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Increasing Trend in Temperature and Moisture Induced Heat Index and Its Effect on Human Health in Climate Change Scenario over the Indian Sub-continent

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Abstract: This paper highlights the temporal and spatial variability of human bio-meteorological conditions based on temperature and relative humidity related index called Heat Index (HI) in India. Monthly mean maximum temperature and relative humidity records from 283 surface meteorological stations in India were used to analyze HI during summer (March to May) and monsoon (June to September) seasons for the last 60 years (1951 to 2010). The long-period climatology of HI suggests that all the regions of the country except the hilly regions are affected by human discomfort of varying levels during summer and monsoon seasons. The results showed increasing trend of HI in almost all the regions of India during the study period. Averaged over the country, HI is increasing during summer and monsoon seasons at the rate of +0.56 ºC/decade and +0.32 ºC/decade respectively which is statistically significant at 95% level. The increasing HI indicates high level of discomfort in both the seasons which is primarily due to increase in humidity in summer season and maximum temperature in monsoon season. Spatial distribution of HI indicates greater chances of heat related illness in India, more prominently in the southeast coastal regions (Andhra Pradesh, Orissa and Tamil Nadu) in summer and over northwest India (Rajasthan and Indo-Gangetic plains) in monsoon.

Keywords: Heat index; Maximum temperature; Relative humidity; Heat stress; Human health.

Introduction

The evidence that humans are affecting the mean state of climate has now become very strong. Intergovernmental Panel on Climate Change (IPCC) in their recent report has stated that effects of climate change will lead to more extreme temperatures and more hot days than cold days (IPCC, 2013). They may include longer and more intense summer heat waves, increase in extreme precipitation events, northward shifts in the ranges of valued plant and animal species and declining yields of key agricultural crops. Most land areas of the world have experienced fewer cold days/nights and more hot days/nights in last few decades (IPCC, 2007). Temperature extremes have been studied by various authors at national and global levels (Pan and Li, 1995; Kumar, 1998; Guest et al., 1999; Piver et al., 1999; Keatinge et al., 2000; Peterson et al., 2002; Donaldson et al., 2003; Vincent et al., 2005; Zhang et al., 2005; Klein Tank et al., 2006; Cristo et al., 2007; Kothawale et al., 2010; Dash and Mamgain, 2011; Revadekar et al., 2012; Jaswal et al., 2014, 2015; Murari et al., 2015). It has now become increasingly clear from these studies that one of the major impacts of global warming on the earth's surface is in the form of increasing frequency and intensity of extreme weather events.

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Climate change is already making a mark on India's landscape and over the coming decades impacts are expected to grow more substantial. There are increased concerns regarding extreme weather events where temperature variability appears to be the dominant aspect. A warming trend in the range of 0.8 to 1.0 ^{o}C per century has been observed over India (Kothawale et al., 2010), with an increasing number of hot days indices (Dash and Mamgain, 2011). Based upon instrumental records, IPCC (2007) reports a number of observed changes in extremes over the past several decades. Projections from the climate models suggest that in a 'warmer world' heat vulnerability may increase significantly (Meehl and Tebaldi, 2004). Numerous studies highlight the increasing frequency of hot days and nights with decreasing trends in cold days and nights in the last few decades in India (Kothawale et al., 2010; Revadekar et al., 2012; Pai et al. 2013; Jaswal et al., 2014; Jaswal et al., 2015; Kumar et al., 2016).

Heat Index (HI) known as apparent temperature, combines air temperature and relative humidity to determine how hot it actually feels. It has been shown by Delworth et al. (1999) that changes in the HI resulting from increases in atmospheric moisture can account for a considerable fraction of the total increases in the HI. The risk of heat-related illness becomes greater as the weather gets hotter and more humid. The human body normally cools itself by perspiration, or sweating, in which the water in the sweat evaporates and carries heat away from the body. However, when the relative humidity is high, the evaporation rate of sweat is reduced. This means heat is removed from the body at a lower rate, causing it to retain more heat than it would in dry air (Ogunsote and Prucnal-Ogunsote 2002).

The rise in HI results in higher heat related mortality rate during summer. Regions most prone to the effect of high HI include humid regions of tropics and extra tropics including southeastern United States, India, Southeast Asia and Northern Australia (Delworth et al., 1999). In SE Asia and Indian subcontinent few studies have highlighted the HI and heat stress (Jaswal and Koppar, 2011; Zahid and Rasul, 2009; Rajib et al., 2011; Rakib, 2013; Opitz-Stapleton et al., 2016; Kumar, 1998; De et al., 2005; Rajib et al., 2011). Heat related mortality has been reported in many parts of the world viz. North America (Davis et al., 2003), Europe (Keatinge et al., 2000), France and Spain (Schar et al., 2004), and Australia (Guest et al., 1999). Heat-related mortality has already become a leading cause of death in the US (Davis et al., 2003; Borden and Cutter, 2008). Summer heat wave in 2003 affected Western Europe and claimed more than 35,000 lives (Schar et al., 2004).

Many national weather centres around the world have formulated a combined temperature and humidity index of some form and more research efforts are being made to this effect. However, very few studies related to combined temperature and humidity index in India are available. Here we have calculated HI based upon the formula given by Steadman (1979) which was later simplified by Rothfusz (1990). Utilizing temperature and relative humidity data of 283 surface meteorological stations for a period of 1951-2010, long-term climatology and trends of HI are studied for summer and monsoon seasons for the first time over India.

Data and Methodology

Definition of Heat Index (HI)

Heat Index is an index that combines air temperature and relative humidity to determine a human-perceived apparent temperature to determine how hot it actually feels. It is a measure of the stress placed on humans by elevated levels of atmospheric temperature and moisture. It implies that an extended period of unusually high heat stress may have adverse health consequences for the affected population (Robinson, 2001).

Calculation of HI

The computation of HI is based upon the formula given by Steadman (1979) where the author has quantified the physiological effects of high heat and humidity on human being. The variables used in the formula include heat generation and loss, fabric resistance, vapour pressure, wind speed, solar radiation, terrestrial radiation, proportion of body clothed and other factors (Steadman, 1984). The Steadman's equation was further modified by Rothfusz (1990) by performing multiple regression analysis on the data from Steadman's table. The resulting equation is considered as a Heat Index equation as given below.

$$HI = c_1 + c_2 \times T + c_3 \times RH + c_4 \times T \times RH + c_5 \times T^2 + c_6 \times RH^2 + c_7 \times T^2 \times RH + c_8 \times T \times RH^2 + c_9 \times T^2 \times RH^2$$

where T is ambient temperature in ^{o}F and RH is relative humidity in %. The constants have values $c_1 = -42.379$, $c_2 = 2.04901523$, $c_3 = 10.14333127$, $c_4 = -0.22475541$, $c_5 = -6.83783 \times 10^{-3}$, $c_6 = -5.481717 \times 10^{-2}$, $c_7 = 1.22874 \times 10^{-3}$, $c_8 = 8.5282 \times 10^{-4}$, $c_9 = -1.99 \times 10^{-6}$

Because this equation is obtained by multiple regression analysis (Steadman, 1979), HI has an error of

±1.3°F. The formula is valid only when air temperature and relative humidity are higher than 80°F (26°C) and 40%, respectively.

Data Used

The long-term behaviour of heat over India has been examined using Heat Index formula discussed above for the summer (March to May) and monsoon (June to September) seasons. The relationship between the heat index and heat disorders has been summarized in Table 1. Mean maximum temperature (TMAX) and mean monthly relative humidity (RH) data are used for calculating bio-meteorological HI for various locations in India. We have selected 283 surface meteorological stations under the network of India Meteorological Department (IMD) for analyzing changes in summer and monsoon season HI over India for the period 1951-2010. Geographical locations of these 283 stations are shown in Figure 1. TMAX and RH at synoptic hours 0300 UTC and 1200 UTC were taken from the archives of IMD. Thus RH used for calculating the HI is the mean of 0300 UTC and 1200 UTC. Monthly HI values were first calculated in ^{o}F. The calculated values were then converted to ^{o}C. From monthly mean values, station-wise and all-India average time series of mean summer and monsoon seasons were generated.

Temporal variations in all-India averaged seasonal time series of HI, TMAX and RH during 1951-2010 are shown in Figures 2 and 3 respectively. Climatology of HI is prepared and its spatial variability for summer and monsoon seasons is shown in Figures 4 and 6, respectively. Long-term variability of HI, TMAX and RH was estimated by using the least square method to fit linear trend to summer and monsoon seasonal time series. The significance of the calculated trend was estimated using the Student's t-test with 5% significance level. Number of stations showing increasing/decreasing trends in HI, TMAX and RH are given in Table 2.

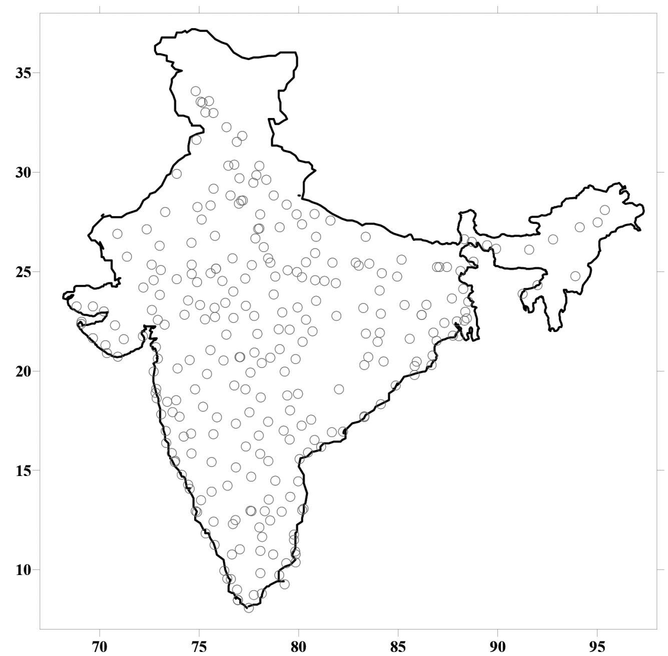

Figure 1: India map showing the geographical location of 283 surface meteorological stations selected for the study.

Spatial distributions of summer (Figure 5) and monsoon (Figure 7) trends in HI, TMAX and RH are shown by marking trends significant at 95% level by an outer circle in black. Temporal variations in number of stations expressed in percent having seasonal mean HI in extremely hot (> 54 ^{o}C) and very hot (41 - 53 ^{o}C) categories (as given in Table 1) for summer and monsoon seasons during the period of study is shown in Figure 8. Scatter plot of all-India averaged HI against TMAX & RH are shown in Figure 9. Long-term mean, coefficient of variation and trends in HI at 25 mega cities in India (cities with population more than one million) for summer and monsoon seasons is given in Table 3.

Table 1: Classification of effects of heat index (HI)

Heat index	*Classification*	*Health effects*
27–32 °C	Warm	Caution–Fatigue possible with prolonged exposure and/or physical activity. Continuing activity could result in heat cramps.
32–41 °C	Hot	Extreme caution–Heat cramps and heat exhaustion possible with prolonged exposure and/or physical activity.
41–54 °C	Very hot	Danger–Heat cramps or heat exhaustion likely and heatstroke possible with prolonged exposure and/or physical activity.
>54 °C	Extremely hot	Extreme danger–Heatstroke highly likely with continued exposure.

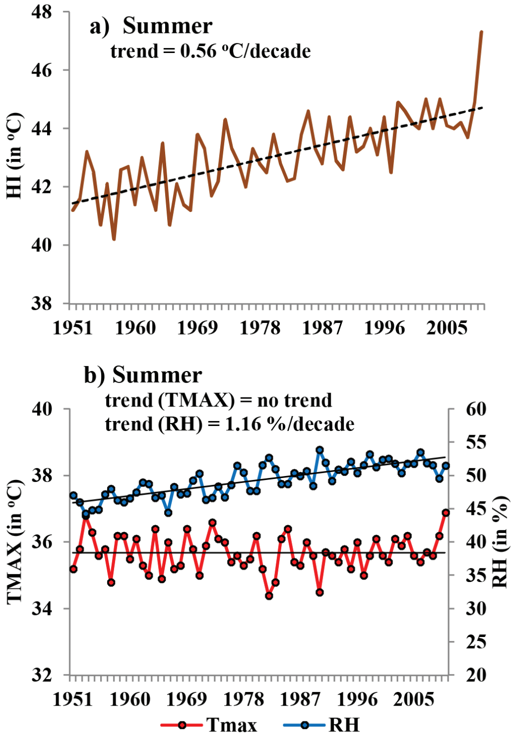

Figure 2: Temporal variations in all-India averaged summer season (a) heat index (HI), (b) mean maximum temperature (TMAX) and relative humidity (RH) during the period 1951-2010.

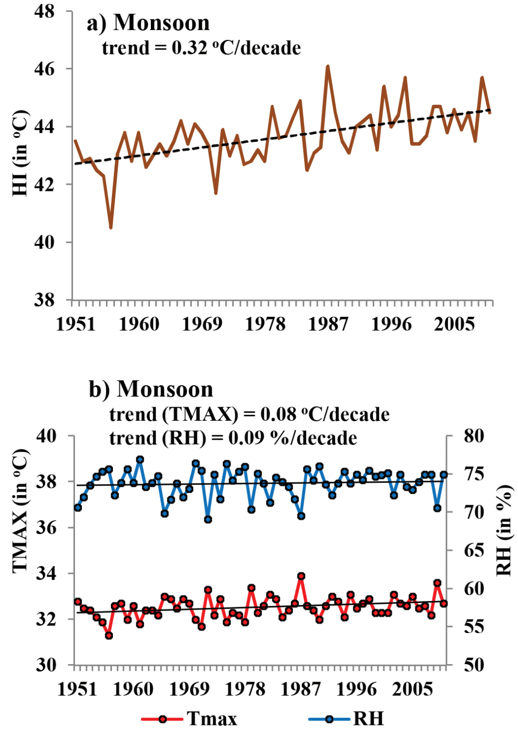

Figure 3: Temporal variations in all-India averaged monsoon season (a) heat index (HI), (b) mean maximum temperature (TMAX) and relative humidity (RH) during the period 1951-2010.

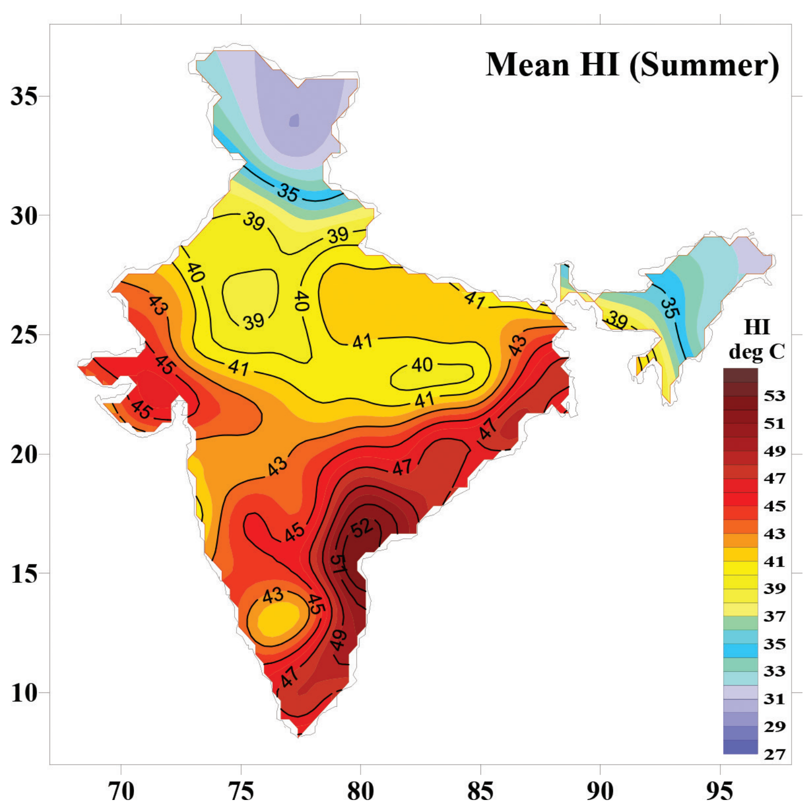

Figure 4: Climatology of summer season heat index (HI) based upon 283 surface stations for the period 1951-2010.

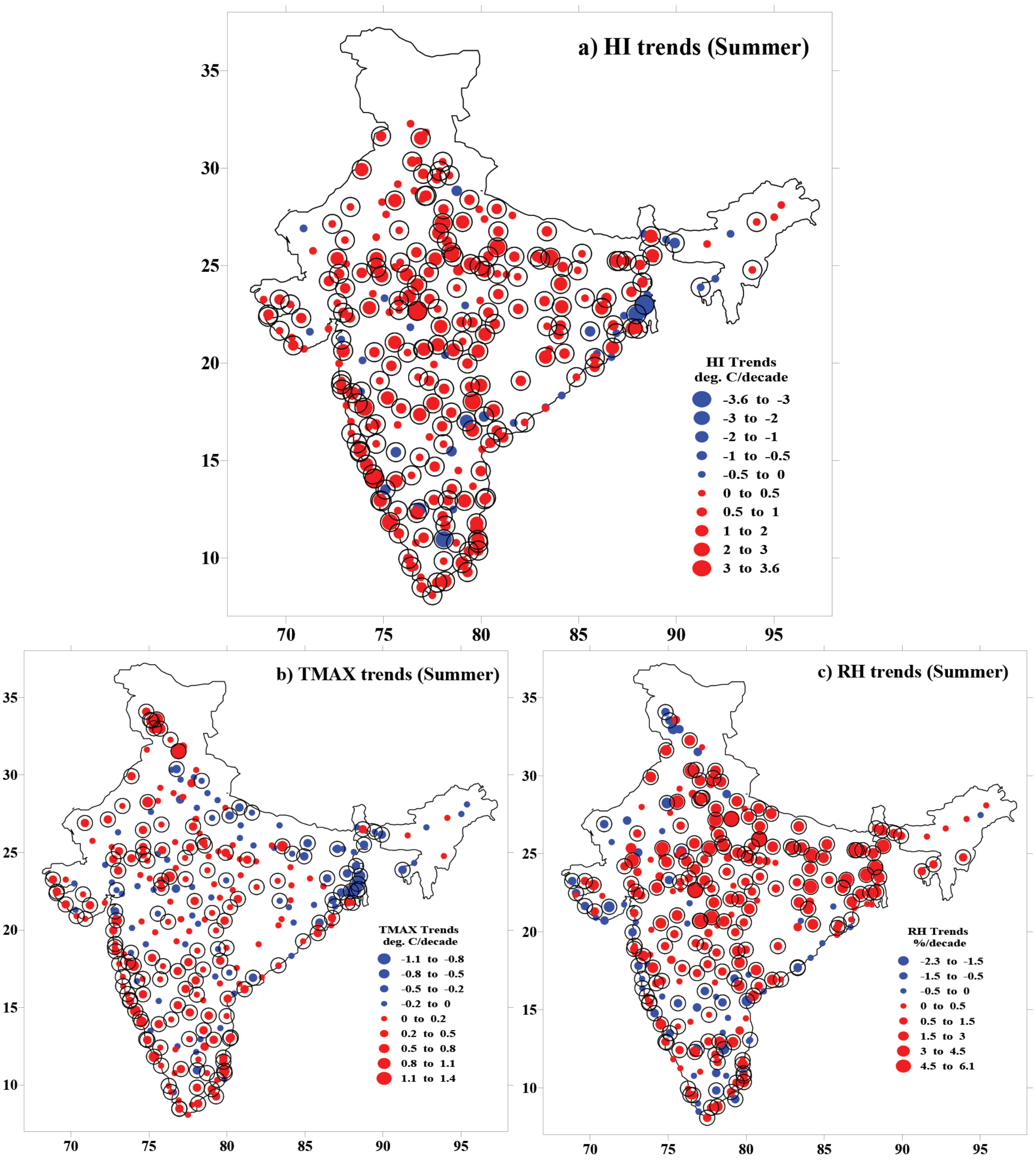

Figure 5: Summer season trends in (a) heat index (HI), (b) mean maximum temperature (TMAX) and (c) relative humidity (RH) for the period 1951-2010.

Results and Discussion

The HI is a measure of the stress placed on humans by elevated levels of atmospheric temperature and moisture. For example, an air temperature of 30 ºC with a relative humidity of 60% translates to an apparent temperature (HI) of 33 ºC. The difference between the HI and air temperature is a measure of the heat stress placed on the human body by elevated atmospheric water vapour content. As the atmosphere is warmed its ability to hold moisture increases almost exponentially. With the increase in atmospheric moisture content,

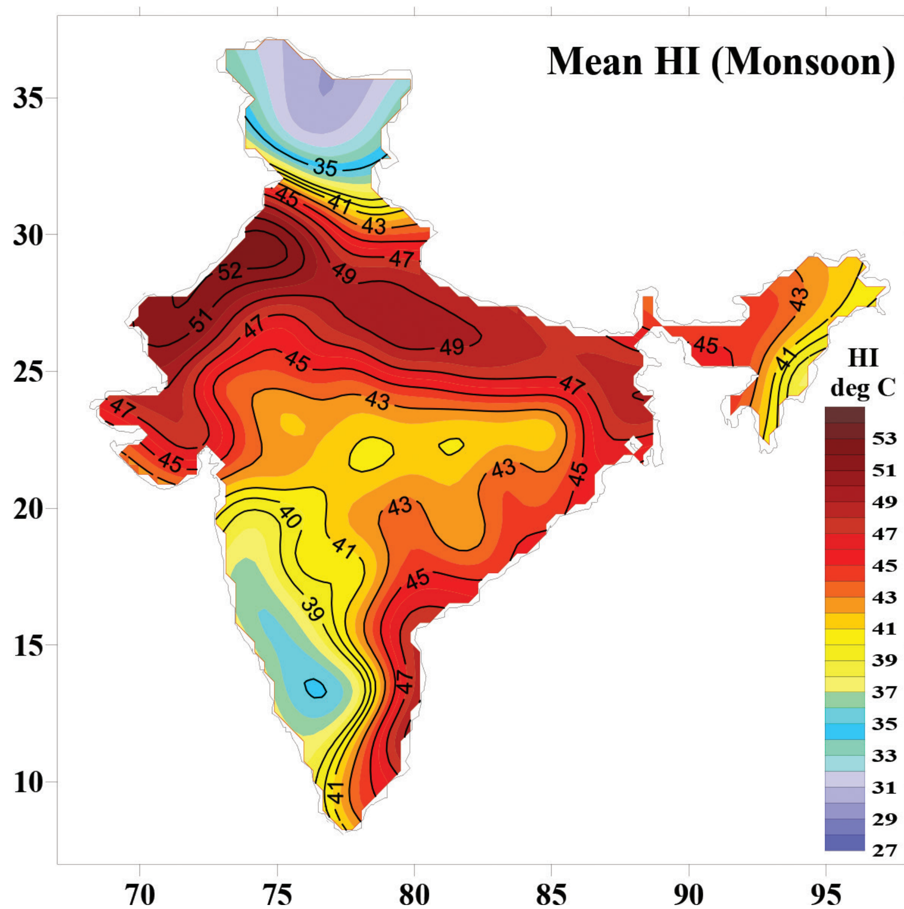

Figure 6: Climatology of monsoon season heat index (HI) based upon 283 surface stations for the period 1951-2010.

Table 2: Numbers of stations having decreasing/increasing trends in summer and monsoon seasons heat index (HI), mean maximum temperature (TMAX) and mean relative humidity (RH) during 1951-2010

	Number of stations					
	HI trends		*TMAX trends*		*RH trends*	
	Summer	*Monsoon*	*Summer*	*Monsoon*	*Summer*	*Monsoon*
Decreasing	39	47	94	61	65	126
Significantly decreasing	15	11	37	14	29	44
Increasing	238	233	189	222	218	157
Significantly increasing	193	178	124	132	163	77

the ability of the human body to release heat through evaporation is inhibited, thereby causing discomfort and stress.

Hot summer time temperatures in India are often accompanied by high humidity, making it feel much warmer than it actually is. The situation is further compounded by anomalous northwesterlies bringing hot air from desert areas overpowering the moist cool southerly winds. A common characteristic of tropical climate is large variability in the weather experienced from one year to the next and India is no exception. For people working outdoors in hot weather, both air temperature and humidity affect how hot they feel. The HI is a single value that takes both temperature and humidity into account. The higher the HI, the hotter the weather one feels, since sweat does not readily evaporate and cool the skin. The episodes of high humidity and air temperature in summer months often

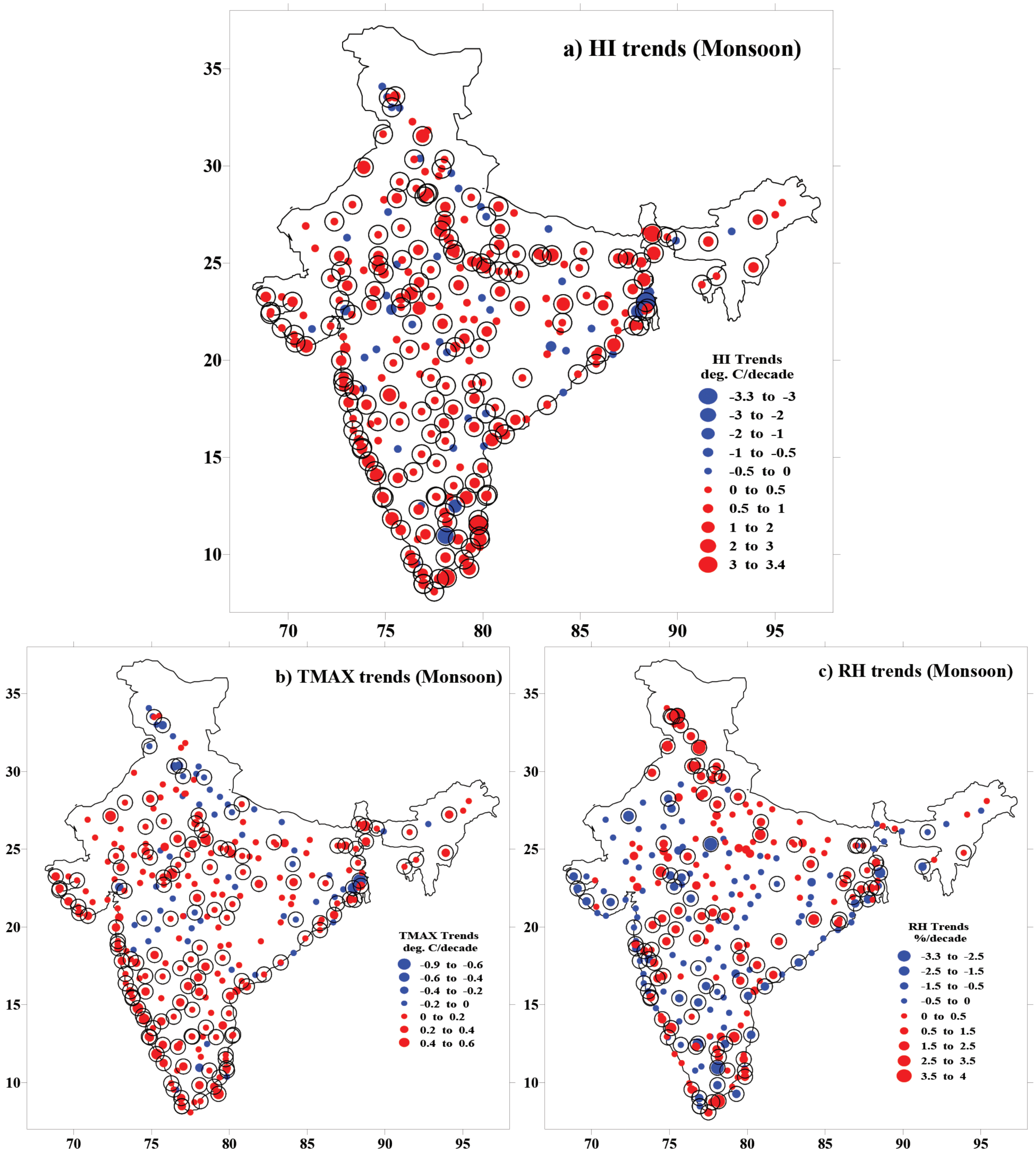

Figure 7: Monsoon season trends in (a) heat index (HI), (b) mean maximum temperature (TMAX) and (c) relative humidity (RH) for the period 1951-2010.

results in oppressive HI values and dangerous heat waves in India.

Temporal Variation of HI, TMAX and RH

Large year-to-year variability has and always will be a characteristic of the climate of tropical region. Due to this variability in the climate, observing changes in trends of climate variables become more difficult. Figure 2 shows temporal variation in all-India averaged time series of HI, TMAX and RH during the study period. Summer season HI is steadily increasing at the rate +0.56 ^{o}C/decade which is significant at 95% level of confidence as shown in Figure 2(a). Summer season mean HI was lowest (40.2 ^{o}C) in 1957 and highest

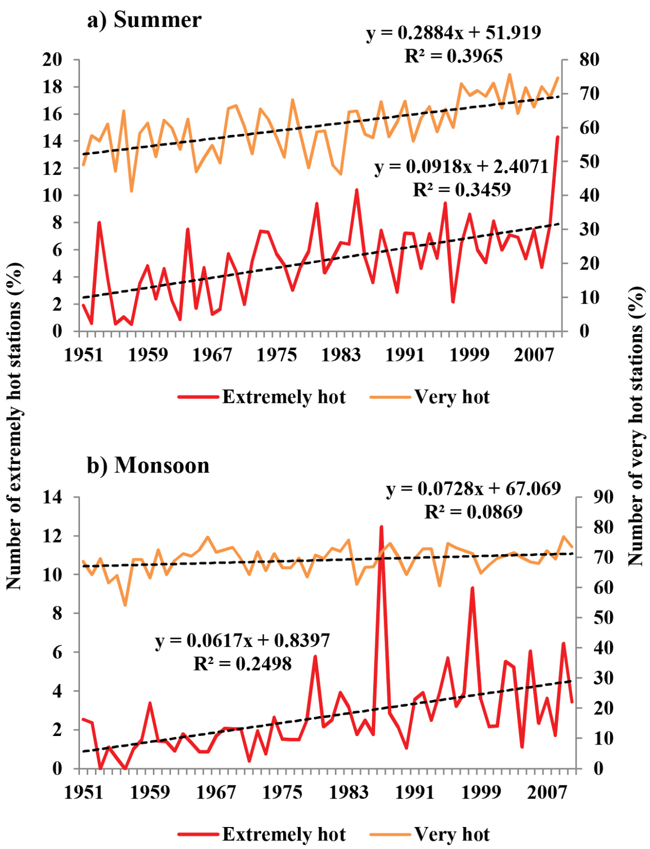

Figure 8: Temporal variations in number of stations expressed in % having seasonal mean heat index (HI) in extremely hot (>54 °C) and very hot (41-53 °C) categories for (a) summer and (b) monsoon seasons during 1951-2010.

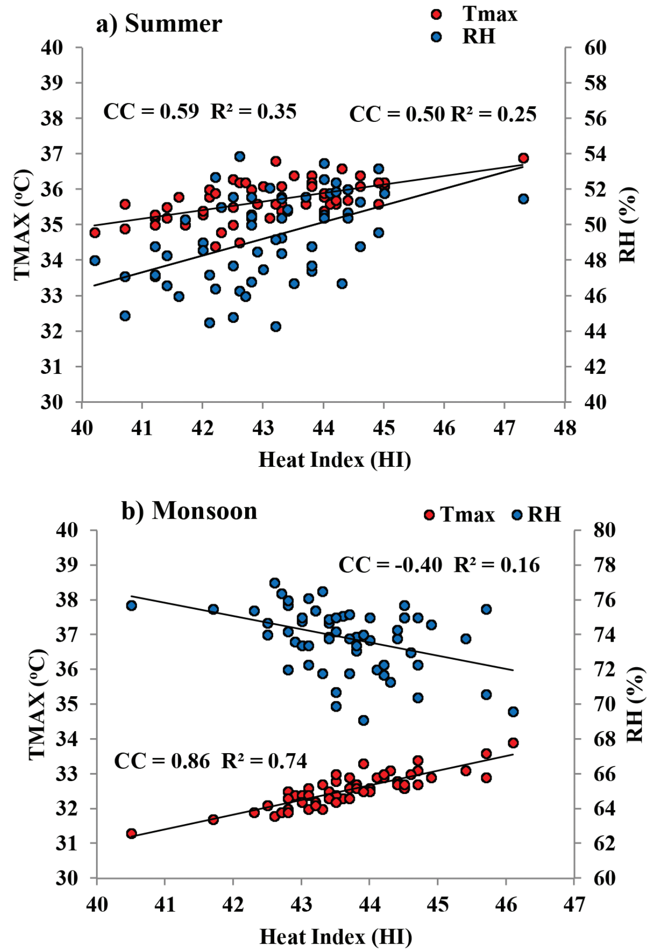

Figure 9: Scatter plot of all-India mean heat index (HI) and mean maximum temperature (TMAX) and relative humidity (RH) for (a) summer and (b) monsoon.

(47.3 °C) in 2010. Incidentally year 2010 was one of the warmest summer seasons in India having highest mean summer TMAX (36.9 °C). Figure 2(b) shows temporal variations in TMAX and RH. While country averaged summer RH is significantly increasing at the rate +1.16%/decade, there is no trend in summer TMAX. Temporal variation in monsoon HI is shown in Figure 3(a) which is also steadily increasing during 1951-2010. Monsoon season mean HI was lowest (40.5 °C) in 1956 and highest (46.1 °C) in 1987 which was a severe drought year with –19.4% rainfall departure from normal. The highest mean monsoon TMAX 33.9 °C was also recorded in 1987. Trend in averaged HI time series is increasing significantly at the rate of +0.32 °C/decade. Monsoon seasonal time series of TMAX and RH are also increasing but not significant as shown in Figure 3(b). In fact, out of the climate variables TMAX and RH analyzed in this study, an increase in RH in summer and TMAX in monsoon is contributing more to the increasing trend in HI which is statistically significant for both the seasons.

Climatology and Long-term Trends in HI

Summer Season

Climatology of HI: The high temperature and humidity often results in oppressive HI and dangerous heat waves during the summer months. The combination of heat and high humidity may cause discomfort, heat related health problems, heat stroke or even death to humans and animals. Climatology of summer season HI based upon 1951-2010 data is shown in Figure 4 which indicates most of west (Gujarat and south Rajasthan) and southeast (Orissa, Telangana, Rayalseema, coastal Andhra Pradesh and Tamil Nadu) parts of India are in very hot and extremely hot categories as given in Table 1. Spatial patterns of HI indicate a clear south to north gradient with higher values in south and lower values in north India with core of highest index value over east coast (14° - 17 °N and 78° - 81 °E). Many stations in Telangana, Andhra Pradesh and north Tamil Nadu have

Table 3: Long-term mean, coefficient of variation (CV) and trend in heat index (HI) for summer (March-May) and monsoon (June-September) seasons at 25 mega cities of India during the period 1951-2010. Trends in HI significant at 95% level are marked '*'

Name of City	*Population[#] (millions)*	*Summer HI*			*Monsoon HI*		
		Mean °C	*CV (%)*	*Trend °C/decade*	*Mean °C*	*CV (%)*	*Trend °C/decade*
Mumbai[@]	18.39	41.2	3.7	+0.38*	39.9	3.5	+0.56*
New Delhi	16.79	36.9	5.4	+0.60*	47.6	3.9	+0.55*
Kolkata[@]	14.06	47.7	4.5	-0.04	47.4	3.0	+0.26*
Chennai[@]	8.65	49.5	4.1	+0.73*	49.9	3.7	+0.36*
Bangalore[@]	8.50	37.9	3.8	+0.51*	32.1	3.6	+0.37*
Hyderabad[@]	7.67	42.0	4.3	+0.69*	38.7	4.3	+0.67*
Ahmedabad[@]	6.36	46.1	5.4	+0.34*	48.4	4.6	+0.31*
Pune	5.06	41.4	3.5	-0.27*	34.8	3.9	-0.02
Jaipur[@]	3.05	36.5	4.2	+0.39*	44.9	3.8	+0.39*
Lucknow[@]	2.90	40.2	5.0	+0.75*	49.7	4.2	+0.73*
Nagpur	2.50	42.1	4.7	+0.41*	43.6	4.3	+0.53*
Indore	2.17	38.5	3.7	+0.39*	39.2	4.7	+0.40*
Coimbatore	2.14	46.2	5.9	+0.63*	41.2	5.5	+0.66*
Patna[@]	2.05	40.8	4.2	+0.43*	47.8	3.7	+0.45*
Bhopal[@]	1.89	38.0	4.3	+0.65*	39.9	4.0	+0.38*
Baroda	1.82	45.8	5.6	+0.59*	47.2	4.3	+0.35*
Vishakhapatnam	1.73	50.4	4.8	-0.17	47.5	3.9	+0.10
Madurai	1.47	47.6	3.3	+0.33*	45.3	3.1	+0.60*
Varanasi	1.43	40.9	4.9	+0.83*	49.7	3.8	+0.75*
Rajkot	1.39	48.6	5.5	+0.53*	48.2	4.7	+0.19
Solapur	1.20	45.4	5.7	+0.82*	41.0	5.3	+0.23
Aurangabad	1.19	40.8	5.6	+0.52*	38.3	3.8	+0.21*
Amritsar	1.18	37.9	7.8	+0.95*	49.8	3.6	+0.34*
Gwalior	1.12	38.3	5.3	+0.84*	47.0	4.2	+0.77*
Tiruchchirappalli	1.02	48.4	3.9	+0.39*	45.6	3.5	+0.55*

[#] INDIA STATS : Million plus cities in India as per Census 2011 http://pibmumbai.gov.in/
[@] State capital cities

long-term mean HI above 50°C suggesting frequent episodes of extremely hot temperatures in these regions. This clearly shows that a large number of people living in these regions are at health risk such as heat stress, heat exhaustion and life-threatening heatstroke (Table 1). Top three long-term mean highest HI values obtained in this season are 56.0 °C (Nalgonda), 55.8 °C (Nellore) and 55.3 °C (Rentachintala) in Telangana and Andhra Pradesh. Another region of higher HI is over Gujarat where many stations have long-term index values in the range of 45-50°C. While central India is having long-term HI values of ~40 °C, hilly regions and northeast India is having values lower than 40 °C in summer season. According to IPCC (2013), more frequent and intense heat waves will negatively impact vulnerable communities and increase mortality.

Trends in HI: Out of 283 stations, 238 stations are having increasing trends in HI suggesting a general increase in HI over almost all parts of India during the study period (1951-2010) as given in Table 2. The increasing trend in summer HI is significant at 95% level at 193 stations. Spatial distribution of trend in summer HI shown in Figure 5(a) ranged between –3.55 ºC/decade and +3.54 ºC/decade. The significantly increasing trends are spatially more coherent over most of the regions except in northeast India. Stations with moderate to strong increasing trends in HI are more concentrated in Indo-Gangetic plains, central India and along west coast and southeast coast where many stations have trends between +1.0 ºC and +3.0 ºC per decade.

Trend in TMAX: Table 2 gives numbers of station having increasing/decreasing trends in summer TMAX. Out of 189 stations having increasing trends in TMAX, 124 stations are having significant increase in this season. However, 37 stations are having significant decrease in summer TMAX. Spatial distribution of TMAX trends suggest general increase over India except at stations in Indo-Gangetic plains and northeast India as shown in Figure 5(b). The calculated trends in summer TMAX are in the range –1.03 ºC/decade and +1.33 ºC/decade. Stations having significant increasing trend in TMAX are spatially more coherent over Western Himalayas, northwest, west and south peninsula where strong rise in temperature is observed. Significant decrease in TMAX is observed over Indo-Gangetic plains and West Bengal where many stations are having decline at the rate of –0.48 to –1.03 ºC/decade.

Trend in RH: Summer season mean RH is increasing at 218 stations out of which it is significant at 163 stations as given in Table 2. Spatial distribution of RH suggests increase over major parts of the country except over Jammu and Kashmir, west Rajasthan, coastal Gujarat and Maharashtra and north interior Karnataka as shown in Figure 5(c). The calculated trends in summer RH are in the range of –2.30 to +6.04%/decade. The significant increasing trends in summer RH are spatially more coherent over Indo-Gangetic plains and central India. Majority of stations in coastal Gujarat and Maharashtra are having significant decrease in RH in this season.

Monsoon Season

Climatology of HI: Monsoon season long-term mean HI variability is shown in Figure 6. In contrast to summer season patterns, zone of highest mean HI in monsoon season shifts to northwest India. Spatial distribution of HI indicates higher values over west Rajasthan, entire Indo-Gangetic plains, Gujarat and southeast coast of India. Stations in Punjab, Haryana, Rajasthan, Uttar Pradesh, Bihar and south Tamil Nadu have long-term mean HI above 50ºC. Considerably large number of population living in these regions are at higher risk of heat related ailments which disproportionately affect those who are poor, elderly, very young, suffering from chronic diseases or otherwise unable to escape the heat. Top three highest long-term mean HI values obtained in this season are 53.9 ºC (Hissar), 53.2 ºC (Sriganganagar) and 52.5 ºC (Parangipettai) in Haryana, Rajasthan and Tamil Nadu respectively. Another region of higher HI is over Gujarat where many stations such as Bhuj, Ahmedabad and Rajkot have long-term values in the range of 45-50ºC. While central India is having long-term HI values between 40 ºC and 45 ºC, hilly regions and stations along Western Ghats (e.g. Belgaum, Satara, Kolhapur and Shimoga) are having values lower than 35 ºC in monsoon season.

Trend in HI: Out of 283 stations, 233 stations showed increasing trends in HI suggesting a general increase in monsoon HI over India during the study period as given in Table 2. The increasing trend in monsoon HI is significant at 95% level at 178 stations. Spatial patterns of trends in monsoon season HI shown in Figure 7(a) ranged between –3.29 ºC/decade and +3.36 ºC/decade. Stations with moderate to strong increasing trends in monsoon HI are more concentrated in central India and along west coast and southeast coast where many stations have trends between +1.0 ºC and +3.0 ºC/decade. Similar to summer season, HI trends obtained are consistent with the reported trends in Pakistan and Bangladesh.

Trend in TMAX: Table 2 gives numbers of stations having increasing/decreasing trends in monsoon TMAX. Out of 222 stations having increasing trends in TMAX, 132 stations are having significant increase in this season. However, 14 stations are having significant decrease in monsoon season TMAX. Spatial distribution of TMAX trends suggests increase over India except at stations in Jammu and Kashmir, Punjab, Haryana and Uttarakhand as shown in Figure 7(b). The calculated trends in summer TMAX are in the range of –0.83 ºC/decade to +0.56 ºC/decade. Stations having significant increasing trend in TMAX are spatially more coherent over central, northeast and south peninsula where strong rise in temperature is observed. Coastal stations are also having moderate to strong increase in TMAX in monsoon season where many stations have trends in the range +0.3 to +0.4 ºC/decade.

Trend in RH: Long-term trends in monsoon RH showed wide variability over the country. Out of 283 stations, monsoon RH is increasing at 157 stations out of which it is significant at 77 stations while 44 stations are showing significant decrease as given in Table 2. Spatial distribution of trends in RH suggests significant increase over Western Himalayas and Indo-Gangetic plains as shown in Figure 7(c). Rest of the country is having mixed trends. While stations in north Maharashtra, Telangana and Rayalseema are having significant increase, stations in Gujarat, west Rajasthan and north interior Karnataka are having significant decrease. Most of the coastal stations are also showing significant decrease in RH during this season as shown in Figure 7(c). The calculated trends in monsoon RH are in the range of –3.25 to +3.95 %/decade.

HI Trends in Mega Cities

This is the age of urbanization as more and more people migrate to the city. Cities with populations of more than one million are on the rise. Rapid urbanization is occurring largely in developing countries where a massive demographic shift has enormous implications in terms of poverty, natural resources and the environment. During summer, most areas of India experience episodes of heat waves every year causing sunstroke, dehydration and death. The rising temperatures and heat waves are likely to make life difficult in such urban centres with million plus population. These cities will be exposed to climate change from greenhouse gas induced radiative forcing and localized effects from urbanization such as the urban heat island (McCarthy et al., 2010). Urbanization causes substantial changes in the energy balance of the region. Studies over north China found urban warming at a rate of +0.11^{o}C per decade contributing to around 38% rise in annual mean surface air temperature trends (Ren et al., 2008).

We have examined the behaviour of summer and monsoon season HI over 25 selected mega cities in India during the study period, some of which are also state capitals and the trends are given in Table 3. Among the selected mega cities, Mumbai is highly populated with 18.39 million people while Tiruchirapalli is having just one million. Out of these 25 mega cities, 17 cities have long-term mean summer HI in very hot category with Visakhapatnam having the highest HI value (50.4 ^{o}C) as given in Table 3. The coefficient of variation is also low indicating persistence in HI during this season. Most of the mega cities in north India are still in hot category (32^{o}-41 ^{o}C) during summer season. Out of these 25 cities, 22 cities showed significantly increasing trend in summer HI and 14 of them have magnitude of increasing trend in the range of +0.51 ^{o}C/decade to +0.95 ^{o}C/decade. Summer HI trend is decreasing at Pune, Kolkata and Visakhapatnam but significant for Pune only.

Long-term mean HI for monsoon season indicates 18 mega cities are in very hot category with Lucknow, Varanasi, Amritsar and Chennai having a mean value ~ 50 ^{o}C as given in Table 5. The coefficient of variation is in the range 3 - 5% in most of the cities indicating persistence in HI during the season. Majority of mega cities in north India are in very hot category during the monsoon season. Out of these 25 cities, 24 cities showed increasing trends out of which 21 cities have significant increase in monsoon HI. Ten mega cities are having significant increasing trends in monsoon HI in the range of +0.53 ^{o}C/decade to +0.77 ^{o}C/decade. These are Mumbai, New Delhi, Lucknow, Gwalior, Varanasi, Nagpur, Madurai, Coimbatore, Hyderabad and Tiruchirapalli.

Temporal Variations in Very Hot and Extremely Hot Seasonal Mean HI

We have evaluated temporal and spatial change in HI over the period of study by counting number of stations each year having seasonal mean heat index for summer and monsoon seasons in the very hot (41^{o} – 54 ^{o}C) and extremely hot (> 54 ^{o}C) categories as per classification given in Table 1. Next, the time series of such number of stations expressed in percent of the total number of stations available each year was prepared for summer and monsoon seasons during the study period and their temporal variations are shown in Figure 8.

During summer season number of stations having mean HI in very hot and extremely hot categories are steadily increasing as shown in Figure 8(a). Also trends in number of stations in very hot and extremely hot categories are significantly increasing at the rate of +2.9 %/decade and +0.9 %/decade respectively. Number of very hot stations in summer varied between 41.3% and 75.7%. Top three years having seasonal mean HI in very hot category at maximum number of stations are 2004 (75.7%), 2010 (74.7%) and 2002 (73.1%) which are also hot summer years in India. Number of extremely hot HI stations in summer season varied between 0.5% and 14.3%. Highest number of stations having extremely hot summer HI are found in 2010 (14.3%) followed by 1985 (10.4%) and 1996 (9.4%). Geographically, most of the stations having highest summer season very hot and extremely hot HI are located in Telangana, coastal Andhra Pradesh, Tamil Nadu and Orissa.

Figure 8(b) shows temporal variation in number of stations having very hot and extremely hot monsoon

HI. Number of stations with monsoon HI in extremely hot category is increasing more strongly as compared to the very hot category. Number of very hot stations in monsoon varied between 54.2% and 77.0% and top three years having maximum number of stations with mean HI in very hot category are 2009 (77.0%), 1966 (76.8%) and 1983 (75.8%) which are also monsoon deficient years. Number of extremely hot stations in monsoon varied between 0 and 12.5%. Highest number of stations having extremely hot monsoon season are found in highly deficient monsoon year 1987 (12.5%) followed by 1998 (9.3%) and 2009 (6.5%). In contrast to summer season, most of the stations having highest monsoon season very hot and extremely hot HI are located in Indo-Gangetic plains, Rajasthan, Uttar Pradesh, Madhya Pradesh and Chhattisgarh.

Relationships between HI, TMAX and RH

Evaluating the impact of HI on human health and comfort it must be emphasized that changes in TMAX is not the only reason but instead changes in RH also plays a significant role. Figure 9 shows the relationship between HI, TMAX and RH for summer and monsoon seasons. Summer HI is having positive correlation with TMAX and RH suggesting contribution of both variables in significant increase in HI as shown in Figure 9(a). The correlation coefficient between HI and TMAX is +0.59 and between HI and RH is +0.50. Relationship of monsoon HI with TMAX and RH is shown in Figure 9(b). It is interesting to note that monsoon HI is having strong positive correlation with TMAX. However, correlation between monsoon HI and RH is moderately negative. Since monsoon season HI is significantly increasing, the dominant role of TMAX is evident with coefficient of determination of 0.74.

As is clear from spatial patterns of trends also (Figure 5), both TMAX and RH are positively contributing to the increase in summer HI during 1951-2010. In contrast, monsoon season TMAX is strongly positively contributing while RH is moderately negatively contributing to net increase in HI. It has been shown by Delworth et al. (1999) that increases in atmospheric moisture can account for a considerable fraction (~ 35%) of the total increases in the HI. These increases are largest over humid regions of the Tropics and summer hemisphere extra-tropics. As the atmosphere warms its ability to hold moisture increases; this translates into an increased stress on the human body, the magnitude of which is dictated by the magnitude of the temperature and moisture increases.

The results of the long-term observational study presented here indicate that summer and monsoon season HI has significantly increased over India during 1951-2010. Almost all regions of the country have experienced significant increase in HI which is consistent with the reported trends in neighbouring countries Pakistan (Gadiwala and Sadiq, 2008; Zahid and Rasul, 2009) and Bangladesh (Rajib et al., 2011; Rakib, 2013). Of 283 surface meteorological stations studied, almost 83% saw a rise in the HI in summer and monsoon seasons over India. Change in HI is associated with two factors. The first one is daytime temperature and the other is relative humidity. Evaluating changes in TMAX and RH, our analysis indicates higher increase in summer RH as compared to TMAX and higher increase in monsoon TMAX as compared to the RH during the study period. IPCC (2013) has projected that Asia (including India) will experience higher temperature and humidity in the future, leading to hot days and even hotter due to increased humidity. Summer season in India has convective rainfall which also causes enhanced level of humidity in almost all regions of the country. As the atmospheric moisture content increases the ability of human body to release heat through evaporation is inhibited thereby causing discomfort and stress. The rise in heat index results in higher heat related mortality rate during summer.

Climate change results in a greater increase of hot nights for cities than neighbouring rural areas, increasing the thermal stress and vulnerability to heat waves of urban citizens in a warmer climate compared to their rural counterparts (McCarthy et al., 2010). High urbanization and population density also contribute to the increased health risk from heat stress (Smoyer-Tomic et al., 2003; Vandentorren et al., 2004). We have analyzed HI trends in 25 mega cities in India having combined population of 116 million. The results show that most of these mega cities are having significant increasing trends in summer and monsoon season HI. The mega cities are densely packed with people, buildings, industries and motor vehicles. Heat released in the atmosphere gets trapped, meaning the ambient temperature is often higher than the immediate surroundings.

An interesting regional phenomenon is the stilling of winds in India (Jaswal and Koppar, 2013; Padmakumari et al., 2013). Wind helps sweat to evaporate and the body to cool. Wind also picks up heat through convection from the skin's surface. Decrease in wind speed may aggravate the effects of heat stress on vulnerable sections of the society and outdoor workers.

As a result of increasing temperatures and humidity and decrease in wind speed in India, the frequency, duration and intensity of higher heat stress days are likely to increase substantially in the future.

Conclusions

The analysis of variations and trends in HI in this study highlighted important features of our changing climate. On the basis of discussed results it is quite obvious that HI trend has shown significant increase in the summer and monsoon seasons in different regions of India during 1951-2010:

(a) A remarkable seasonal shift in zone of higher HI pattern has been observed from summer to monsoon season. Higher summer mean HI is observed over coastal Andhra Pradesh and north Tamil Nadu, while higher monsoon mean HI is found over west Rajasthan and Indo-Gangetic plains.

(b) All-India averaged HI is increasing significantly at the rate of +0.56 ºC/decade and +0.32 ºC/decade in summer and monsoon seasons, respectively.

(c) Spatially, the increasing trends in HI are significant in all regions of the country suggesting substantial increase in human discomfort and illness exacerbated by climate change.

(d) Almost all the mega cities of India showed significant increasing trends in HI during summer as well as in monsoon season indicating heat related public health problems may further aggravate in these highly urbanized centres.

(e) Summer season HI has increased due to higher rate of change in RH as compared to air temperature, while increase in monsoon season HI is more influenced by increase in air temperature as compared to RH.

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