

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

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**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 to 2015 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 uncomfortable 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 portrayed a 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<sup>th</sup> 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<sup>th</sup> 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 termed the 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. Rothfus and described in a 1990 National Weather Service-National Oceanic and Atmospheric Administration (NWS-NOAA), United States of America (USA) (Rothfus, 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 experimental 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 is 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 eye lens 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) (Rothfus, 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 (Rothfus, 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 (Rothfus, 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:

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

where,

HI = Heat Index (°Fahrenheit)

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

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 evaluating 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.

**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

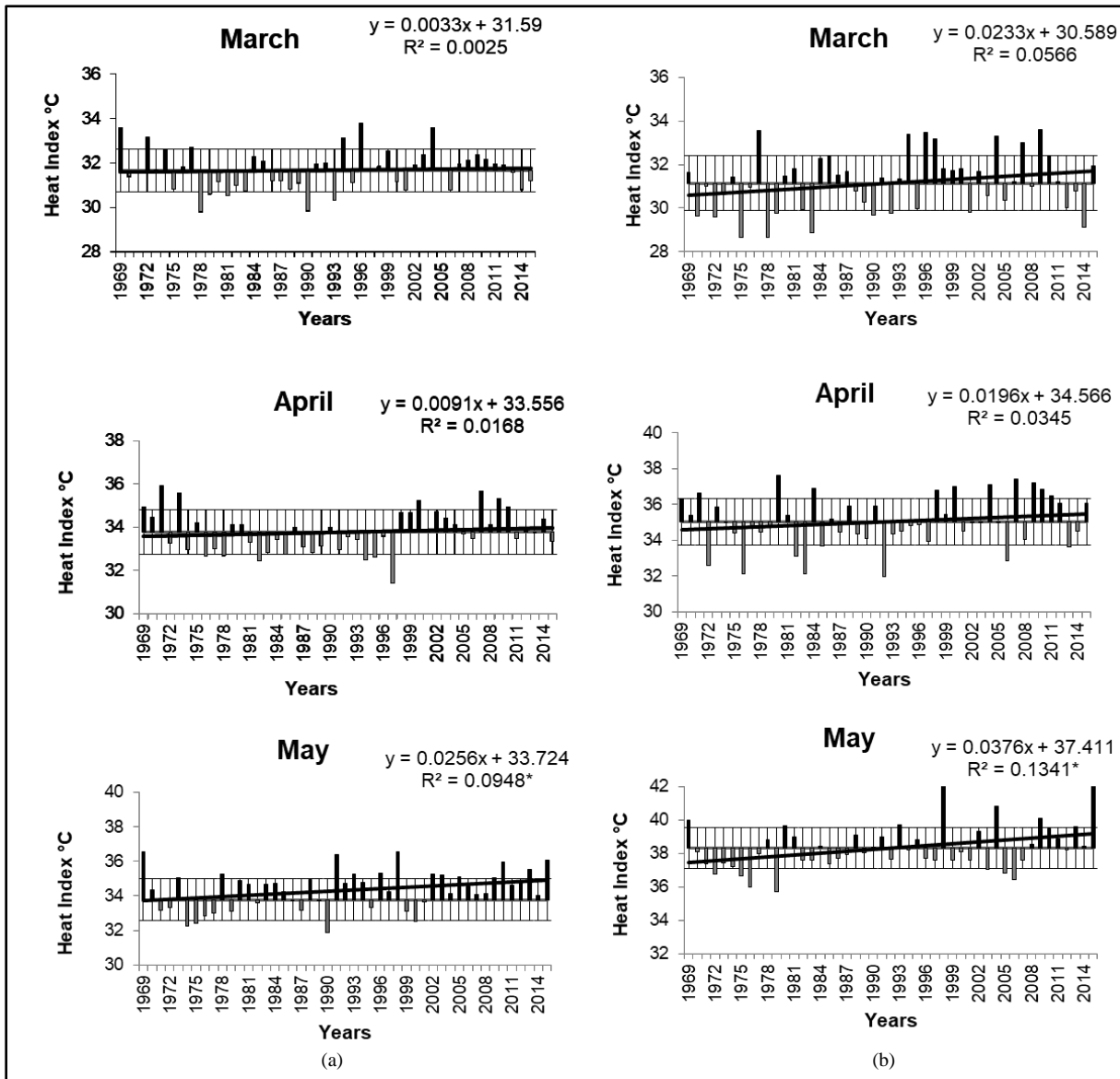
Stepwise multiple regression was applied to evaluate which of the meteorological parameters were closely associated with changes in HI and PET index during summer and monsoon seasons. In the stepwise multiple regression model, HI and PET were dependent variables while DBT, WBT, RH, VP, WS and mean radiant 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

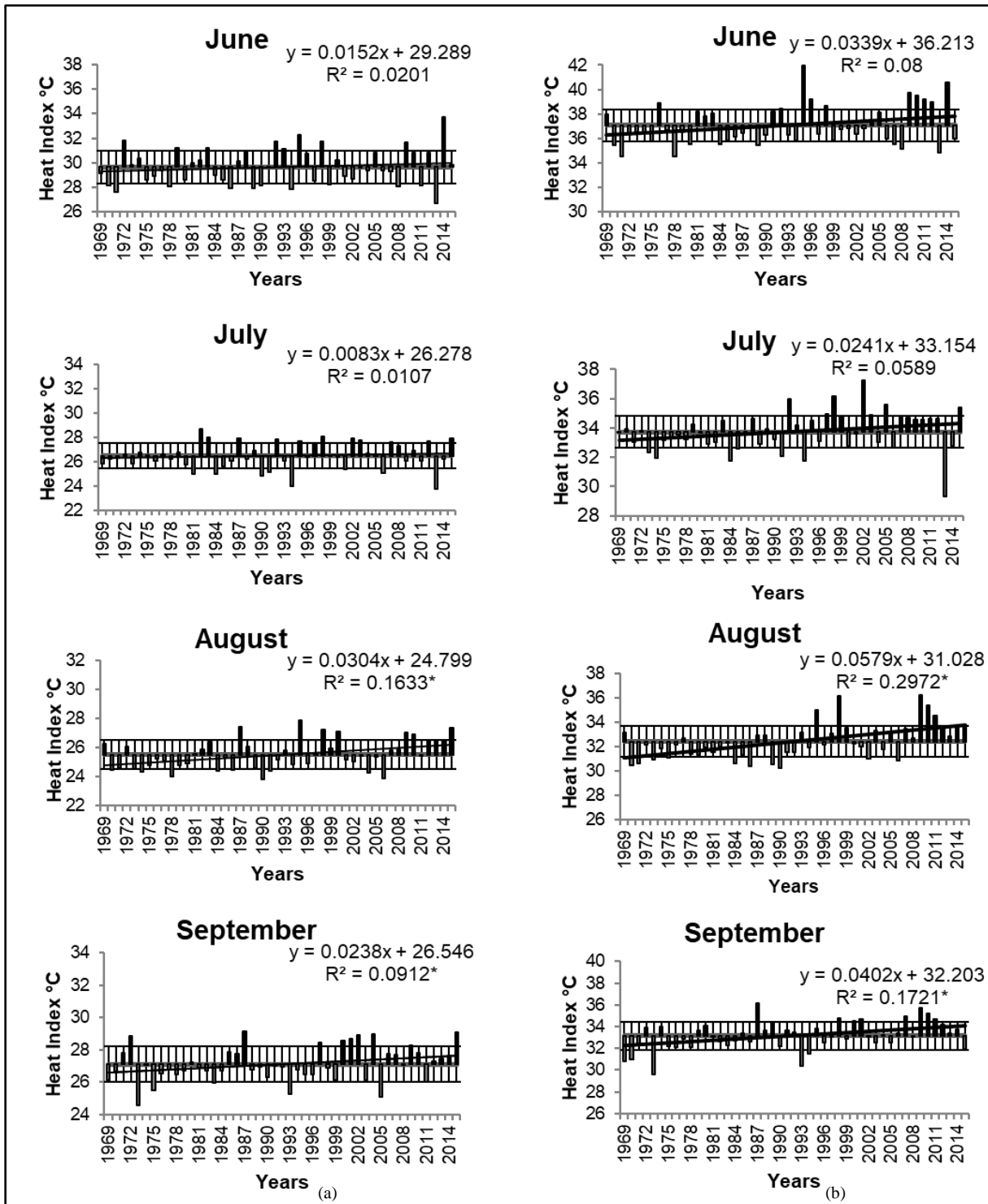
A linear trend was analyzed for 47 years of Heat Index values for summer (March to May) and monsoon (June to September) season months at Pune and Mumbai. For Pune city, in the month of March, the heat stress was near or above the mean for most of the years after 1990. During 1994, 1996 and 2004, the 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 Niño 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.



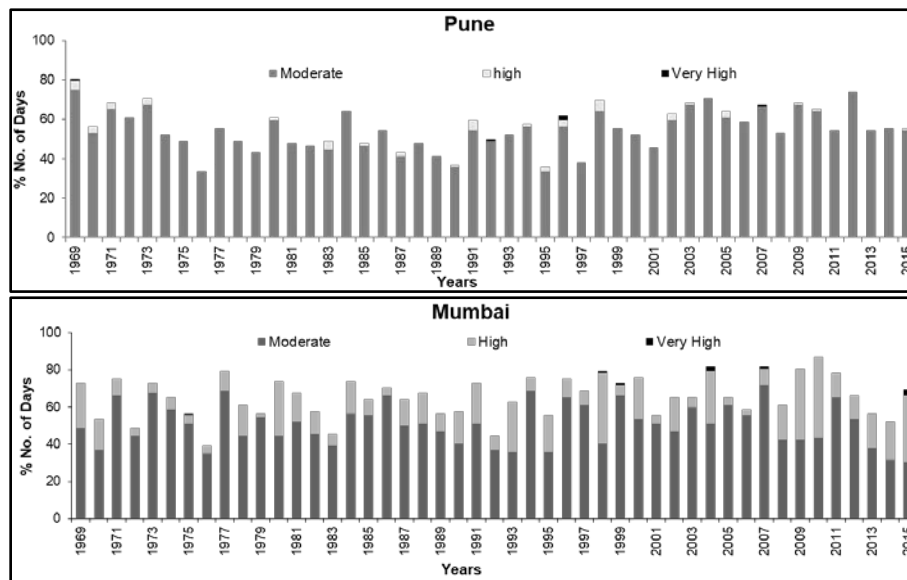


Fig. 4. Number of heat stress days in summer at Pune and Mumbai

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

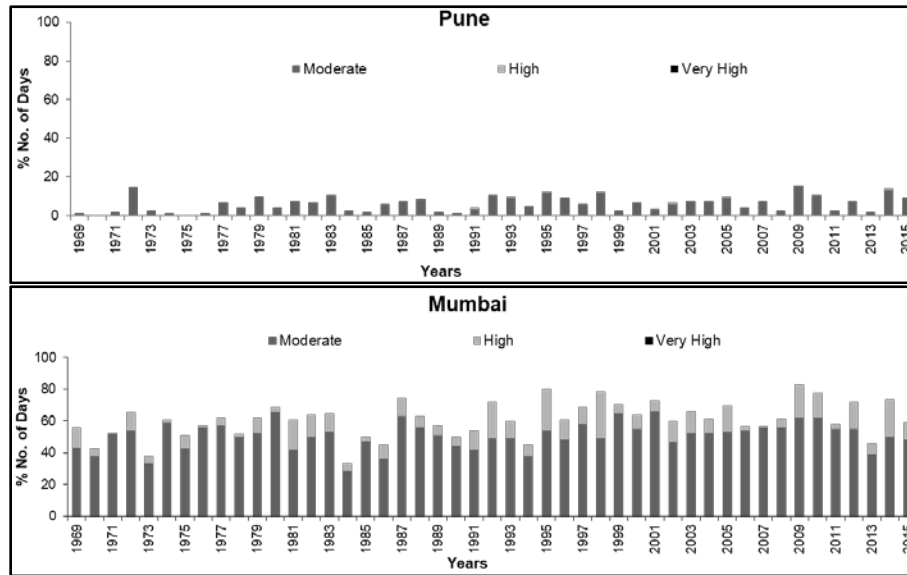


Fig. 5. Number of heat stress days in monsoon at Pune and Mumbai

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.

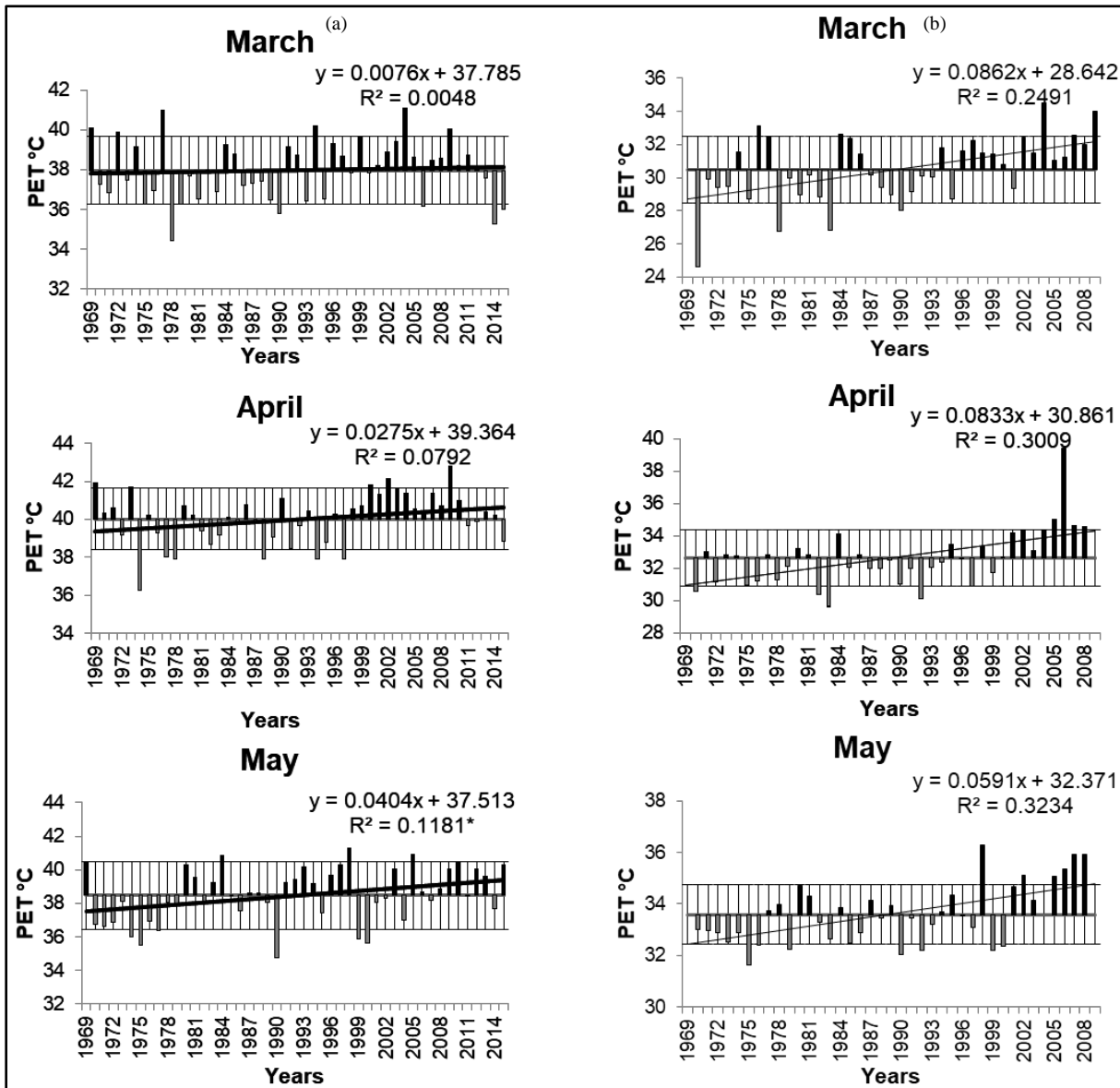
During monsoon season at Pune city, moderate risk days were less than 20% (Fig. 5). Thus for the rest of the monsoon season days, at Pune, there was low risk of heat stress, or days were thermally comfortable. While at Mumbai, due to the high humidity, percentage of days with moderate risk was well above 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 2014 which 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.

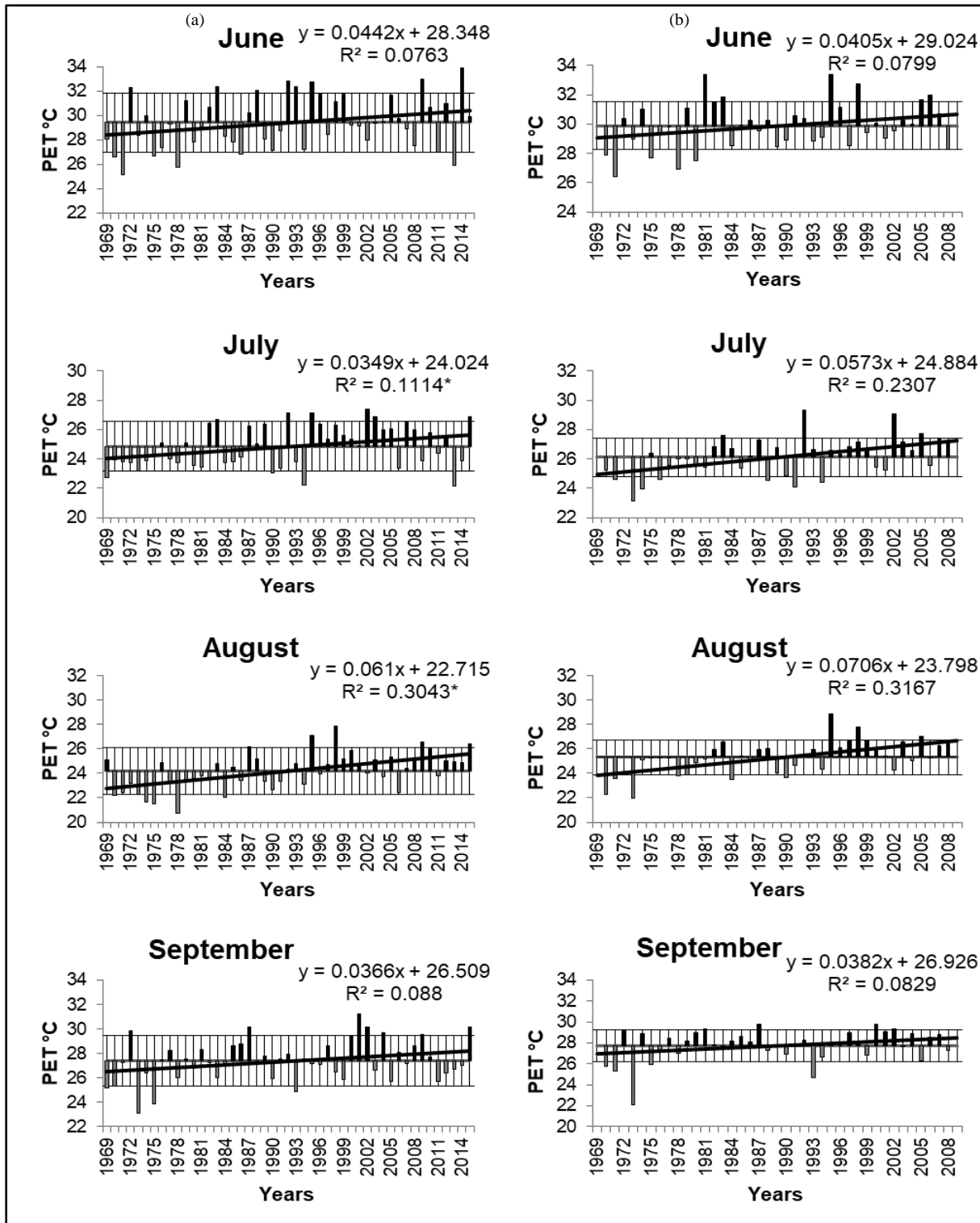
Over Pune city, there was significant increase in PET in May. Though the increasing trend in March was not statistically substantial, above average ( $41^{\circ}\text{C}$ ), PET was consistent from 1996 onwards till 2013, except for the year 2006 [Fig. 6(a)]. During the same month, notable changes can be observed during 1977-1978, wherein 1977 PET increased by  $2^{\circ}\text{C}$  above the mean. Contradictory to this, PET showed a decrease of  $2^{\circ}\text{C}$  in 1978. The absolute increase during April was  $1.3^{\circ}\text{C}$ . 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  $41^{\circ}\text{C}$ . In May absolute increase in PET was  $1.9^{\circ}\text{C}$ .



**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 poses a 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

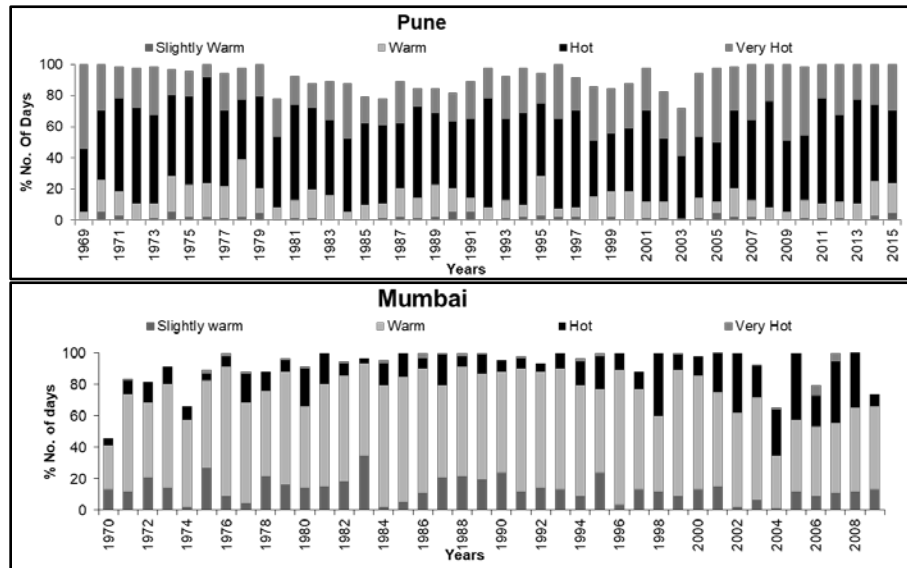


Fig. 8. Number of heat stress days in summer for Pune and Mumbai

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

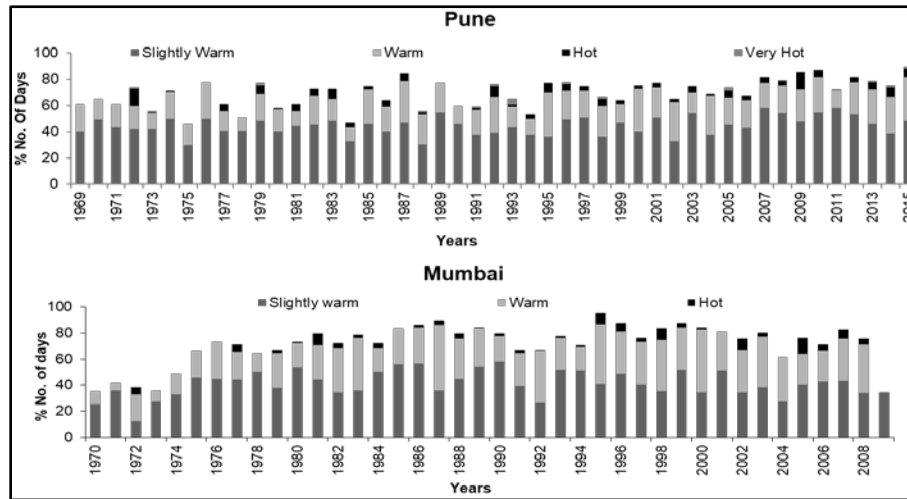


Fig. 9. Number of heat stress days in monsoon for Pune and Mumbai

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 in WS (-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 Beta	Pearson r
	B	Std. error		
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 Beta	Pearson r
	B	Std. error		
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 substantial rise 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  $T_{mrt}$  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.

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