs. 6(a&b). PET trends during summer at Pune (a) and Mumbai (b). Horizontal lines above and below the mean line represent +1 and-1 standard deviation. Significant trends are and marked with '*.'

The absolute increase in PET during April and May of above 1 °C in recent years surpassing one standard deviation above mean PET indicates high thermally uncomfortable conditions. The average PET value of these months is near and above 38 °C that posesa severe risk of heat stress casualties. At Mumbai, mean PET values in the summer season range between 30 °C and 34 °C. It may be due to smoothening factors of coastal location and land and sea breeze effect (Nordio *et al.*, 2015). At Mumbai during all summer months later to 1999, consistent above mean PET can be observed. Exceptionally high PET of more than 3 °C above mean PET of 32.2 °C was recorded during April in 2006, one of the ten warmest years from 1880 to 2016 (NOAA). During all the summer months over Mumbai, PET values were above mean since the year 2002. Fig. 6(b) shows that the deviation of PET from the mean was highest in March, whereas lowest in May. Overall at both the stations during summer season frequency of years with above mean PET was high during recent years, that is after the year 2000. It points out that thermal comfort conditions in these cities are getting worse. In comparison, Pune is more vulnerable, as the average PET in this city was consistently above 40 °C, which already falls in the category of high heat stress and thus calls for essential precautionary measures from thermal stress adversities.



Figs. 7(a&b). PET trends during monsoon at Pune (a) and Mumbai (b). Horizontal lines above and below the mean line represent +1 and -1 standard deviation. Significant trends are and marked with '*.'

During monsoon season, global radiation tends to be low due to cloud cover. Monsoon rains provide sudden relief from the scorching summer heat during wet spells and establish thermally comfortable conditions. However, dry spells with reasonably high temperatures and high moisture content of air create sultry, oppressive

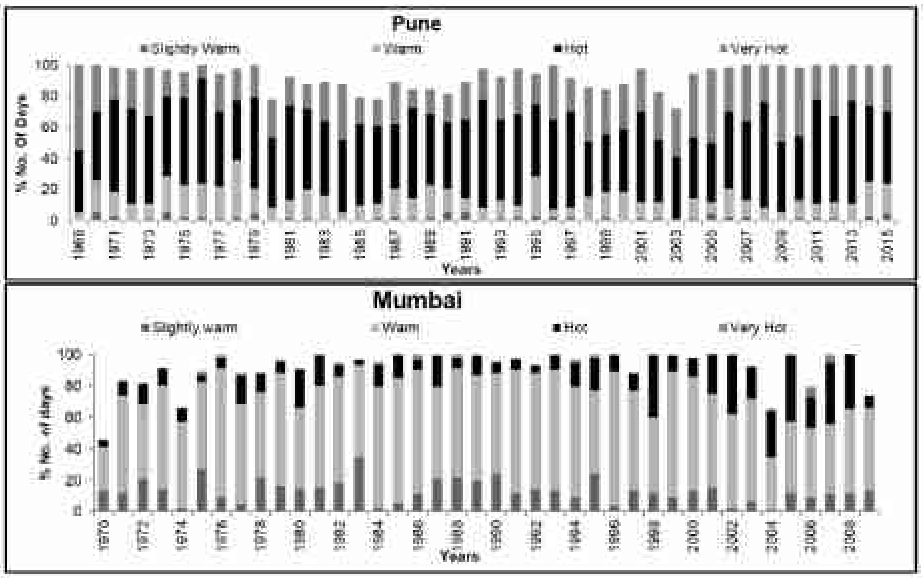


Fig. 8. Number of heat stress days in summer for Pune and Mumbai

conditions. June is a transition month between summer and monsoon season, and the mean PET values were still high. For the cities of Pune and Mumbai mean PET was 32 °C and 30 °C, respectively. In the successive months, from July till August, mean PET values were between 22 °C to 26 °C in Pune and 26 °C to 28 °C in Mumbai. Both the cities depicted a significant increasing trend in PET values in July and August.

Over Pune, the highest absolute increase of 3.4 °C PET was noticed in August. The discernible increase of about 3 °C above the mean PET was detected in the same month during 1998, which is co-incident with the year 1998 being the eighth warmest year on record (NOAA). Over Pune, in July and August, most of the years later to 1995 depicted high positive anomaly from mean except for 2005, 2008 and 2013-2014 in July [Fig. 7(a)]. In September at Pune, most of the years later to 2000 showed above mean increase in PET with the noticeable rise over consecutive years from 2000 to 2002. The monsoon season at Mumbai is marked by heavy rainfall, high humidity and comparatively low temperatures, which are reflected in relatively low mean PET values compared to the summer season. At Mumbai, during June, PET fluctuates around the mean value, and no consistent long period of increase or decrease was observed. The increasing trend in June was not statistically significant. For July 1992 and 2002 were the years of the positive anomaly of almost 2 °C higher PET than mean. During August a considerable increase was noticed and later to 1995 most of the years had above mean PET. The above mean PET pattern was initiated during the last decade (2000-2009) in September, but exceptionally low PET was observed in the year 1973 during this month. The monsoon PET graphs of Mumbai also depicted that the frequency of below mean PET has decreased towards recent years, consistent with summer trends. However there is an increasing discomfort level in the peak monsoon months of July and August [Fig. 7(b)].

3.2.2. Heat Stress Intensity Categorization and Percentage Distribution (Physiologically Equivalent Temperature)

According to the heat stress categories of PET suggested and applied by various authors (Matzarakis and Nastos, 2011; Bauche *et al.*, 2013; Ndetto and Matzarakis, 2013), the PET values for summer and monsoon days were categorized in percentage number of days in slight warm (23 °C to 29 °C) to extremely high risk (very hot) category for the Pune and Mumbai cities. During the summer season at Pune city percentage of days in warm and hot categories were discernible throughout the study period from 1969 to 2015 [Fig. 8(a)]. The rate of warm and hot heat stress days was 61% in 1995, increasing by 10% in 2005 (71%). The percentage of days with extreme heat stress (very hot) rose from the year 1990 till 2015, from 20% reached up to 40%. At Pune city, it is conspicuous to note that strong (hot) and extreme heat stress had a discernible increase later to 2004. In Mumbai, the percentage of slight heat stress days have decreased after the year 2000. Warm heat stress days were 50% to 60% until the year 1980, while during the decade of 1980 to 1990s they increased to 60%-70%. From 2000 to 2010, the percentage of warm days decreased at the cost of increase in hot days from 10% to 20% until the year 2000

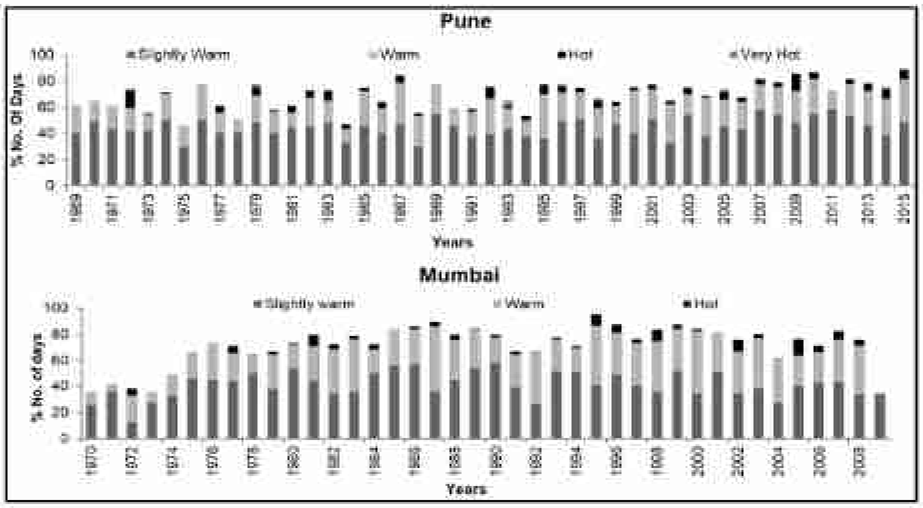


Fig. 9. Number of heat stress days in monsoon for Pune and Mumbai

and reached upto 40%. Very hot days were meager 1% to 2% till the year 2000 but in 2006 and 2007 extreme heat stress days increased to 7%. Compared to Pune, the percentage of sweltering very hot days, strong and extreme heat stress days, was less in Mumbai. Mumbai mainly experienced moderate heat stress during the summer season for the study period of 1969 to 2010 [Fig. 8(b)].

The monsoon season at Pune city was also marked with a substantially high percentage of thermally discomfortable days; this may be peculiar during the breaks in monsoon season. Decrease in slight warm days, in contrast, reflected to increase in warm days. During the last decade and a half, from 2000 to 2015 percentage of warm days increased and varied between 20% and 35% (Fig. 9). Similarly, the frequency of hot days has increased. Later to 1990s, very hot days were recorded in almost all years which varied between 10% and 20%. In the case of Mumbai, during monsoon season, the thermal discomfort was lower than that of Pune city, and percentage days in slight warm to hot can be observed, that is from slight heat stress to strong heat stress. The condition of extreme heat stress was absent in the case of Mumbai. Slightly warm days were 25% to 50% till the year 1980, while they were in the range of 50% to 60% in the 1990s. Again, towards the end of 1990s percentage of slight warm days decreased, and increase in warm days was observed after 1991 till the end of the study period. The rate of warm days, that is, moderate heat stress days, varied between 20% and 45%. In each of the years after 1976, about 5% to 12% of days were hot days, that are a percentage of days experiencing intense heat stress. However, the tendency of hot days that are thermally uncomfortable remained similar during the study period in Mumbai city.

3.3. *Analysis of selected meteorological parameters*

The stepwise multiple regression initially selects the variable showing the highest correlation coefficient with the dependant variable and then subsequently sets other variables (Johnsson, 1992). Applying this technique, meteorological parameters acting as significant predictors affecting thermal discomfort (or heat stress), here in terms of HI and PET (as a dependant variable) during summer and monsoon season were identified and analyzed (Tables 3 to 10).

The linearity of each variable was checked with a linear matrix plot. The linearly distributed variables in terms of predictors were included in the model to calculate stepwise multiple regression. For the Pune city during summer and monsoon seasons, the correlation matrix depicted a statistically significant correlation between the dependent variable and each of the independent variables. The R square and adjusted R square values for the final model showed that the weighted combination of predictor variables explained more than 90% variance in HI and PET both in summer and monsoon season at Pune city. The unstandardized coefficients represent what effect one unit of change in *x* will have on the variable *y*.

In contrast, standardized coefficients refer to how many standard deviations a dependent variable will change per standard deviation increase in the predictor variable. Standardization of the coefficient is usually done to answer the question : Which independent variables have a more significant effect on the dependent variable in multiple regression analysis when the variables are measured in different units of measurement. In the present study, climatic parameters used are in different units of

TABLE 3

Results of stepwise multiple regression of summer HI for Pune city

Model	Unstandardized coefficient		Standardized coefficient Beta	Pearson r
	B	Std. error		
Constant	-7.166	1.149		
DBT	0.797	0.031	0.743*	0.872
WBT	0.651	0.040	0.471*	0.675

The dependent variable was heat index. R^2 = 0.988, Adjusted R^2 = 0.987, *indicates significance at 0.05 level

TABLE 4

Results of stepwise multiple regression of summer PET for Pune city

Model	Unstandardized coefficient		Standardized coefficient Beta	Pearson r
	B	Std. error		
Constant	-8.787	1.004		
DBT	0.955	0.035	0.622*	0.870
T_{mrt}	0.344	0.019	0.429*	0.837
WS	-0.180	0.014	-0.239*	-0.357

The dependent variable was heat index. R^2 = 0.999, Adjusted R^2 = 0.990, *indicates significance at 0.05 level

TABLE 5

Results of stepwise multiple regression of monsoon HI for Pune city

Model	Unstandardized coefficient		Standardized coefficient Beta	Pearson r
	B	Std. error		
Constant	-10.513	1.010		
DBT	1.335	0.031	0.982*	0.983
VP	0.110	0.024	0.105*	0.108

The dependent variable was heat index. R^2 = 0.984, Adjusted R^2 = 0.984, *indicates significance at 0.05 level

TABLE 6

Results of stepwise multiple regression of monsoon PET for Pune city

Model	Unstandardized coefficient		Standardized coefficient Beta	Pearson r
	B	Std. error		
Constant	-11.740	1.015		
DBT	1.140	0.051	0.549*	0.853
WS	-0.253	0.012	-0.391*	-0.482
T_{mrt}	0.302	0.018	0.401*	0.821

The dependent variable was heat index. R^2 = 0.987, Adjusted R^2 = 0.986, *indicates significance at 0.05 level

TABLE 7

Results of stepwise multiple regression of summer HI for Mumbai city

Model	Unstandardized coefficient		Standardized coefficient Beta	Pearson r
	B	Std. error		
Constant	-26.777	1.737		
WBT	1.650	0.082	0.750*	0.965
DBT	0.663	0.084	0.294*	0.843

The dependent variable was heat index. R^2 = 0.993, Adjusted R^2 = 0.992, *indicates significance at 0.05 level

TABLE 8

Results of stepwise multiple regression of summer PET for Mumbai city

Model	Unstandardized coefficient		Standardized coefficient Beta	Pearson r
	B	Std. error		
Constant	-14.829	4.388		
DBT	1.279	0.127	0.561*	0.824
WS	-0.330	0.034	-0.557*	-0.749
T_{mrt}	0.228	0.056	0.210*	0.165

The dependent variable was heat index. R^2 = 0.914, Adjusted R^2 = 0.907, *indicates significance at 0.05 level

measurement, thus for analysis purpose, both unstandardized and standardized coefficients are used. During the summer season at Pune city, the dependent variable (*i.e.*, HI) has the highest correlation with the independent variable DBT (0.872). Column of standardized coefficients beta values shows that predictors positively affecting dependant variable (HI) were DBT (0.743) and WBT (0.471) that have high positive beta weights (Table 3). Thus, a substantial increase in ambient air temperature during the summer season increase in HI can be explained. In the case of the PET index, significant increase in the summer season months of April and May can be explained by increasing temperature and radiation (T_{mrt}) and a decrease in wind velocity (Table 4). The PET index values positively correlate with T_{mrt} (0.837) and DBT (0.870). Table 4 depicts that DBT has the highest positive beta weight followed by T_{mrt}, while a decrease in wind speed (WS) contributes to an increase in PET. High T_{mrt} accounts for high radiation, which is ultimately responsible for high temperature. Combined with the absence of wind velocity to dissipate bodily heat, these factors explain a significant increase in PET during the summer season. During monsoon season at Pune city, the temperature is a dominating factor for a notable rise in HI; the unstandardized coefficient B value of independent variable DBT is (1.335) (Table 5). The significant increasing trend in PET during all the monsoon season months was well explained by an increase in DBT and T_{mrt}, which have a high positive Pearson correlation with a PET value of 0.853 and 0.821. Similar to the summer season, a significant negative correlation of PET and wind speed (WS) existed during the monsoon season (Table 6). The standardized beta weights depict 0.401 weightage of T_{mrt}, 0.549 of WBT, and the negative beta weight of WS (-0.391), contributing to an overall increase in PET.

At Mumbai during the summer season, the parameters selected as predictors correlate with HI and PET's dependant variable. The model summary proved that R square and adjusted R square values for all the summer and monsoon season stepwise multiple regression models were above 0.90. During the summer season, HI had a high correlation with WBT (0.965) and DBT (0.843) (Table 7). A significant increase in summer season HI was prominently due to the presence of water vapor at lower atmospheric levels, which has been reflected by standardized beta value weightage of WBT (0.750). The significant increasing trend in summer months PET during the study period was determined by substantial positive standardized beta weights of DBT (0.561) and T_{mrt} (0.210) (Table 8) with a simultaneous decrease inWS (-0.557). Thus,an increase in sensible heat and radiation heat together was responsible for the increase in

TABLE 9

Results of stepwise multiple regression of monsoon HI for Mumbai city

Model	Unstandardized coefficient		Standardized coefficient	Pearson
	B	Std. error	Beta	r
Constant	32.901	1.274		
DBT	1.914	0.054	0.700*	0.916
VP	0.638	0.044	0.558*	0.824
WBT	-0.321	0.124	-0.119	0.902

The dependent variable was heat index. $R^2 = 0.999$, Adjusted $R^2 = 0.999$, *indicates significance at 0.05 level

TABLE 10

Results of stepwise multiple regression of monsoon PET for Mumbai city

Model	Unstandardized coefficient		Standardized coefficient	Pearson
	B	Std. error	Beta	r
Constant	-28.387	4.752		
DBT	1.693	0.187	0.681*	0.928
T_{mrt}	0.192	0.043	0.284*	0.574
WS	-0.091	0.029	-0.213*	-0.564

The dependent variable was heat index. $R^2 = 0.915$, Adjusted $R^2 = 0.908$, *indicates significance at 0.05 level

PET. During monsoon season similar pattern can be observed concerning factors affecting PET (Table 10). DBT and T_{mrt} had a high positive correlation with PET and beta values, contributing to an increase in PET values of 0.681 and 0.284, respectively. Hindered and thus lowered wind velocity in the city area reflected a significant decrease in WS with a beta value of -0.213. Therefore, wind speed was also a crucial factor to bring about positive change in PET. In monsoon season HI, the correlation between HI and independent variable DBT was high (Table 9), with a beta value of 0.700. Though this may be the case, successive variable derived from the final model of stepwise regression VP reflects significant increase with the standardized beta weight of 0.558 (Table 9). Thus it can be inferred that the substantialrise in monsoon season HI at Mumbai was due to high air temperature and added sultriness affected due to high moisture content.

5. Conclusion

The study evaluates heat stress conditions at two prominent thriving urban centers of Maharashtra, having different climatic regimes, the hot and humid climate of Mumbai and the hot and dry conditions of Pune. The HI index emphasizes thermal discomfort caused by temperature and humidity, while other climatic parameters included through the regression equation are assumed constant. On the other hand, PET is a more comprehensive index, considers all the relevant meteorological parameters and physiological specifications can also be incorporated. According to both the indices, increasing heat stress in all the summer and monsoon season months at Pune and Mumbai was evident. At Pune, increasing HI was not statistically significant, but the PET index depicted a considerable increase during the end months of summer and monsoon seasons. However, in Mumbai, an increase in HI was significant in May. Besides the monsoon months of June and July, significant increase in HI was noticed in the late monsoon months of August and September. In accordance with the PET index though all summer and monsoon season months reflected a noticeable increase at Mumbai, PET's rise was statistically insignificant. Although the increasing trend was prominent in both cities, the magnitude of the increase was higher in Mumbai than in Pune. Thus, in Mumbai, heat stress was building faster over the study period of 1969-2015. For Pune city mean HI value during the summer season ranges between 32 °C and 35 °C while heat stress condition becomes quite amiable in monsoon with HI range lowering upto 25 °C to 29 °C. In contrast, in Mumbai HI range during summer and monsoon do not vary much. Similarly, PET value during summer was 38 °C to 40 °C and decreased to 24 °C to 29 °C during monsoon at Pune, while at Mumbai, variation in mean PET range between consecutive seasons was meager (3 °C to 4 °C).

The analysis thus reveals that, though the magnitude of increase over Pune was less, the city was already experiencing high mean heat stress in summer. Any positive deviation from mean HI and PET values may develop the risk of high to extreme heat stress. However, monsoon heralds immediate relief from hot, oppressive summer conditions, though an increasing trend in monsoon months during recent years is pronounced. The most thermally uncomfortable month and month of highest magnitude increase in heat stress was May in Pune city, while at Mumbai transition month of March was vulnerable to increasing heat stress. The actual categorization of heat stress days in different categories showed that the percentage of moderate-risk and slight/moderate heat stress decreased during the study period from 1969-2015. While percentage days of high risk, extreme heat stress increased over the last decade, particularly during the summer season.

Investigation of meteorological parameters responsible for changes in HI and PET indices revealed that over Pune increase in HI during the summer season can be explained by increasing temperature and partially by high air moisture content. On the other hand, multiple regression analysis for summer PET reveals that high T_{min} leads to a rise in ambient air temperature, and restricted wind flow subsequently increases PET and heat stress. Mumbai's high humidity in the summer season and temperature rather than radiation heat were causative factors for high heat stress. In the monsoon season, though temperature remains a dominant factor for the increase in HI at Pune city, contrary to it, at Mumbai, temperature and vapor pressure increase in combination were responsible for HI increase during summer months. However, during monsoon at both the stations, radiation heat and sensible heat were formative in significant growth of PET. Among the indices used in this study, PET is applicable to elucidate thermal discomfort conditions of hot and dry climates. In contrast, higher weightage to the HI index's combined effect of temperature and humidity makes it relevant for hot and humid conditions. The study reveals that, though the growing urban centers act as a magnet due to innumerable opportunities, the population in these cities is exposed to increasing heat stress, which may deteriorate healthy living conditions and affect human performance.

Acknowledgments

The authors are grateful to India Meteorological Department (IMD) for supplying the required data. The research is funded by the Council of Scientific and Industrial Research (CSIR)-Delhi. The authors also thank anonymous reviewers for providing their suggestions, which helped to improve the quality of this article.

Disclaimer : The contents and views expressed in this research paper/article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

Ahmed, K. S., 2003, "Comfort in urban spaces: defining the boundaries of outdoor thermal comfort for the tropical urban environments", *International Labour Review*, **142**, 2, 103-110. doi:10.1111/j.1564-913X.2003.tb00261.x.

Alexandersson, H. and Moberg, A., 1997, "Homogenization of Swedish Temperature Data. Part I : Homogeneity Test for Linear Trends", *Int. J. Climatol.*, **17**, 25-34. doi : 10.1002/(SICI)10970088(199701)17.

Álvarez, J. R., 2013, "Heat Island and Urban Morphology : Observations and analysis from six European cities", PLEA 2013 Sustain Archit a Renew Futur.

Amirtham, L. R., Horrison, E. and Rajkumar, S., 2014, "Study on the Microclimatic Conditions and Thermal Comfort in an Institutional Campus in Hot Humid Climate", 30th International PLEA conference 16-18 December 2014, CEPT University, Ahmedabad.

Anderson, G. B., Bell, M. L. and Peng, R. D., 2013, "Methods to calculate the heat index as an exposure metric in environmental health research", *Environ. Health Perspect.*, **121**, 10, 1111-1119.

Arnfield, A. J., 2003, "Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island", *Int. J. Climatol.*, **23**, 1-26. doi : 10.1002/joc.859.

ASHRAE Standard 55, 2004, "Thermal environmental conditions for human occupancy", American Society of Heating, Refrigerating and Air-conditioning Engineers.

Auliciems, A. and Szokolay, S. V., 2007, "Thermal Comfort. Passive Low Energy Architecture (PLEA)", Int. Des TOOLS Tech Note, 3, 66, doi : 10.1007/s00484-010-0393-2.

Bates, B. C., Kundzewicz, Z. W., Wu, S. and Palutikof, J. P. Eds., 2008, "Climate change and water", Technical Paper of the Intergovernmental Panel on Climate Change (IPCC) Secretariat, Geneva, 210.

Bauche, J. P., Grigorieva, E. A. and Matzarakis, A., 2013, "Human-biometeorological assessment of urban structures in extreme climate conditions : The example of Birobidzhan, Russian far east", *Adv. Meteorol.*, doi : 10.1155/2013/749270.

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H. and Tinz, B., 2012, "Comparison of UTCI to selected thermal indices", *Int. J. Biometeorol.*, **56**, 515-535. doi :10.1007/s00484-011-0453-2.

Blennow, K., 1995, "Sky View Factors from High-Resolution Scanned Fish-eye Lens Photographic Negatives", *J. Atmos. Ocean Technol.*,**12**, 1357-1362. doi : 10.1175/15200426(1995)012 <1357:SVFFHR>2.0.CO;2.

Bröde, P., Błażejczyk, K., Fiala, D., Havenith, G., Holmer, I., Jendritzky, G., Kuklane, K. and Kampmann, B., 2013, "The Universal Thermal Climate Index UTCI Compared to Ergonomics Standards for Assessing the Thermal Environment", *Industrial Health*, **51**, 16-24.

Brooke, A. G., Bell, M. L. and Peng, R. D., 2013, "Methods to calculate the heat index as an exposure metric in environmental health research", *Environ. Health Perspect*, **121**, 1111-1119. doi : 10.1289/ehp.1206273.

Census of India, 2011, "Urban Agglomeration/Cities having population 1 lakh and above", Censusindia, The Registrar General and Census Commissioner, India.

De, U. S., Dube, R. K. and Prakasa Rao, G. S., 2005, "Extreme weather events over India in last 100 years", *J. Indian Geophys. Union*, **9**, 3, 173-187.

Diffenbaugh, N. S., Pal, J. S., Giorgi, F. and Gao, X., 2007, "Heat stress intensification in the Mediterranean climate change hotspot", *Geophys. Res. Lett.*, **34**, 1-6. doi : 10.1029/ 2007GL030000.

Epstein, Y. and Moran, D. S., 2006, "Thermal comfort and the heat stress indices", *Ind. Health*, **44**, 388-398. doi : 10.2486/ indhealth.44.388.

Erell, E., Pearlmutter, D. Boneh, D. and Kutiel, P. B., 2014, "Effect of high-albedo materials on pedestrian heat stress in urban street canyons", *Urban Clim.*, **10**, 367-386. doi : 10.1016/j.uclim. 2013.10.005.

Glazer, J. L., 2005, "Management of heatstroke and heat exhaustion", *Am. Fam. Physician*, **71**, 11, 2133-2142.

Goggins, W. B., Chan, E. Y. Y., Ng, E., Ren, C. and Chen, L., 2012, "Effect Modification of the Association between Short-term Meteorological Factors and Mortality by Urban Heat Islands in Hong Kong", *PLoS ONE*,**7**, 6, e38551. doi : 10.1371/ journal.pone.0038551

Gómez, F., Cueva, A. P., Valcuende, M. and Matzarakis, A., 2013, "Research on ecological design to enhance comfort in open spaces of a city (Valencia, Spain)", Utility of the physiological equivalent temperature (PET). *Ecol. Eng.*, **57**, 27-39. https://doi.org/10.1016/j.ecoleng.2013.04.034.

Hijioka, Y. E., Lin, J. J., Pereira, R. T., Corlett, X., Cui, G. E., Insarov, R. D., Lasco, E., Lindgren and Surjan, A., 2014, Asia. In : Climate Change 2014 : Impacts, adaptation, and vulnerability. Part B : Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V. R., Field, C. B., D. J.Dokken, MD Mastrandrea, K. J. Mach, T. E.Bilir, M. Chatterjee, K. L.Ebi, Y. O. Estrada, R. C. Genova, B.Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R.Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1327-1370.

Höppe, P., 1999, "The physiological equivalent temperature - A universal index for the biometeorological assessment of the thermal environment", *Int. J. Biometeorol.*, **43**, 71-75. doi : 10.1007/s004840050118.

IPCC, 2014a, "Climate Change 2014 Synthesis Report Summary Chapter for Policymakers".

IPCC, 2014b, "The IPCC's Fifth Assessment Report : What's in it for South Asia?", *Intergov. Panel Clim. Chang.*, **79**. doi: http://cdkn.org/wp content/uploads/2014/04/J1731CDKN Fifth Assesment Report WEB.pdf.

Jaswal, A. K., Padmakumari, B., Kumar, N. and Kore, P. A., 2017, "Increasing Trend in Temperature and Moisture Induced Heat Index and Its Effect on Human Health in Climate Change Scenario over the Indian Sub-continent", 1 Jan, 2017, 11-25.

Jaswal, A. K., Rao, P. C. S. and Singh, V., 2015, "Climatology and trends of summer high-temperature days in India during 1969-2013", *J. Earth Syst. Sci.*, **124**, 1-15. doi : 10.1007/s12040-014-0535-8.

Johnsson, T., 1992, "A procedure for stepwise regression analysis", Stat. Pap., **33**, 21-29. doi : 10.1007/BF02925308.

Jones, P. D., New, M., Parker, D. E., Martin, S. and Rigor, I. G., 1999, "Surface air temperature and its changes over the past 150 years", *Rev. Geophys.*, **37**, 173-199.

Kothawale, D. R. and Rupa Kumar, K., 2005, "On the recent changes in surface temperature trends over India", *Geophys. Res. Lett.*, **32**, 1-4. doi : 10.1029/2005GL023528.

Kothawale, D. R. Deshpande, N. R. and Kolli, R. K., 2016, "Long Term Temperature Trends at Major, Medium, Small Cities and Hill Stations in India during the Period 1901-2013", *Am. J. Clim. Chang.*, **5**, 383-398. doi : 10.4236/ajcc.2016.53029.

Kothawale, D. R., Revadekar, J. V. and Kumar, K. R., 2010, "Recent trends in pre-monsoon daily temperature extremes over India", *J. Earth Syst. Sci.*, **119**, 51-65. doi : 10.1007/s12040-010-0008-7.

Krüger, E., Drach, P., Emmanuel, R. and Corbella, O., 2013, "Assessment of daytime outdoor comfort levels in and outside the urban area of Glasgow, UK", *Int. J. Biometeorol.*, **57**, 521-533. doi : 10.1007/s00484-012-0578-y.

Lindberg, F., Onomura, S. and Grimmond, C. S. B., 2016, "Influence of ground surface characteristics on the mean radiant temperature in urban areas", *Int. J. Biometeorol.*, **60**, 1439-1452. doi : 10.1007/s00484-016-1135-x

Matzarakis, A. and Nastos, P. T., 2011, "Human-biometeorological assessment of heat waves in Athens", *Theor. Appl. Climatol.*, **105**, 99-106. doi : 10.1007/s00704-010-0379-3.

Matzarakis, A. Mayer, H. and Iziomon, M. G., 1999, "Applications of a universal thermal index: physiological equivalent temperature", *Int. J. Biometeorol.*, **43**, 76-84. doi : 10.1007/s004840050119.

Matzarakis, A., Rutz, F. and Mayer, H., 2007, "Modelling radiation fluxes in simple and complex environments-application of the RayMan model", *Int. J. Biometeorol.*, **51**, 323-334. doi : 10.1007/s00484-006-0061-8.

Matzarakis, A., Rutz, F. and Mayer, H., 2010, "Modelling radiation fluxes in simple and complex environments : Basics of the RayMan model", *Int. J. Biometeorol.*, **54**, 131-139. doi : 10.1007/s00484-009-0261-0.

Memon, R. A., Leung, D. Y. C. and Chunho, L. I. U., 2008, "A review on the generation, determination and mitigation of pdf", *J. Environ. Sci.*, **20**, 120-128.

Michelozzi, Paola, Accetta, Gabriele, Sario, Manuela De, D'Ippoliti, Daniela, Marino, Claudia, Baccini, Michela, Biggeri, Annibale, Anderson, H. Ross, Katsouyanni, Klea, Ballester, Ferran,Bisanti, Luigi, Cadum, Ennio, Forsberg, Bertil, Forastiere, Francesco, Goodman, Patrick G., Hojs, Ana, Kirchmayer, Ursula, Medina, Sylvia, Paldy, Anna, Schindler, Christian, Sunyer, Jordiand Perucci and Carlo A., 2009, "High temperature and hospitalizations for cardiovascular and respiratory causes in 12 European cities", *Am. J. Respir. Crit. Care Med.*, **179**, 383-389. doi : 10.1164/rccm.200802-217OC.

Mohan, M., Gupta, A. and Bhati, S., 2014, "A Modified Approach to Analyze Thermal Comfort Classification", 7-19.

Morabito, M., Crisci, A., Messeri, A., Capecchi, V., Modesti, P. A., Gensini, G. F. and Orlandini, S., 2014, "Environmental temperature and thermal indices : What is the most effective predictor of heat-related mortality in different geographical contexts?", *Sci. World J.*, 1-15. doi : 10.1155/2014/961750.

Muthers, S., Matzarakis, A. and Koch, E., 2010, "Summer climate and mortality in Vienna - A human-biometeorological approach of heat-related mortality during the heat waves in 2003", *Wien Klin Wochenschr*, **122**, 525-531. doi : 10.1007/s00508-010-1424-z.

Nastos, P. T. and Matzarakis, A., 2013, "Human Bioclimatic Conditions, Trends and Variability in the Athens University Campus, Greece", *Advances in Meterology*, 1-8.

Nathans, L., Oswald, F. and Nimon, K., 2012, "Interpreting Multiple Linear Regression: A Guidebook of Variable Importance", *Pract. Assessment Res. Eval.*, **17**, 19. doi : 10.3102/00346543074004525.

Ndetto, E. L. and Matzarakis, A., 2013, "Basic analysis of climate and urban bioclimate of Dar es Salaam, Tanzania", *Theor. Appl. Climatol.*, **114**, 213-226. doi : 10.1007/s00704-012-0828-2.

NOAA National Centers for Environmental Information, State of the Climate : Global Climate Report for January 2018, published online February 2018, Retrieved on March 14, 2018, from https://www.ncdc.noaa.gov/sotc/global/201801.

Nordio, Francesco, Zanobetti, Antonella, Colicino, Elena, Kloog, Itai and Schwartz, Joel, 2015, "Changing patterns of the temperature-mortality association by time and location in the US, and implications for climate change", *Environ. Int.*, **81**, 80-86. doi : 10.1016/j.envint.2015.04.009.

Oke, T. R., 1982, "The energetic basis of the urban heat island", *Q. J. R.Meteorol. Soc.*, **108**, 1-24. doi : 10.1002/qj.49710845502.

Owen, T. W., Carlson, T. N. and Gillies, R. R., 1998, "An assessment of satellite remotely-sensed land cover parameters in quantitatively describing the climatic effect of urbanization", *Int. J. Remote Sens.*, **19**, 1663-1681. doi : 10.1080/014311698215171.

Pai, D. S., Nair, S. A. and Ramanathan, A. N., 2013, "Long term climatology and trends of heat waves over India during the recent 50 years (1961-2010)", *MAUSAM*, **64**, 585-604.

Pai, D. S., Thapliyal, V. and Kokate, P. D., 2004, "Decadal variation in the heat and cold waves over India during 1971-2000", *MAUSAM*, **2**, 281-292.

Pantavou, Katerina, Lykoudis, Spyridon, Nikolopoulou, Marialena and Tsiros, Ioannis X., 2018, "Thermal sensation and climate: a comparison of UTCI and PET thresholds in different climates", *Int. J. Biometeorol.*, **62**, 1695-1708. https://doi.org/10.1007/s00484-018-1569-4

Rajib, Mohammad Adnan, Mortuza, Md. Rubayet, Selmi, Saranah, Ankur, Asif Khan and Rahman, Md. Mujibur, 2011, "Increase of Heat Index over Bangladesh: Impact of Climate Change", *International Scholarly and Scientific Research & Innovation*, 5.

Rao, G. S. P., Jaswal, A. K. and Kumar, M. S., 2004, "Effects of urbanization on meteorological parameters", *MAUSAM*, **55**, 429-440.

Robinson, P. J., 2000, "On the Definition of a Heat Wave", *J. Appl. Meteorol.*, **40**, 762-775. doi : 10.1175/1520-0450(2001)040<0762:OTDOAH>2.0.CO;2.

Rohini, P., Rajeevan, M. and Srivastava, A. K., 2016, "On the Variability and Increasing Trends of Heat Waves over India", *Sci. Rep.*, **6**, 1-9. doi : 10.1038/srep26153.

Rothfusz, L. P., 1990, "The heat index equation (or, more than you ever wanted to know about heat index)", *Fort Worth, Texas Natl Ocean Atmos. Adm Natl. Weather Serv. Off Meteorol.*, 23-90.

Steadman, R. G., 1979, "The Assessment of Sultriness. Part I : A Temperature-Humidity Index Based on Human Physiology and Clothing Science", *J. Appl. Meteorol*, **18**, 861-873.

Steeneveld, G. J., Koopmans, S., Heusinkveld, B. G., van Hove, L. W. A. and Holtslag, A. A. M., 2011,"Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands", *J. Geophys. Res. Atmos.*, **116**, 1-14. doi :10.1029/2011JD015988.

Stone, B. and Rodgers, M. O., 2001, "Urban form and thermal efficiency: How the design of cities influences the urban heat island effect", *J. Am. Plan. Assoc.*, **67**, 186-198. doi : 10.1080/01944360108976228.

Tahbaz, M. and Beheshti, 2010, "Towards a new chart for outdoor thermal analysis. Adapting to change : New thinking on comfort", Cumberland Lodge, Windsor, UK London: Network for comfort and energy used in building. http://nceub.org.uk.

Tsiros, I. X., Efthimiadou, A. P., Hoffman, M. E. and Tseliou, A., 2012, "Summer Thermal Environment and Human Comfort in Public Outdoor Urban Spaces in a Mediterranean Climate (Athens PLEA2012 - 28th Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture Lima", Perú 7-9 November 2012, 5-10.

Unger, J., 1999, "Comparisons of urban and rural bioclimatological conditions in the case of a central-European city", *Int. J. Biometeorol.*, **43**, 139-144. doi : 10.1007/s004840050129.

Van Hoof, J., 2008, "Forty years of Fanger's model of thermal comfort: Comfort for all?", *Indoor Air*, **18**, 182-201. doi : 10.1111/j.1600-0668.2007.00516.x.

Voogt, J. A. and Oke, T. R., 2003, "Thermal remote sensing of urban climates. Remote Sens", *Environ.*, **86**, 370-384.

Yan, Y. Y. and Oliver, J. E., 1996, "The CLO: A utilitarian unit to measure weather/climate comfort", *Int. J. Climatol.*, **16**, 1045-1056.

Yuan, F. and Bauer, M. E., 2007, "Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery", *Remote Sens. Environ.*, **106**, 375-386. doi : 10.1016/j.rse.2006.09.003.

Zahid, M. and Rasul, G., 2010, "Rise in Summer Heat Index over Pakistan", *Pakistan J.Meteorol.*, **6**, 85-96.

Zare, Sajad, Hasheminejad, Naser, Shirvan, Elahi Hossein, Hemmatjo, Rasoul, Sarebanzade, Kayvanand and Ahmadi, Saeid, 2018, "Comparing Universal Thermal Climate Index (UTCI) with selected thermal indices/environmental parameters during 12 months of the year", *Weather Clim. Extrem.*, **19**, 49-57. https://doi.org/10.1016/j.wace.2018.01.004.

Applied Ecology and Environmental Sciences, *2021, Vol. 9, No. 7, 656-679*
Available online at http://pubs.sciepub.com/aees/9/7/5
Published by Science and Education Publishing
DOI:10.12691/aees-9-7-5

Assessment of Post-monsoon Drought Over Marathawada Region (Maharashtra, India) Using MODIS Data

Vishal Somni[1], Nishikant Kudale[2], Amit Dhorde[2,*], Manasi Desai[3]

[1]GIS Department, GeoSpoc Geospatial Services Pvt. Ltd., Pune, India
[2]Department of Geography, Savitribai Phule Pune University, Pune, India
[3]Department of Geography, Symbiosis College of Arts & Commerce, Pune, India
*Corresponding author: amitdhorde@unipune.ac.in

Received June 02, 2021; Revised July 05, 2021; Accepted July 15, 2021

Abstract Drought is a natural hazard that has a significant effect on the socio-economic, agricultural, and environmental aspects of a region. The Marathwada division of Maharashtra state is infamous for recurring drought situations. Poor precipitation, lack of water storage, relatively high temperature in pre and post-monsoon seasons, and variable unfavorable weather conditions lead to drought in this region. Post-monsoon drought mainly occurs due to deficit rainfall and a sudden increase in temperature. This study represents the overall assessment of post-monsoon drought over Marathwada during October, November, and December for the period 2001 to 2017. Monsoon rainfall deficit results in post-monsoon drought in subsequent months. Detection and monitoring of drought over large areas are possible through remote sensing indices namely, Temperature Condition Index (TCI), Vegetation Condition Index (VCI), and Vegetation Health Index (VHI). VHI is the resultant index from temperature and vegetation indices, which helps to understand vegetation health. During the last 17 years, moderate to severe drought has been observed in two successive years of 2014 and 2015, where TCI, VCI, and VHI indices indicated these years as drought-prone years for the post-monsoon season. Particularly, Bid, Osmanabad, Latur, Nanded, and Parbhani districts suffered severe drought in these successive years. Whereas, all the other years except 2010 and 2017 experienced normal conditions to moderate drought in the Marathwada region. Due to erratic rainfall, it is necessary to plan water utilization and storage in Marathwada to overcome the recurrent drought experienced in the region. This may help agronomists and planners in better management of water resources, particularly for the agricultural sector.

Keywords: *drought, TCI, VCI, VHI, Marathwada, MODIS*

Cite This Article: Vishal Somni, Nishikant Kudale, Amit Dhorde, and Manasi Desai, "Assessment of Post-monsoon Drought Over Marathawada Region (Maharashtra, India) Using MODIS Data." *Applied Ecology and Environmental Sciences*, vol. 9, no. 7 (2021): 656-679. doi: 10.12691/aees-9-7-5.

1. Introduction

Drought is a natural hazard occurring mainly due to lack or deficiency of precipitation and adversely affecting all human activities of the area, primarily agriculture. Its onset and evolution are very slow and therefore it is difficult to predict. It is often said that drought is a most complex natural hazard than any other, and it affects a large number of people [1]. It has significant adverse effects on the economy, agriculture, and environmental conditions. High evapotranspiration, scanty rainfall and overuse or exploitation of water resources, or a combination of these parameters and insufficient moisture content in the atmosphere might be responsible for drought conditions [2,3]. Direct impacts of drought are forest fires, reduced crop production, and water level, damage of fish habitat, livestock mortality rate, and its indirect effects include reduction in crop production, the increased market value of goods, vegetables, and other commodities [4].

In India, several studies have been done on drought monitoring using spatial indices on various geographic regions like western India [4] Aravalli Region [2], Indian Gangetic Plains [6], Gujarat [6], and Maharashtra [8]. It is important to monitor drought continuously in time and space during the drought period with the help of Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), and other indices [9]. In India, Rajasthan, Kutch of Gujrat, Marathwada, and Vidarbha in Maharashtra, and some parts of Orrisa are major drought-prone areas (DPA). Marathwada is one of the DPA in Maharashtra which has serious issues related to agricultural crops, water storage, and temperature increase since the last decade.

Various studies in the past have used geospatial data and indices derived from them to study drought. Some studies have used NOAA AVHRR data to estimate temperature condition index (TCI) and vegetation condition index (VCI) [10,11] which were ultimately used to derived vegetation temperature condition index (VTCI) using the formula VTCI = 0.7×VCI+0.3×TCI. A comparative study has been carried out between SPI, Standardized Water-level Index (SWI), and VHI for the pre-monsoon and monsoon season over the Aravalli part of India [2]. According to this study, meteorological and hydrological conditions have to be considered to understand the phenomenon of drought. Droughts are estimated by using TCI, VCI and VHI validated through SPI and SWI [6]. Landsat data has been used for estimation of TCI, VCI, and VHI where Digital Numbers (DN) values, Brightness Temperature (BT), Normalized Difference Vegetation Index (NDVI), and Land Surface Temperature (LST) algorithm has been used to estimate drought over Lebanon [2]. MODIS instrument is another way to achieve RS data for EVI and LST. Indices derived were TCI, VCI, and VHI and compared with each other over East Java during El Nino year of 2015 [2]. Different indices discussed above reveal different information relevant to drought studies.

It has been reported that extremely hot days during winter and summer are increasing in some parts of Maharashtra and Karnataka [2] which makes it imperative to analyze drought conditions over this area. Also, in Maharashtra, over Vidarbha and Marathwada, scarcity of rainfall and misuse of available groundwater leads to droughts in almost every successive year and an increasing rate of farmer suicides is one of the consequences of increasing droughts in this region. Changing agricultural practices, less rainfall, water scarcity, and changing weather conditions play a crucial role in incidences of droughts in the study region.

2. Study Area and Data Used

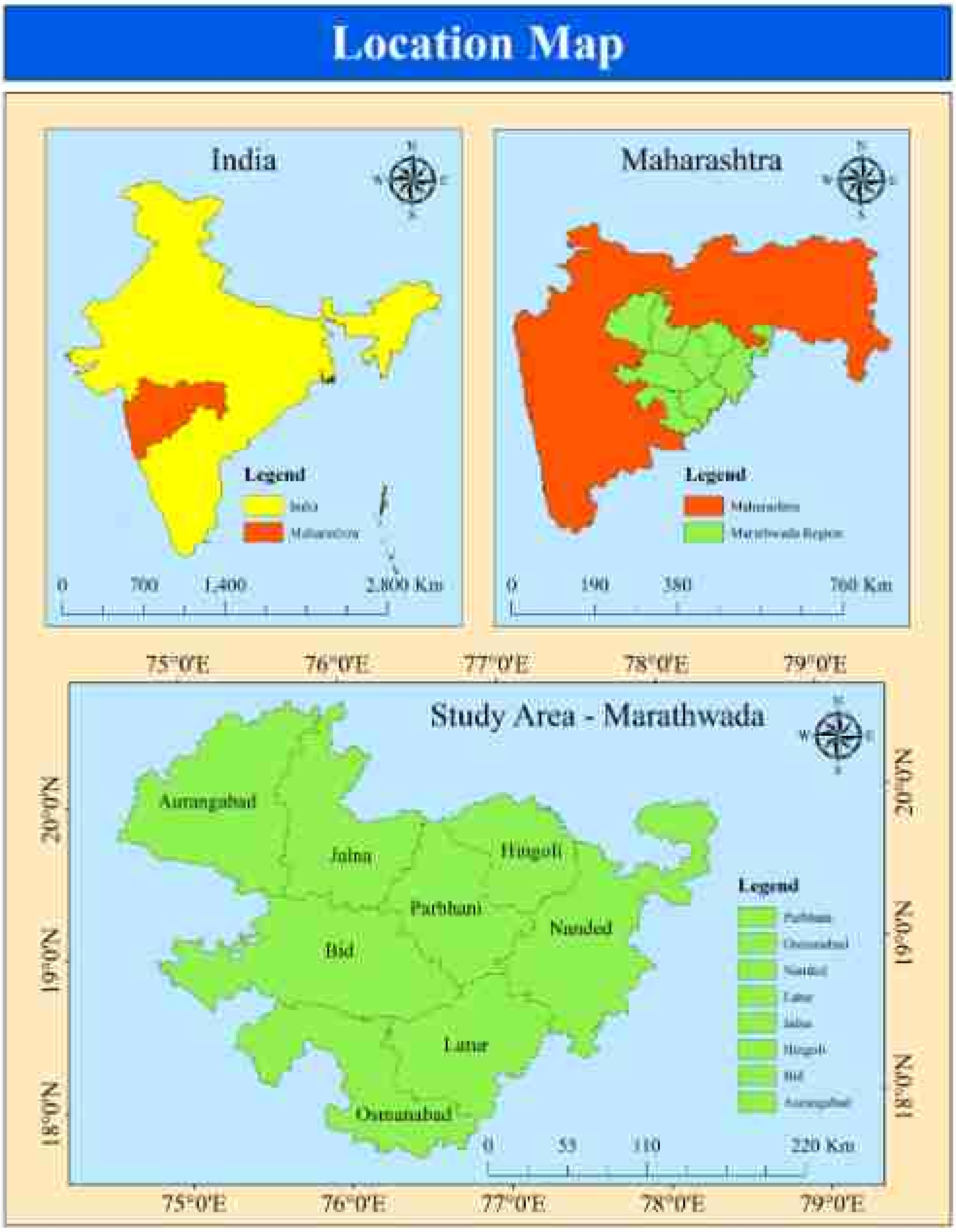


Figure 1. Location map

The main aim of the study is to investigate spatial and temporal aspects of drought over the Marathwada region (Figure 1) of Maharashtra (India) during the post-monsoon season using various indices like TCI, VCI, and VHI for the period of 17 years from 2001 to 2017. Marathwada region includes 8 districts of Maharashtra namely, Aurangabad, Nanded, Latur, Parbhani, Jalna, Beed, Hingoli, and Osmanabad. The total geographical area of the region is 64590 km^2. The major part of the region is located in the Godavari river basin, the largest river in southern India. The study area is one of the low precipitation zones in Maharashtra with an annual rainfall of approximately 882 mm from June to September (Source: http://www.rainwaterharvesting.org/urban/rainfall.htm). In the last 15 years of the study period, the lowest annual rainfall is observed over Aurangabad and the highest rainfall is received over Nanded. The study has been carried out in the post-monsoon season and it is known as "Rabi Crop Season" in Maharashtra. The average day temperature (maximum temperature) ranges from 28°C to 38°C and the average night temperature (minimum temperature) ranges from 20°C to 27°C. During summer temperature goes around 46°C in Nanded.

Satellite data and remote sensing technology play a vital role in monitoring natural hazards as well as crop health and development related to climatic conditions. The present study has utilized satellite data from Moderate Resolution Imaging Spectro Radiometer (MODIS) on-board terra satellite with two products namely MOD11A2 and MOD13A2. MOD1A2 is LST 8 days' composite L3 product at 1 km spatial resolution with emissivity bands whereas, MOD13A2 is NDVI and EVI 16 days' composite L3 product at 1 km spatial resolution available in the sinusoidal grid.

3. Pre-processing

The present study is based on Spatio-temporal analysis along with trend analysis of temperature and vegetation condition. All the satellite data has been projected to Albers Conical Equal Area projection with WGS1984 Datum. For the study, ENVI, ArcGIS, and ERDAS Imagine softwares has been used. For statistical analysis, ArcGIS and Microsoft Excel have been used. The study is carried out over Marathwada for the period of 17 years (2001 to 2017) and therefore required satellite data were acquired for 17 years.

4. Methodology

All pre-processed data of MOD11A2 and MOD13A2 is used to estimate TCI, VCI, and VHI using the methodology illustrated in Figure 2. Minimum and Maximum LST and NDVI are required to run the algorithm for achieving TCI and VCI, which were derived by building a model using the ERDAS Imagine software. The vegetation health index was computed using TCI and VCI index.

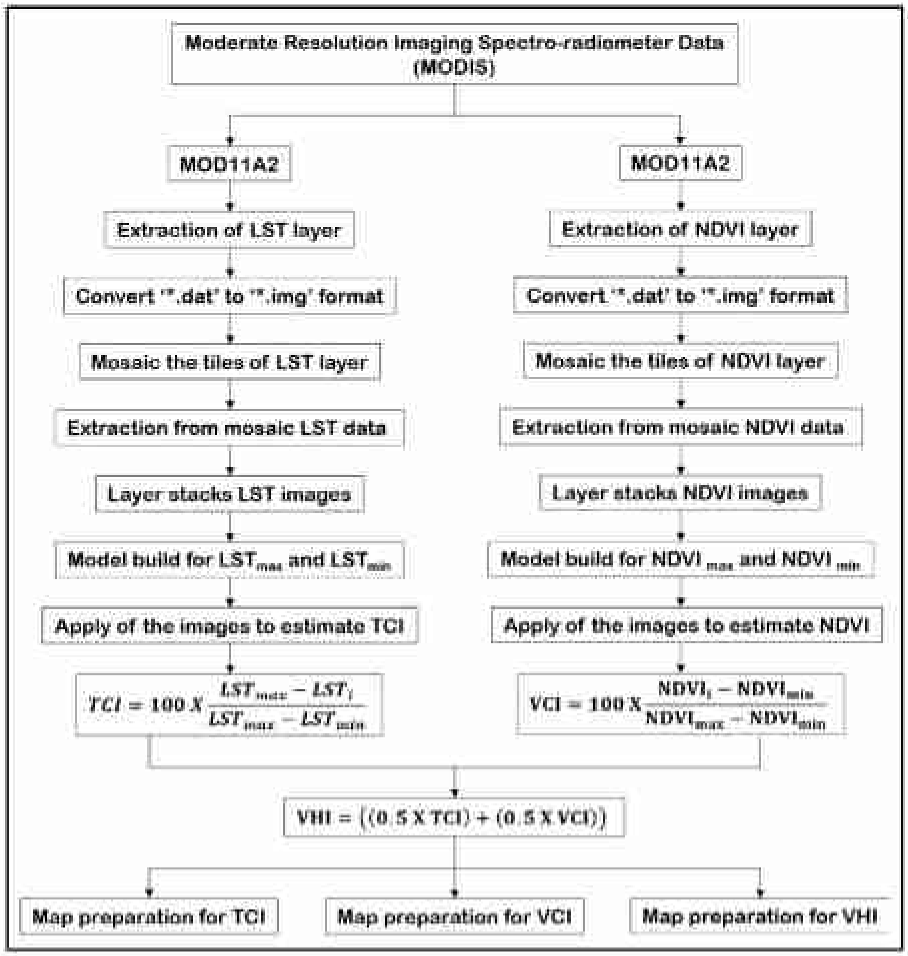


Figure 2. Methodology Tree Diagram

4.1. Remote Sensing Indices

There are several types of droughts among them agricultural drought has been monitored using the most efficient and popular spectral indices such as TCI, VCI, and VHI, which are focused on temperature-based stress, vegetation stress, and overall health of the vegetation respectively.

4.1.1. Temperature Condition Index (TCI)

Temperature Condition Index is used to estimate vegetation stress due to temperature and excessive wetness [10]. It represents relative changes in the thermal conditions obtained from land surface temperature data. Changes in the vegetation health due to thermal stress can be observed using TCI. It can be expressed in the formula as,

$$TCI = 100X\frac{LST_{\max} - LST_i}{LST_{\max} - LST_{\min}} \quad (1)$$

Where, LST_i, LST_{min}, and LST_{max} are defined as LST of the current month, minimum, and maximum LST values in multi-year series respectively. TCI values range from 0 to 100, where low TCI indicates unfavorable condition with high temperature and dryness and high TCI values indicates favorable condition with minimal temperature stress. Values near and more than 50 indicate moderate to good vegetation condition due to temperature.

4.1.2. Vegetation Condition Index (VCI)

The Vegetation condition index is a NDVI normalization pixel-based index, where it shows vegetation health due to vegetation condition. Stressed vegetation with lower NDVI depicts poor health of vegetation whereas NDVI of 1 depicts dense vegetation with good health. The use of NDVI is the primary tool for the description of vegetation phenology, continental land cover, vegetation classification, and dynamics and cropping practices [2]. VCI can be expressed as:

$$VCI = 100X\frac{NDVI_i - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \quad (2)$$

Where $NDVI_i$, $NDVI_{min}$, and $NDVI_{max}$ are defined as NDVI of the current month, minimum, and maximum of NDVI values in multi-year series respectively. VCI values range from 0 to 100, where low VCI values indicate unfavorable condition with high dryness and high VCI values indicates the favorable condition. This index indicates current vegetation conditions. VCI values around 50 suggest fair vegetation condition and values between 50 and 100 suggest good condition.

4.1.3. Vegetation Health Index (VHI)

This index is the combination of the moisture and thermal condition of vegetation which shows overall vegetation health [14]. Equal weights have been assigned to TCI as well as VCI since the moisture and temperature condition during the vegetation cycle is currently not known and it is assumed that the share of weekly TCI and VCI is equal [14]. Extremely unhealthy vegetation conditions (low VHI) are normally associated with both severe moisture stress (VCI) and thermal stress (TCI) and vice versa [14].

Vegetation Heath Index can be expressed as:

$$VHI = \left(\left(0.5X\ \ TCI\right) + \left(0.5X\ \ VCI\right)\right) \quad (3)$$

Lower values of VHI have a greater intensity of drought whereas higher values of VHI have lower intensity of drought. VHI has been used for many applications depending on purposes, like drought severity, time and period of drought, and normal drought identification. There are 5 classes of drought for identifying the vegetation health or drought condition.

Table 1. Drought class for VHI

Drought Class	VHI
Extreme Drought	< 10
Severe Drought	≥ 10 and ≤ 20
Moderate Drought	≥ 20 and ≤ 30
Mild Drought	≥ 30 and ≤ 40
No Drought	≥ 40

5. Results and Discussion

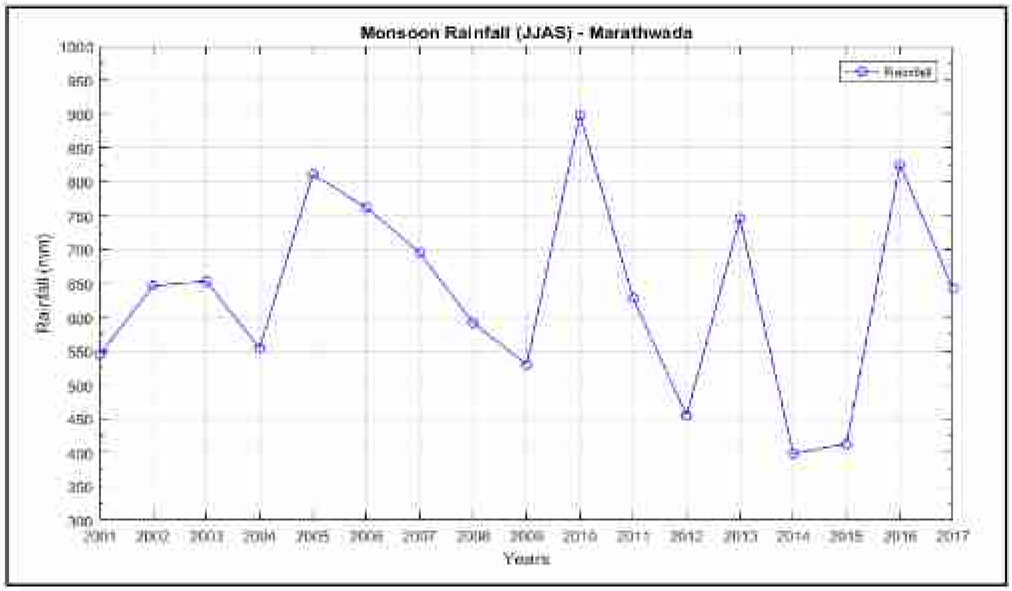


Figure 3. Rainfall during Monsoon (JJAS) – Marathwada

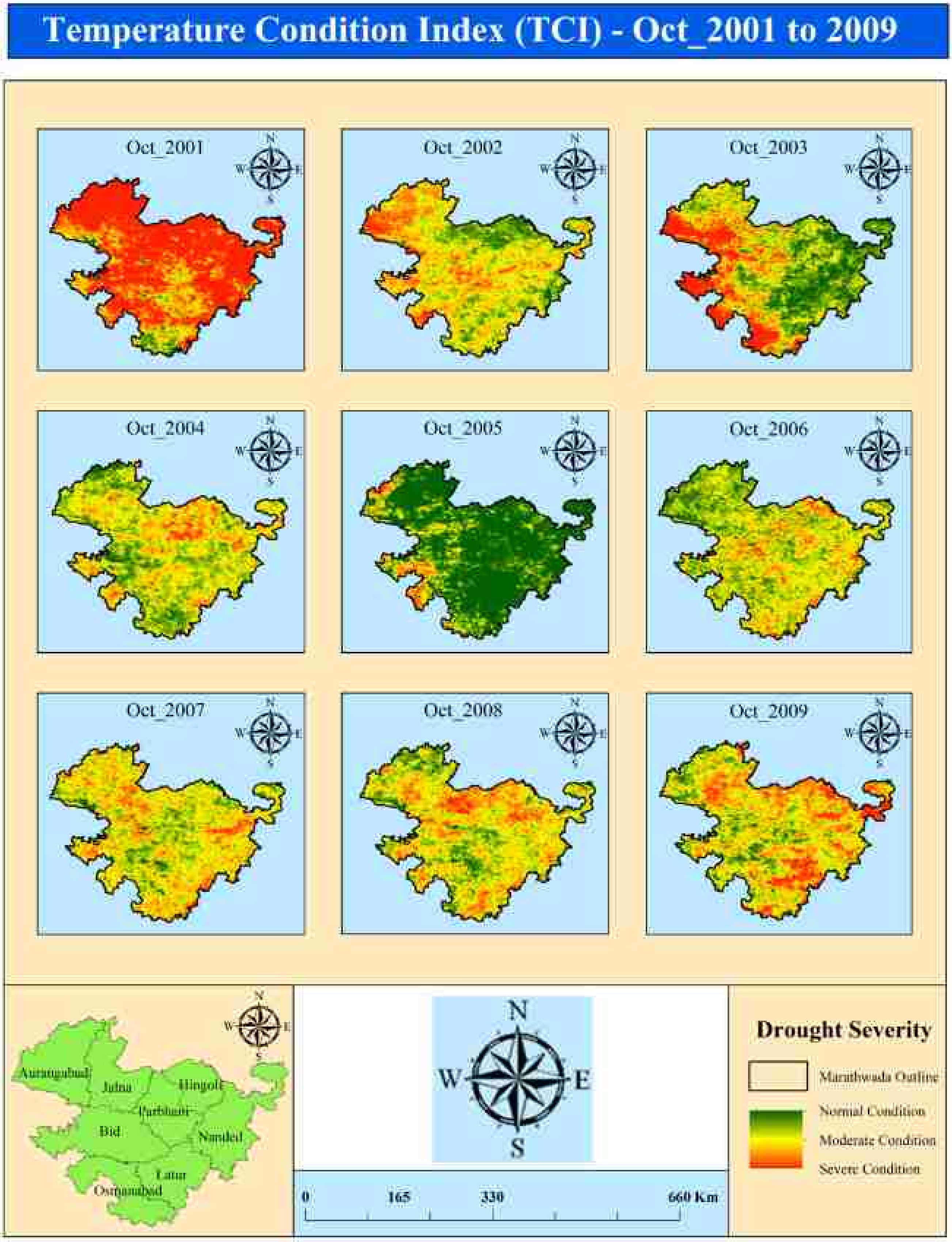


Figure 4. Temperature Condition Index (TCI) - October 2001 to 2009

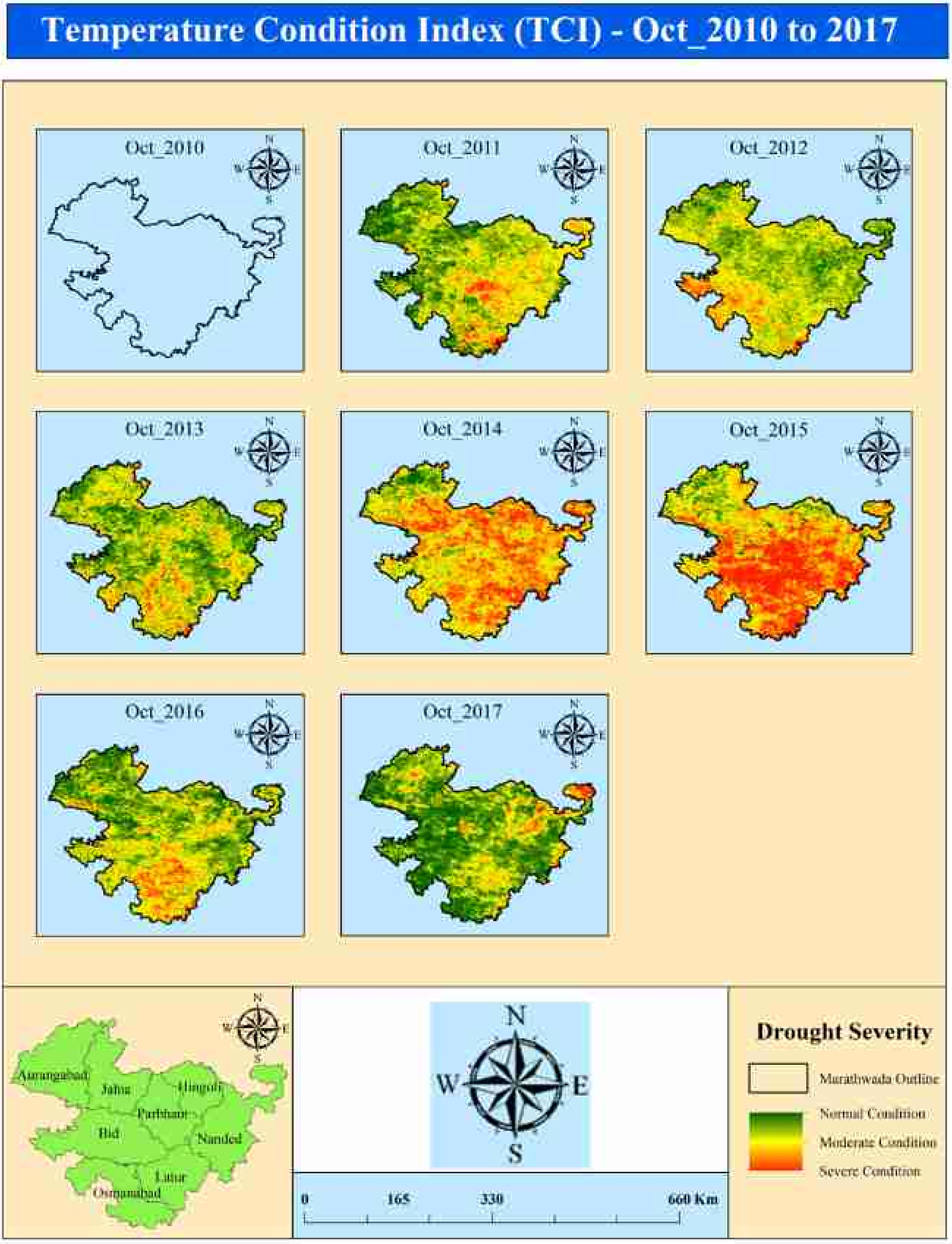


Figure 5. Temperature Condition Index (TCI) - October 2010 to 2017

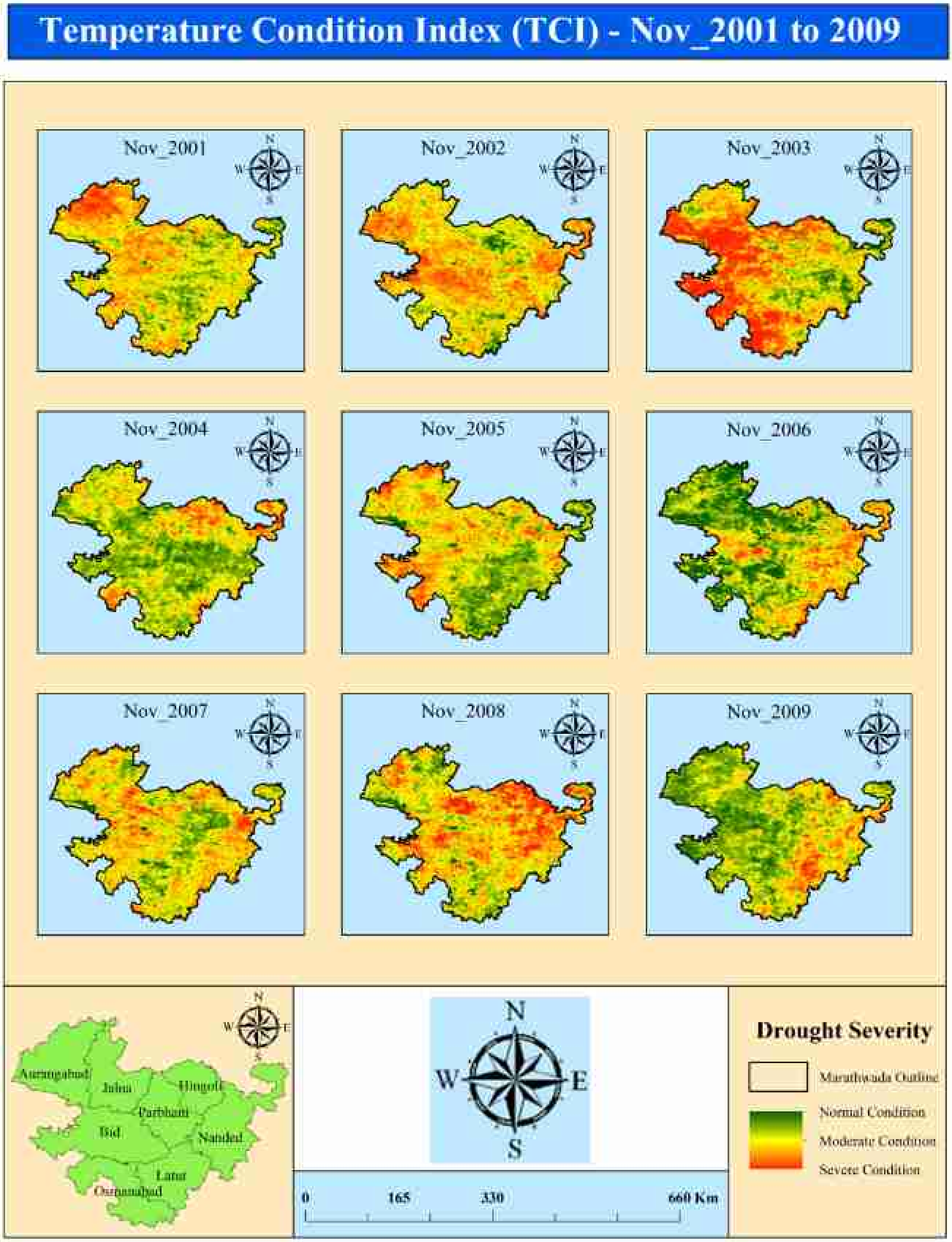


Figure 6. Temperature Condition Index (TCI) - November 2001 to 2009

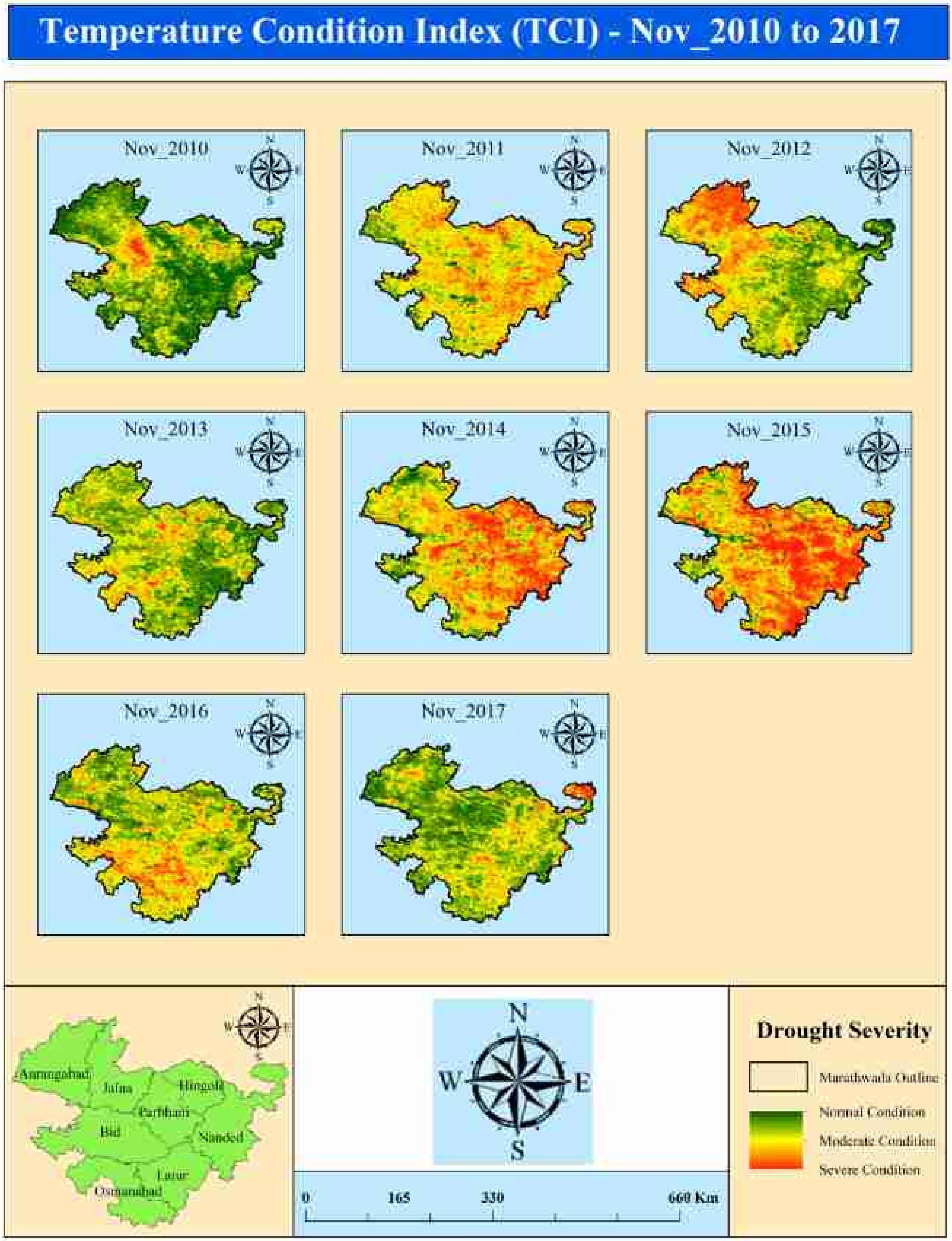


Figure 7. Temperature Condition Index (TCI) - November 2010 to 2017

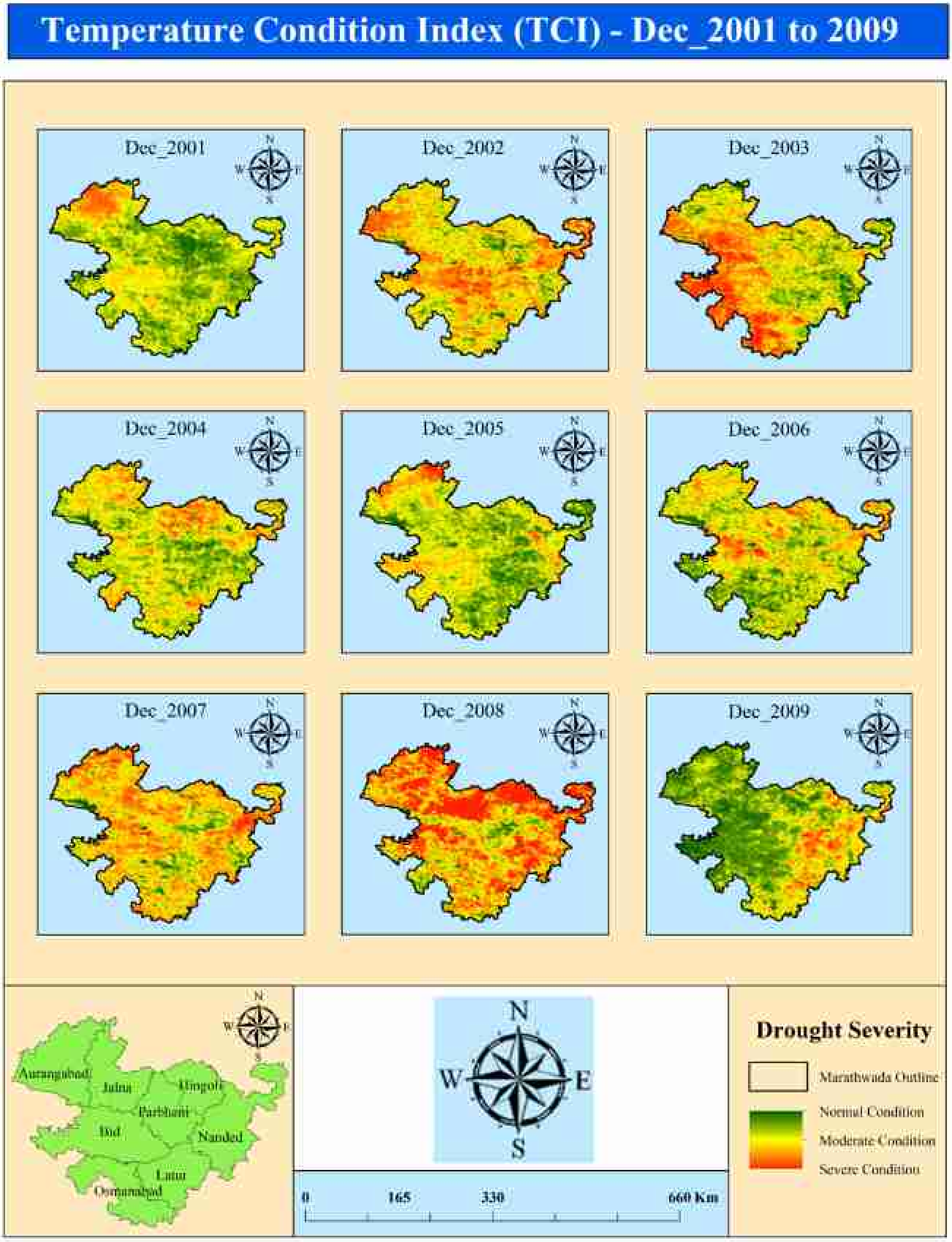


Figure 8. Temperature Condition Index (TCI) - December 2001 to 2009

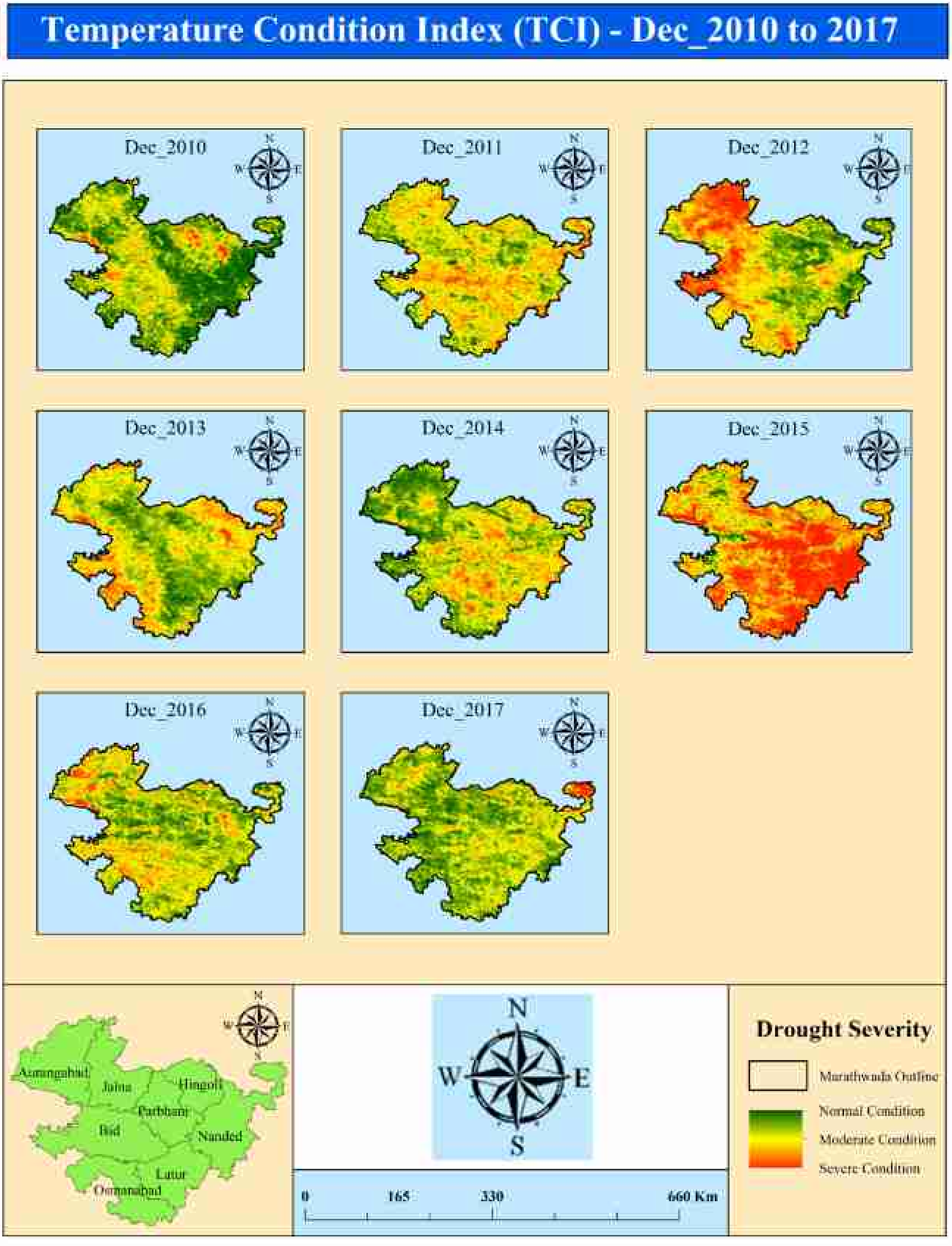


Figure 9. Temperature Condition Index (TCI) - December 2010 to 2017

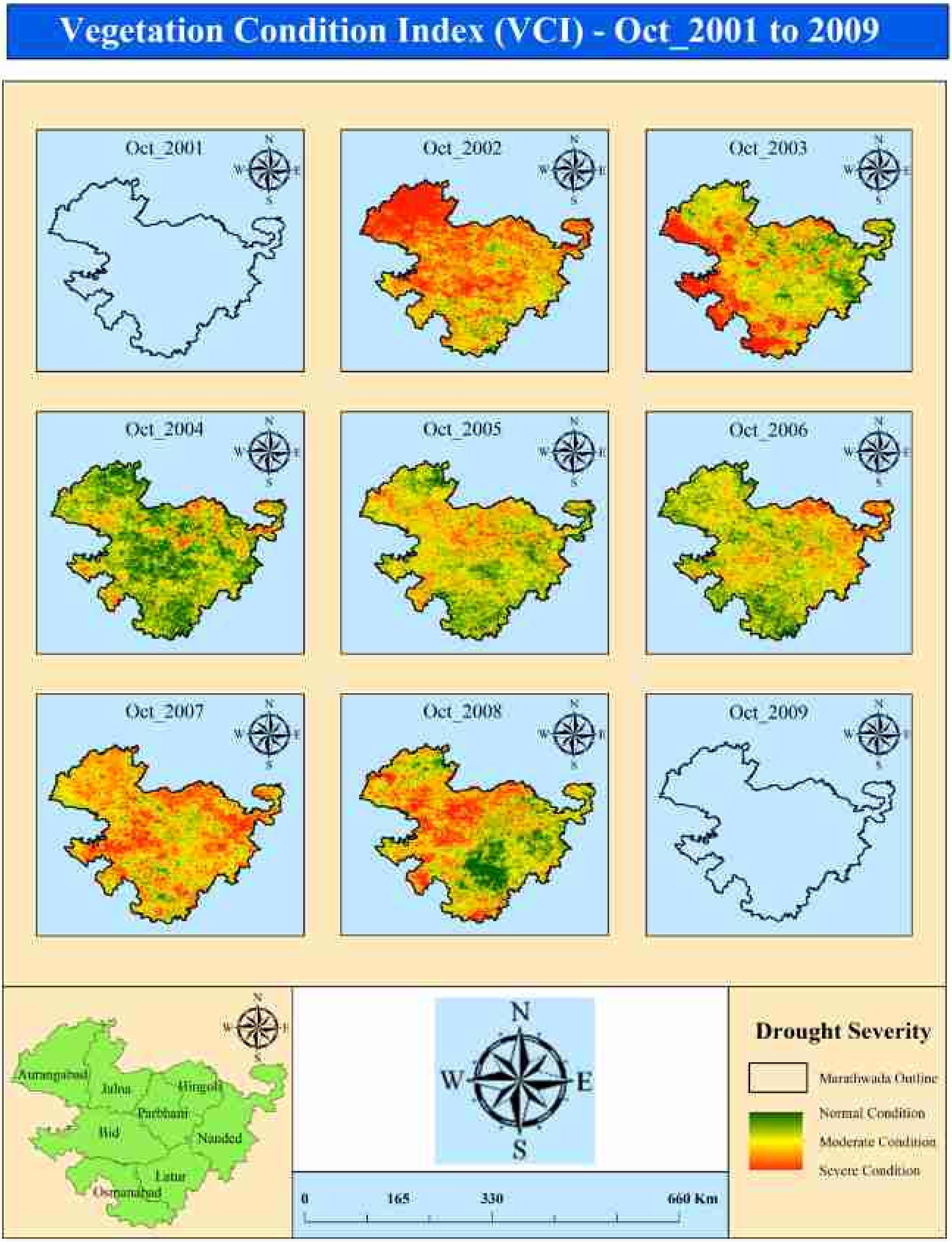


Figure 10. Vegetation Condition Index (VCI) - October 2001 to 2009

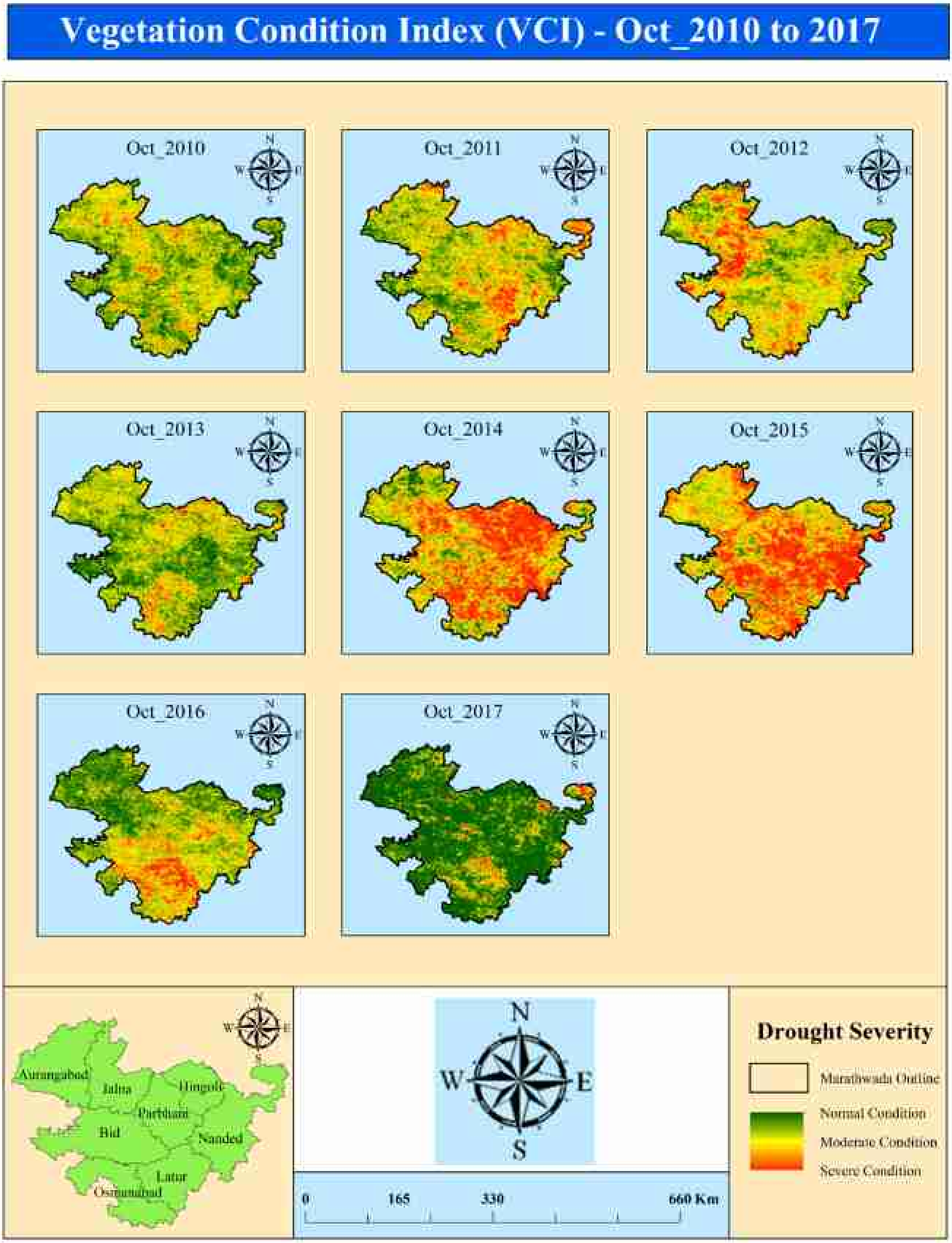


Figure 11. Vegetation Condition Index (VCI) - October 2010 to 2017

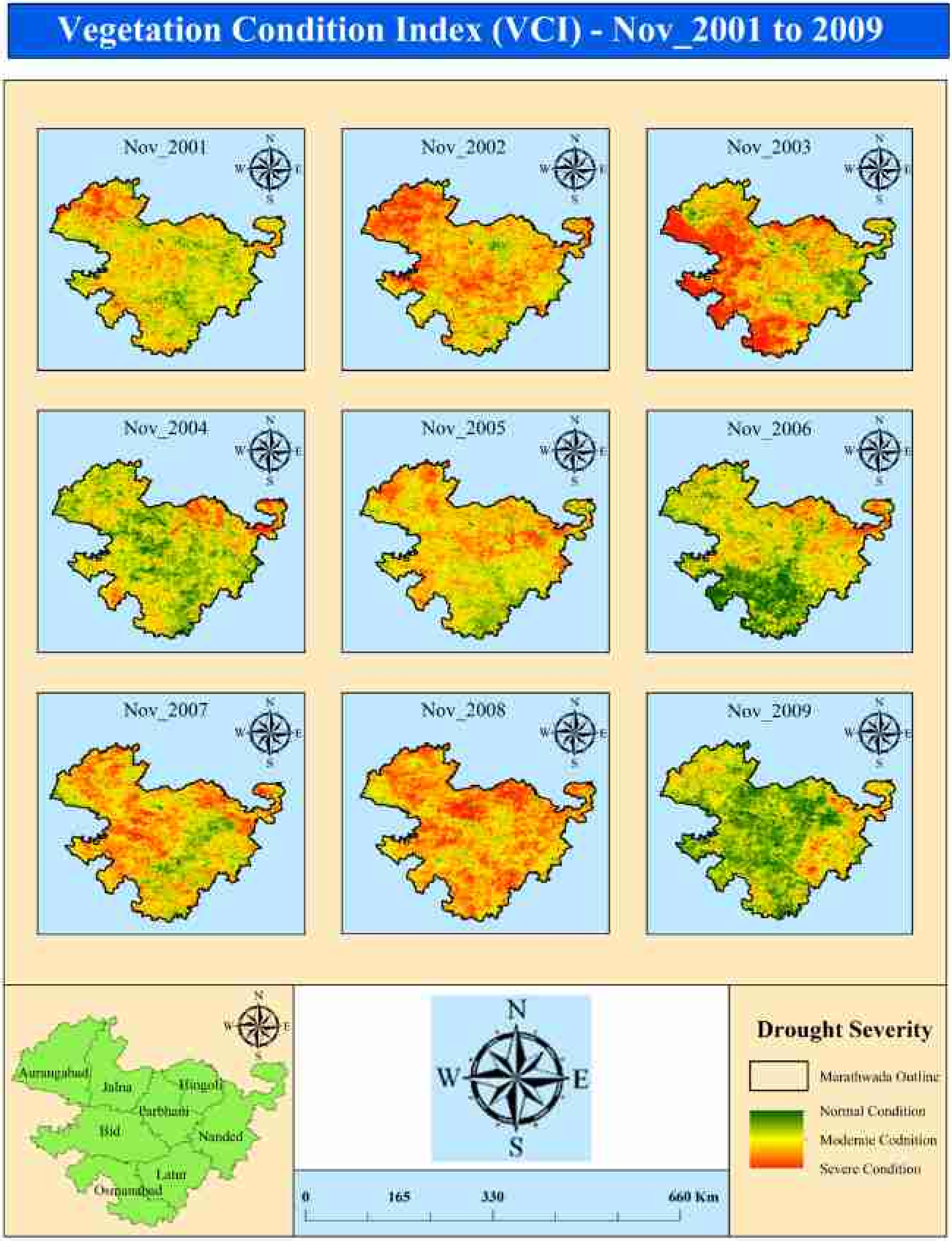


Figure 12. Vegetation Condition Index (VCI) - November 2001 to 2009

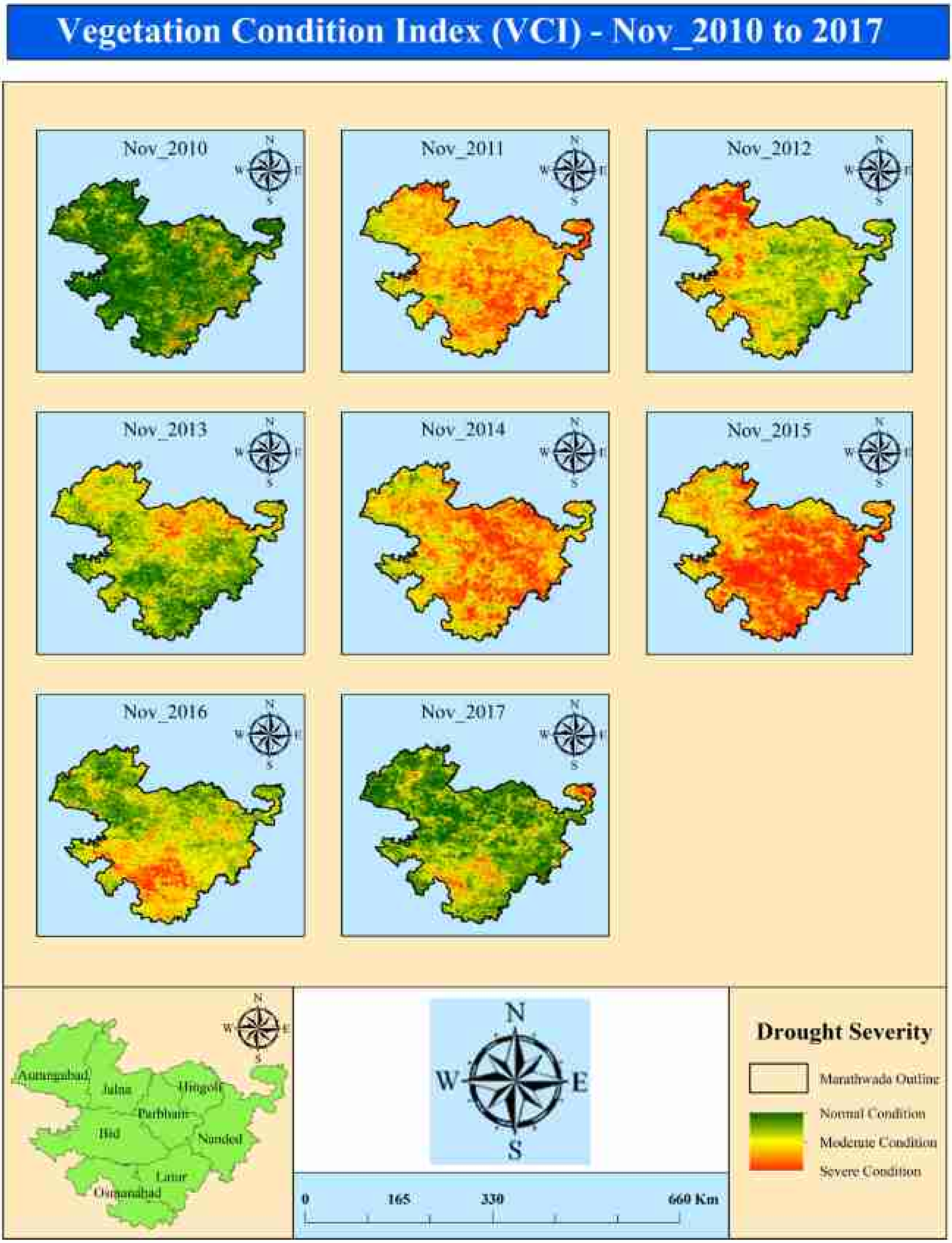


Figure 13. Vegetation Condition Index (VCI) - November 2010 to 2017

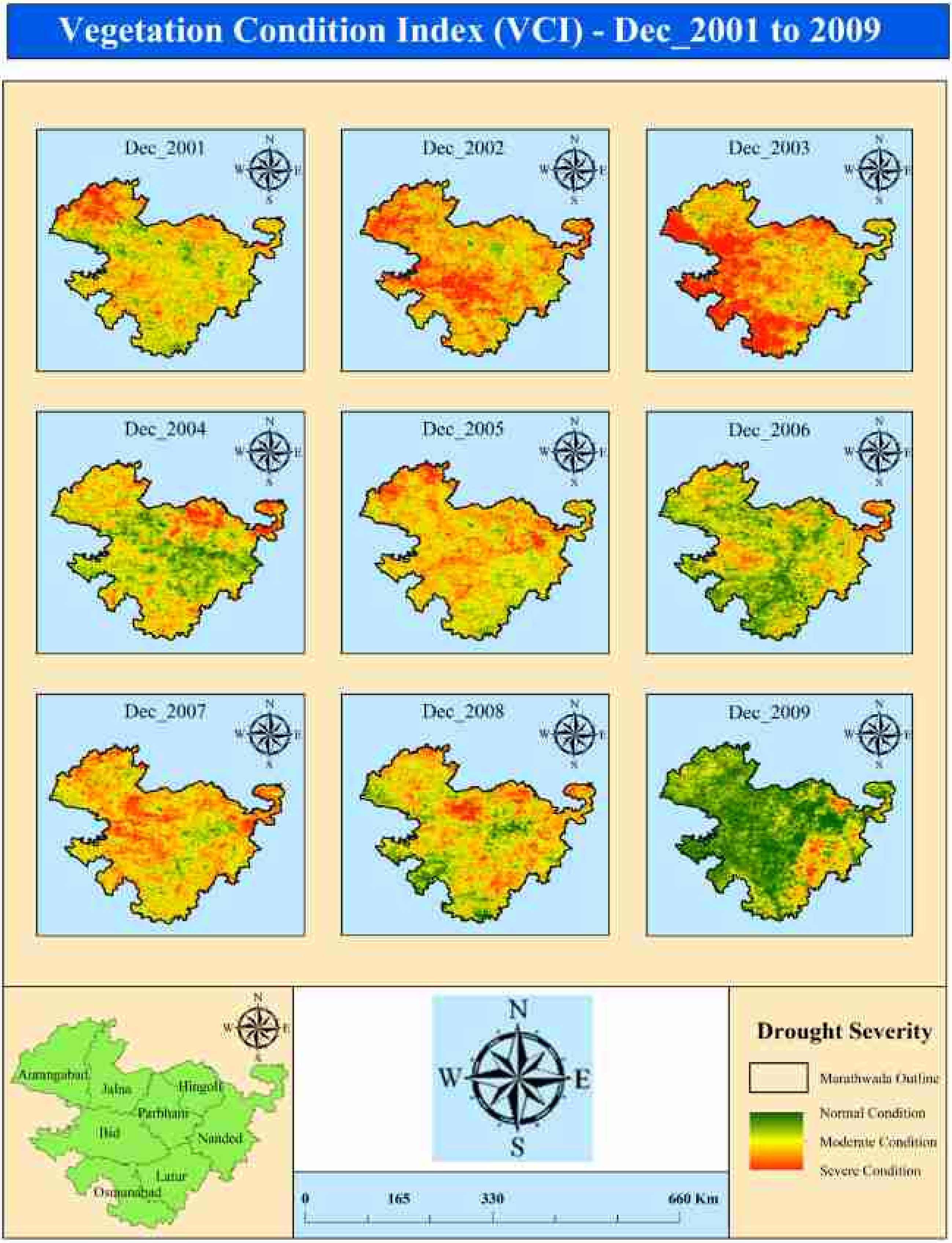


Figure 14. Vegetation Condition Index (VCI) - December 2001 to 2009

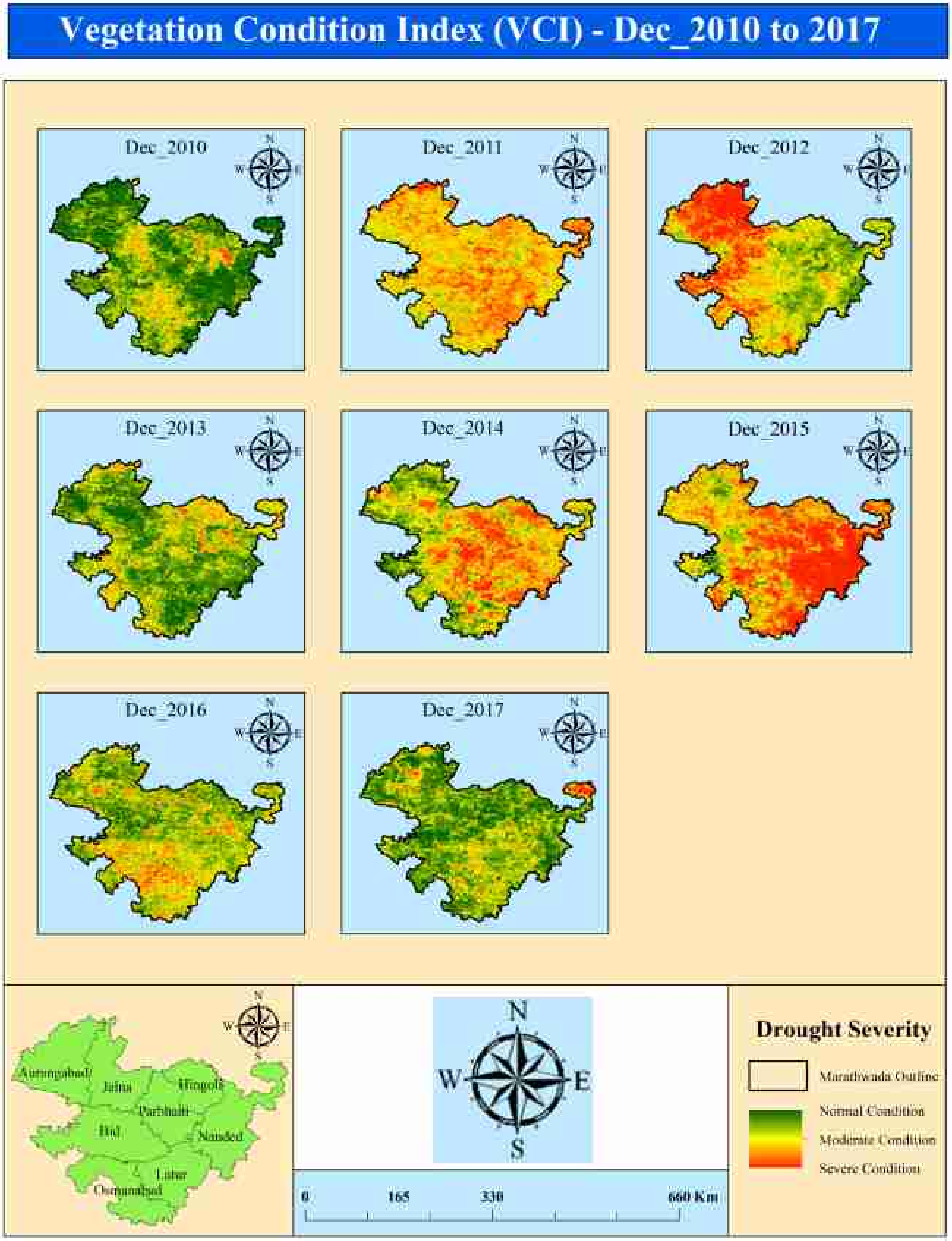


Figure 15. Vegetation Condition Index (VCI) - December 2010 to 2017

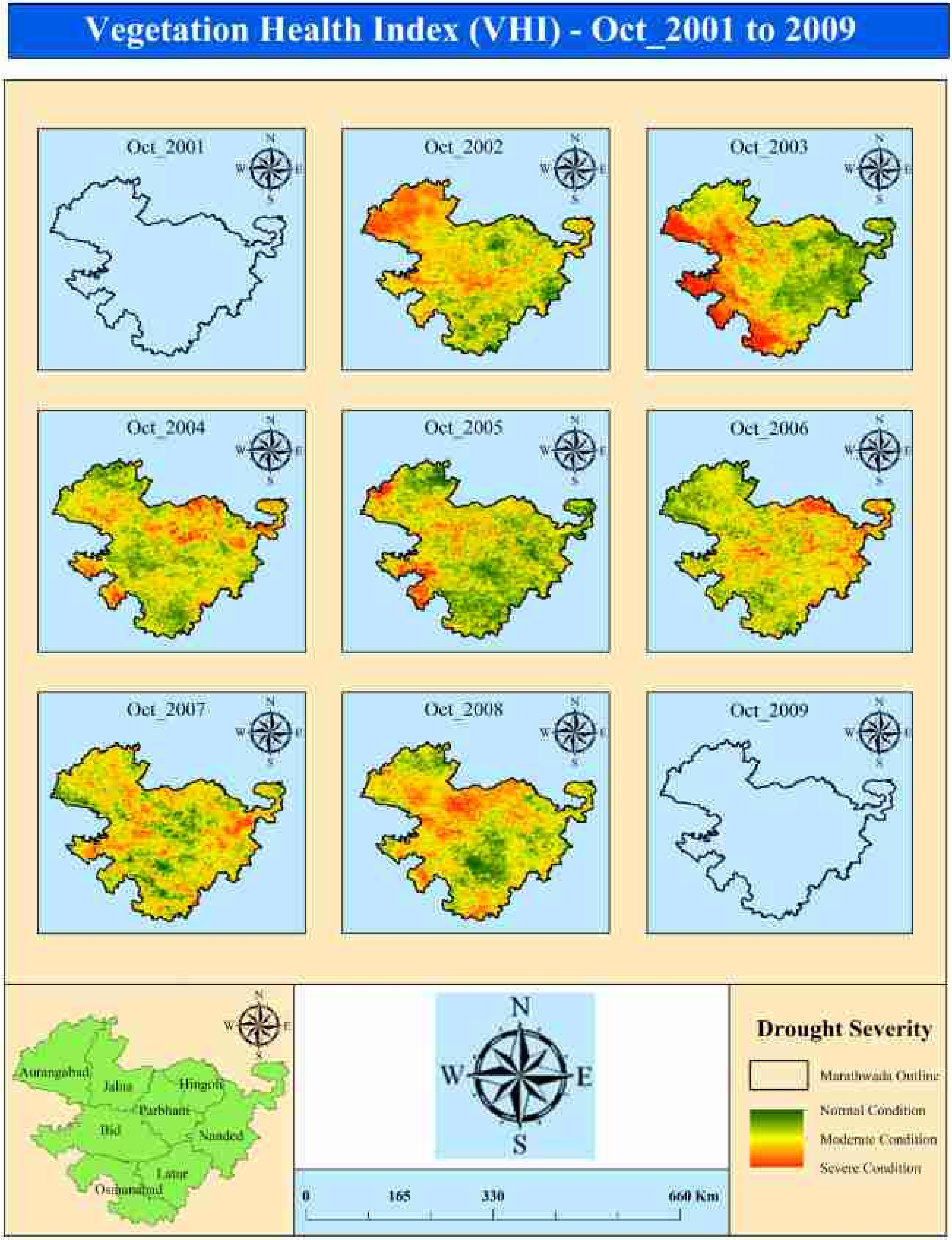


Figure 16. Vegetation Health Index (VHI) - October 2001 to 2009

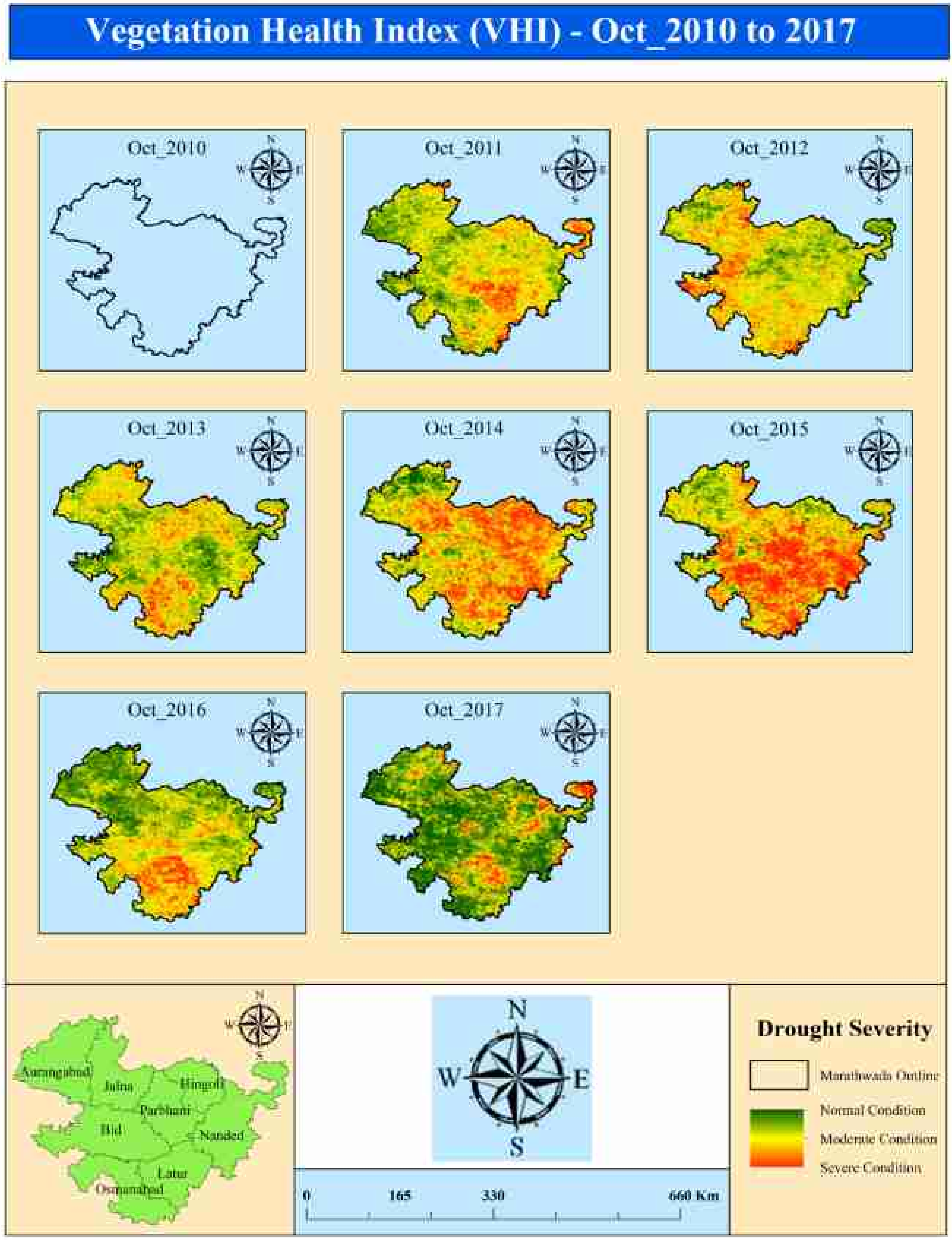


Figure 17. Vegetation Health Index (VHI) - October 2010 to 2017

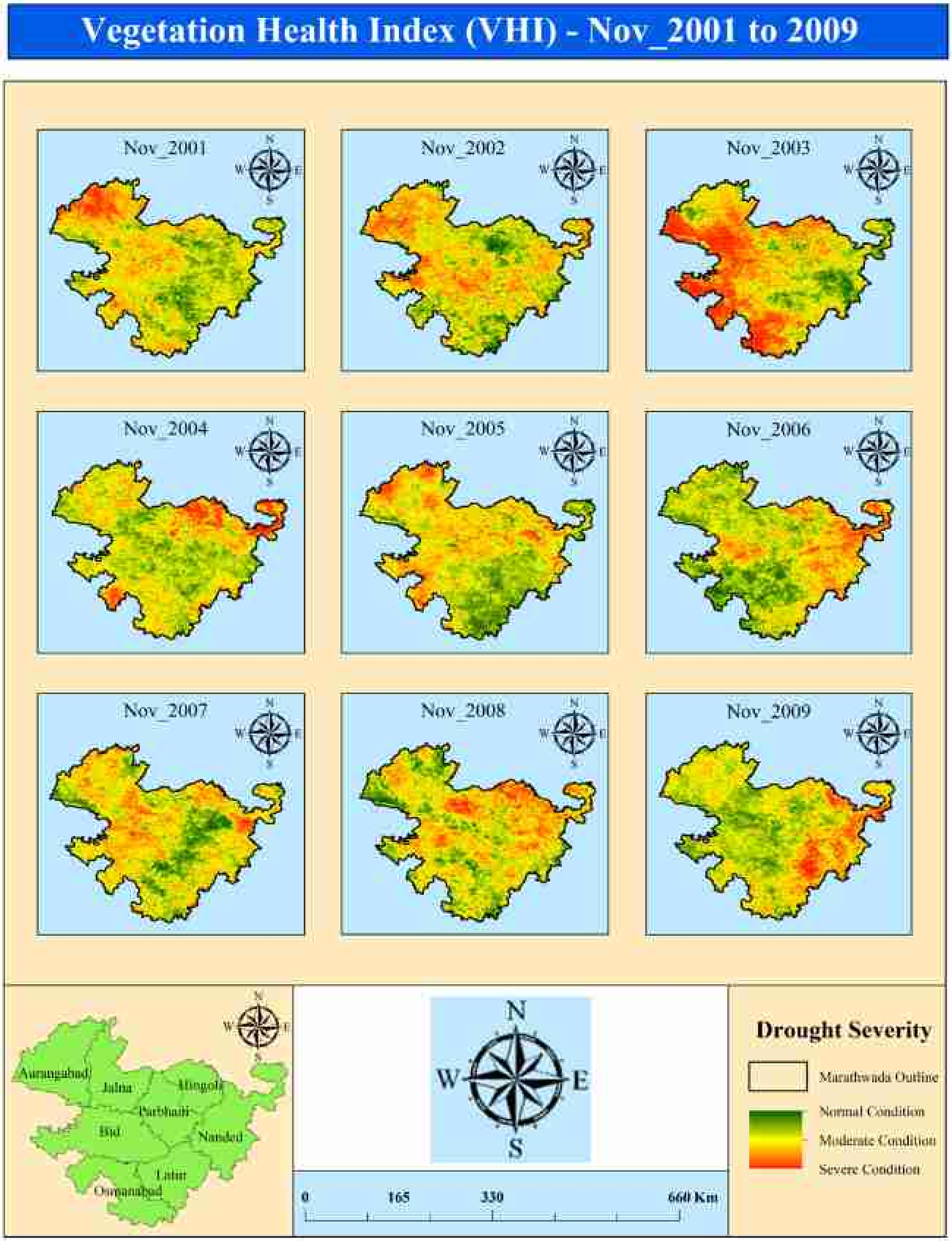


Figure 18. Vegetation Health Index (VHI) - November 2001 to 2009

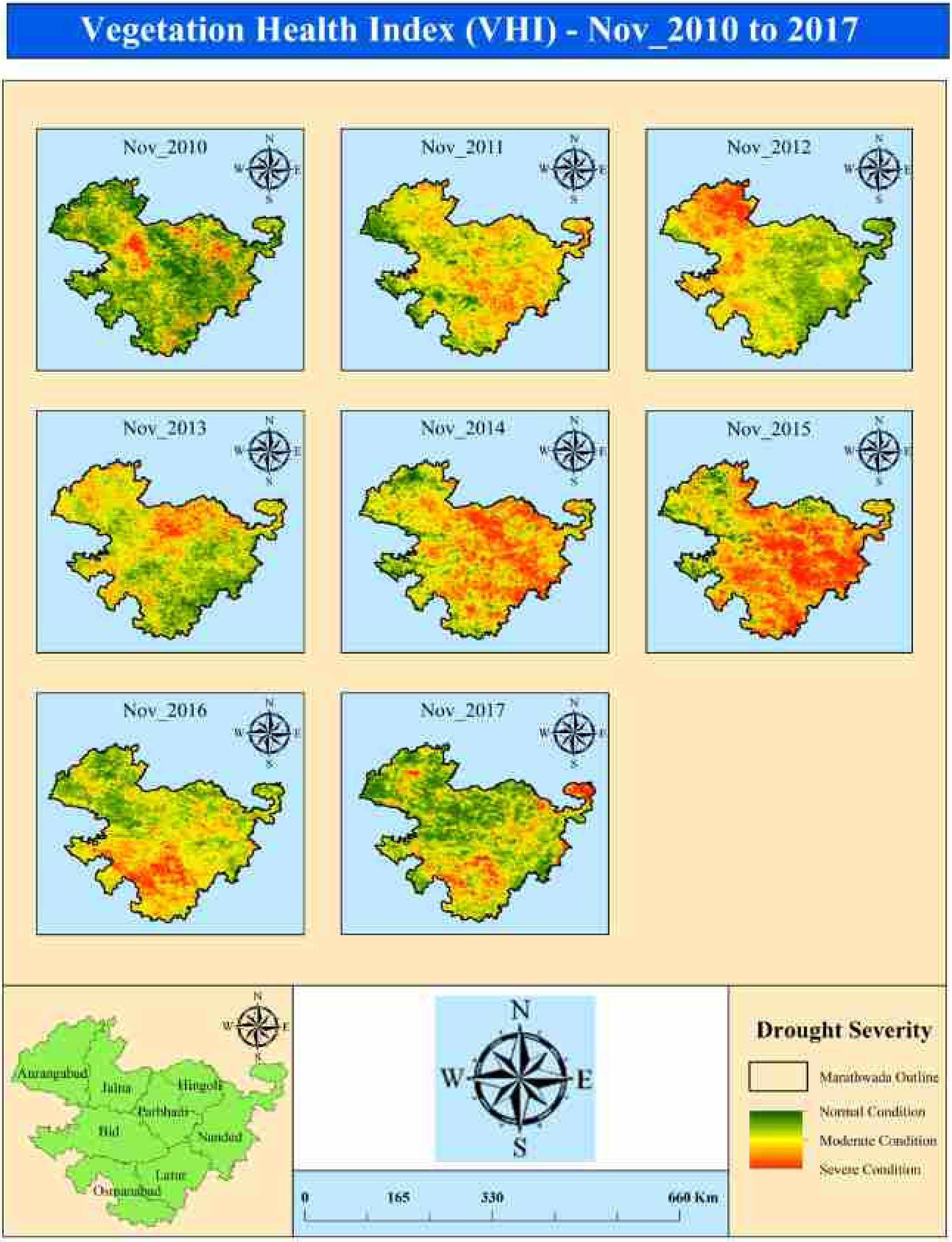


Figure 19. Vegetation Health Index (VHI) - November 2010 to 2017

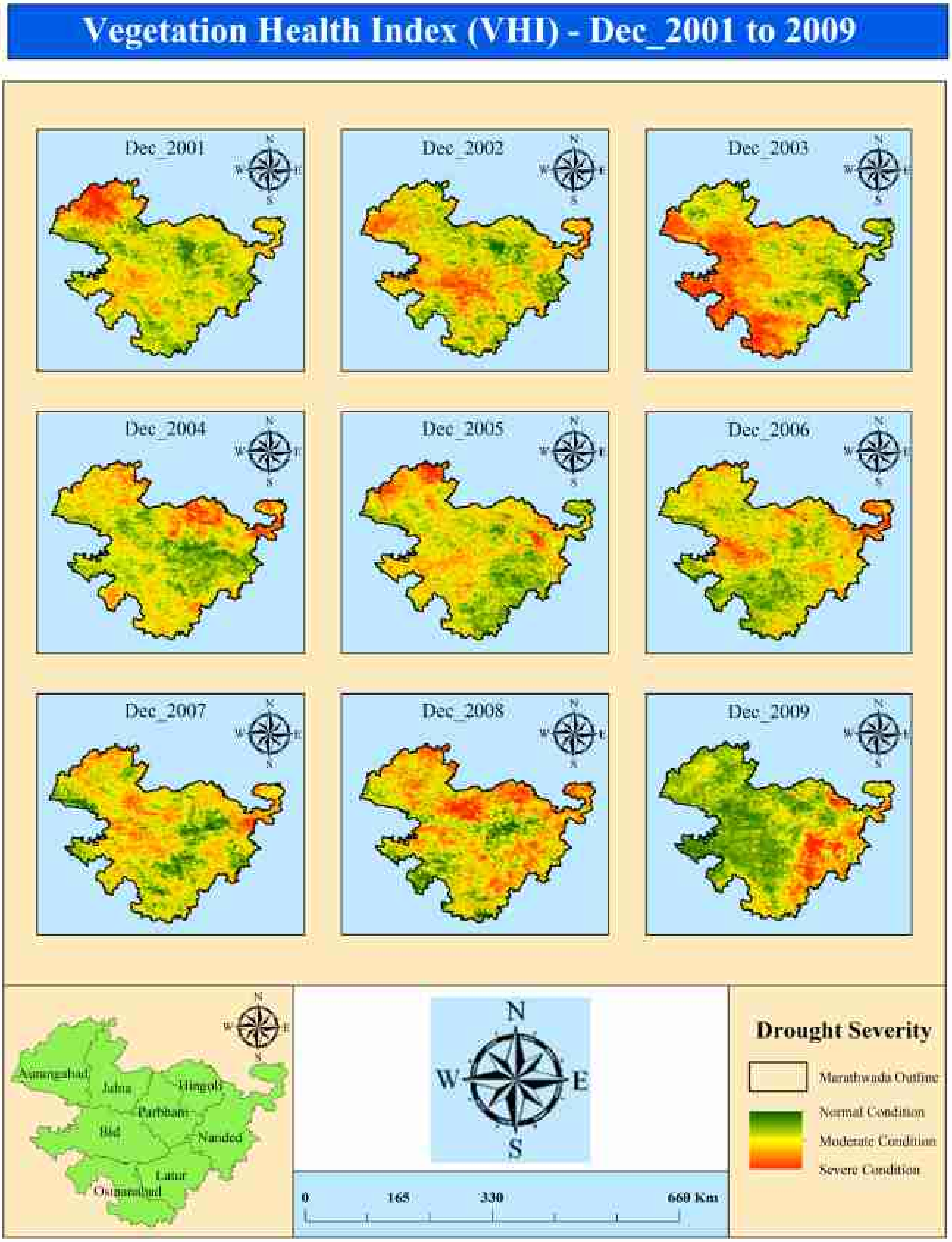


Figure 20. Vegetation Health Index (VHI) - December 2001 to 2009

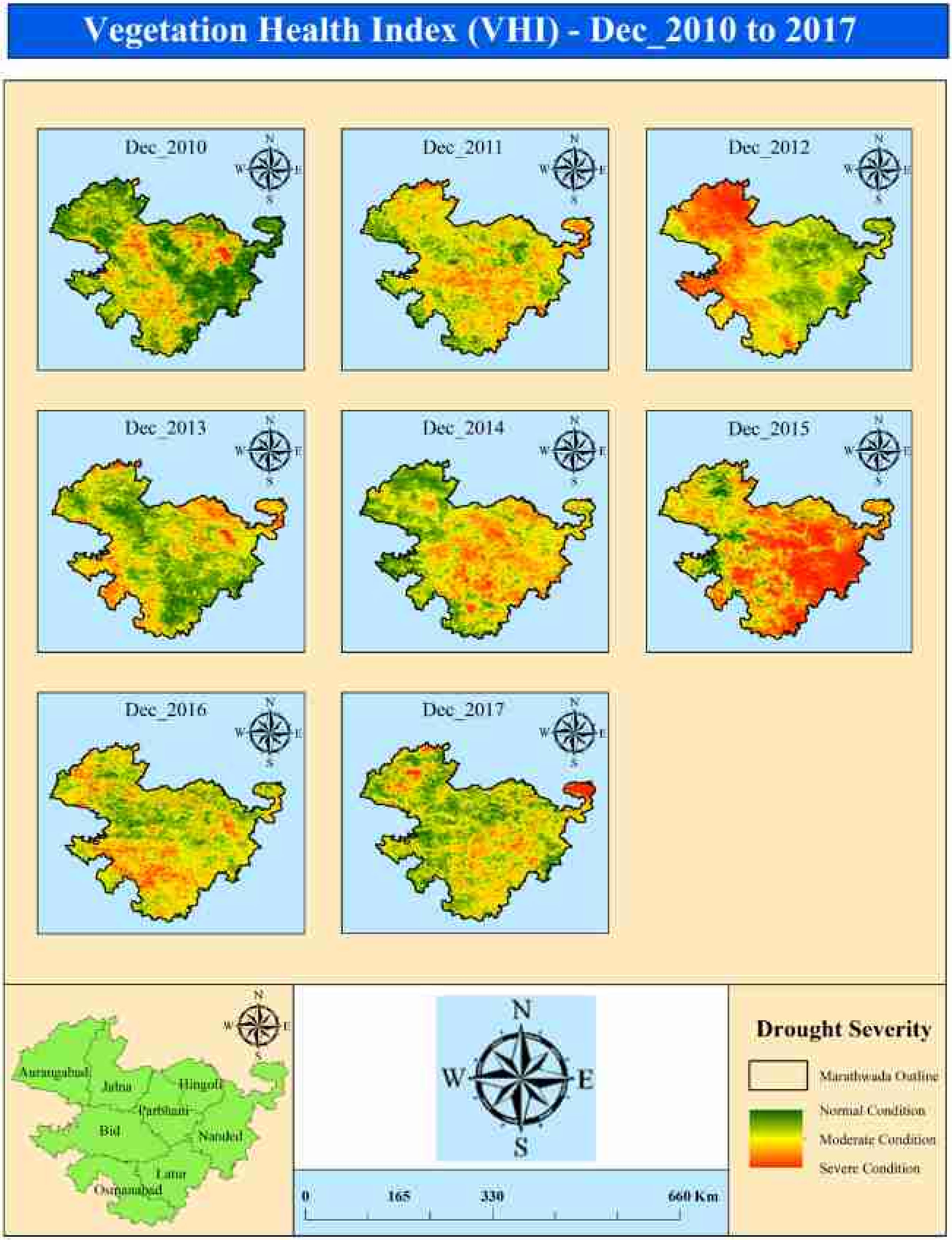


Figure 21. Vegetation Health Index (VHI) - December 2010 to 2017

In the present study agricultural drought-based remote sensing indices namely TCI, VCI and VHI were implemented for the year 2001 to 2017. The highly variable nature of rainfall over Marathwada can be understood from Figure 3, which is the primary reason for high drought frequency in the region. Scanty rainfall in the monsoon season over the Marathwada region leads to dryness and poor vegetation condition. Changes in the drought condition due to thermal impact, vegetation condition, and overall crop health were identified in this research. Overall crop health helps to understand the intensity of drought. As drought depends on various factors, such as rainfall deficiency, the moisture-holding capacity of the soil, heat waves, etc. These indices assist in identifying and assessing drought situations without any subjectivity.

TCI, VCI, and VHI results were obtained for the post-monsoon season (i.e. October, November, and December). The spatial pattern of the above three indices for the month of October is shown in Figure 4, Figure 5, Figure 10, Figure 11, Figure 16, and Figure 17. Wherever VHI shows green shades in these maps, it implies better NDVI and LST values over the same due to normal precipitation/moisture availability.

It can be noticed that overall the years 2014 and 2015 (Figure 5, Figure 11, and Figure 17) suffered a lot from dryness and thermal stress than any other years over Marathwada. Whereas if observed district-wise then, the western part of Beed and Aurangabad suffered from temperature stress. In the years 2007, 2008, and 2009 (Figure 4), most of the parts of Jalna and Hingoli suffered from moderate stress. In October 2001 (Figure 4), a severe drought situation occurred due to thermal stress covering almost the entire region. Due to the unavailability of October 2010 LST data, TCI for the same has not been generated (Figure 4).

In the case of VCI, October data for the years 2001 and 2009 were not available (Figure 10), and therefore, maps for these could not be generated. Like TCI, in VCI again 2014 and 2015 show poor vegetation conditions with severe drought (Figure 11). The years 2002, 2003, 2007, 2008, 2011, and 2012 appeared as moderate to poor vegetation conditions. If observed district-wise, Aurangabad suffered from dryness and less moisture during 2002 and 2012 identified with low NDVI values during the study. Good vegetation conditions with high NDVI values were observed in the years 2010, 2016, and 2017 where rainfall seems to be more prominent and sufficiently high (Figure 10, Figure 11). Except for the years 2014 and 2015, all the other years detected moderate to no drought conditions due to vegetation cover (moisture condition). In most of the years, moderate vegetation condition has been observed over the central part of Marathwada during the study of VCI.

It has been noticed that vegetation health is a combination of TCI and VCI representing thermal stress and unfavourable moisture condition. Therefore the results observed through VHI closely match with those of TCI and VCI results.

The TCI map for the month of November (Figure 6, Figure 7) revealed severe drought conditions during the years 2001, 2002, 2003, 2008, 2012, 2014, 2015 in some districts or over the entire region. Moderate to fair conditions were observed for the rest of the years. The three years 2003, 2014, and 2015 stand out with sweeping drought situations over the region. Similar conditions are represented by the VCI index represented in Figure 12 and Figure 13. But the year 2007 indicates more severity in the case of VCI than TCI. VHI results for the month of November brought out similar characteristics (Figure 18, Figure 19).

During December the severity of drought increased during the years 2008 and 2012 according to TCI (Figure 8, Figure 9). Severe conditions observed during October and November in the year 2015 are also observed in December, suggesting a prolonged drought situation during the end of the season. The same result can be concluded for the results obtained with VCI (Figure 14, Figure 15). The VHI map for the year 2012 (Figure 21) indicated more severe drought in the eastern part of the region (Aurangabad, Jalna, and Bid districts) compared to the months of October and November. Close observation during this year suggests that drought propagated from west to east in the region.

6. Conclusion

Over Marathwada, rainfall is very scanty which has led to semi-arid to arid climatic conditions. One of the geographical factors that contribute to the scanty rainfall is the location of this region in the rain shadow zone. Despite its climatic adversity, Marathwada contributes to about 10.10% of the state gross domestic product of Maharashtra, and 73.83% of its population is engaged in agriculture [16]. The study of drought over this region using remote-sensing-based indices has led to the identification of geographical variations in the intensity and severity of drought over this area. Since the remote sensing data are more continuous spatially, they are best suited to bring out the minor details of a hazard that inflicts a vast region. The present study has been successful in identifying the districts in the region which are more prone to drought. These are mostly the western districts of Aurangabad, Jalna, Bid, and Osmanabad. They are very well represented by the drought of 2003. But the drought in 2014 and 2015 also revealed that the eastern districts of Nanded, Parbhani, Latur, and to some extent Hingoli are equally susceptible to drought. In most case, it is noticed that drought usually begins first in the northeastern or eastern part. During the entire study period it was noticed that during more than 50% of years, at least half of the area was under moderate to severe drought conditions. With changing climate Marathwada has to be ready for higher rainfall variability and increased uncertainty of assured rainfall. The districts that are highly prone to drought will have to formulate plans for mitigation of future droughts.

References

[1] Wilhite, D.A., Svoboda, M.D., Hayes, M.J. "Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness," *Water Resource Manage*, 21, 763-774, 2007.

[2] Bhuiyan, C., "Various Drought Indices for Monitoring Drought Condition in Aravalli Terrain of India,". *XXth ISPRS Conference, Int. Soc. Photogrammetry and Remote Sensing, Istambul*, 2004.
[3] McKee, T.B., Doesken, N.J., Kleist, J., "The Relationship of Drought Frequency and Duration to Time Scales," *Eighth Conference on Applied Climatology-California*, 17-22. 1993.
[4] Othman, M., Ash'aari Z.H., Muharam F.M., Sulaiman W.N.A., Hamisan H., Mohamad N.D., Othman N.H. "Assessment of drought impacts on vegetation health: a case study of Kedah". *IOP Conference Series: Earth and Environmental science,* 37. 1-13, 2016.
[5] Dhorde, A.G., Patel, N.R., "Spatio-temporal variation in terminal drought over western India using dryness index derived long-term MODIS data", Ecological Informatics, 32. 28-38, 2016.
[6] Kundu, A., Dwivedi, S., Dutta, D., "Monitoring the vegetation health over India during contrasting monsoon years using satellite remote sensing indices," *Arabian Journal of Geosciences*, 9 (2). 1-15. 2016.
[7] Himanshu, S.K., Singh, G., Kharola, N., "Monitoring of Drought using Satellite Data," *International Research Journal of Earth Sciences*, 3 (1). Jan.2015.
[8] Kulkarni, S., Gedam S., Dhorde A., "Assessment of impacts of agro-climatological droughts over Marathwada, India, using remote sensing technologies," *38th Asian Conference on Remote Sensing-Space Applications: Touching Human Lives*, 2017.
[9] Guttman, N.B., "Comparing the Palmer Drought Index and the Standardized Precipitation Index," *Journal of the American Water Resource Association*, 34 (1). 113-121. 1998.
[10] Singh, R.P., Roy, S., Kogan F., "Vegetation and Temperature Condition Indices from NOAA AVHRR Data for Drought Monitoring Over India," *International Journal of Remote Sensing*, 24 (22). 4393-4402, Nov.2003.
[11] Kogan, F.N., "Droughts of the Late 1980s in the United States as Derived from NOAA Polar-Orbiting Satellite Data," *Bulletin of the American Meteorological Society*, 76 (5), 655-668, May.1995.
[12] Ghaleb, F., Mario, M., Sandra, A.N., "Regional Landsat-Based Drought Monitoring from 1982 to 2014," *MDPI Climate*, (3). 563-577. 2015.
[13] Amalo, L.F., Hidayat, R., Haris, "Comparison between remote-sensing-based drought indices in East Java". *IOP Conference Series: Earth and Environmental Science*, 1-7, Jan.2009.
[14] Dhorde, A.G., Korade, M.S., Dhorde, A.A., "Spatial distribution of temperature trends and extremes over Maharashtra and Karnataka states of India", *Theoretical and Applied Climatology*, 130. 191-204, 2017 .
[15] Kogan, F.N., "Operational Space Technology for Global Vegetation Assessment," *Bulletin of the American Meteorological Society*, 82 (9), 1949–1964, Sep.2001.
[16] Kelkar, Vijay (2013): "Report of the High Level Committee on Balanced Regional Development of Maharashtra," Planning Department, Mumbai.