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Research article

Spatial and statistical characteristics of heat waves impacting India

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Abstract: The climate of a place has a decisive role in human adaptations. Man's health, adaptability, behavioural patterns, food, shelter, and clothing are mainly influenced by the temperatures of the area. Hence, a study is undertaken to analyse the spatial distribution, frequency, and trend in the heat waves over the country. The statistical characteristics of heat waves over India are addressed in this study. Gridded daily temperature data sets for the period 1951–2019 were used to compute the arithmetic mean (AM), standard deviation (SD), coefficient of variation (CV), and trends of monthly maximum temperature. The number of heat wave days were identified using the criteria given by India Meteorological Department (IMD) i.e., a heat wave is recognized when the daily normal maximum temperature of a station is less than or equal to (greater than) 40 ℃ than it will be considered as a heat wave if the daily maximum temperature exceeds the daily normal maximum temperature by 5 ℃ (4 ℃). The analysis was confined to the two summer months of April and May only. The spatial distribution of the AM shows higher values during May, and the core hot region with temperatures exceeding 40 ℃ lies over central India extending towards the northwest. The SD distribution shows higher values over the northeast of central India decreasing towards the southwest. The CV distribution shows higher values over the north decreasing toward the south. Higher numbers of heat waves are observed during May and the number is higher over Andhra Pradesh and south Telangana regions of southeast India. This study concludes that a moderate hot region experiences a higher number of heat wave days over India.

Keywords: heat waves; maximum temperatures; climate; statistical metrics; trends

1. Introduction

The climate of a place has a say in human adaptability. The people in an area make suitable adaptations of food, shelter, and clothing, etc., in commensuration with the perceived climatic conditions of that place. Despite all these modifications, the extremes in temperatures and humidity can lead to discomfort, health issues, and morbidity. A prolonged period of higher maximum temperatures than the adaptable values of maximum temperatures in hot weather season can lead to what is known as heat waves. Heat waves can aggravate dry and drought conditions. Increasing urbanization and industrialization and unbridled development leads to increasing temperatures trapped in concrete structures what we call the urban heat island effect. As the global mean surface air temperatures have escalated extreme weather events and natural hazards such as heat waves, excess precipitation events, droughts etc. have amplified in intensity, durability, and frequency [1,2].

The extreme weather event heat wave is every so often referred to as the "silent atmospheric killer" and this is strongly connected to anthropogenic climate warming especially in areas where senior citizens reside [3–5]. The disaster due to this heat wave is high, for example during 2003 in Europe higher than 70000 death rates were reported due to heat wave and in Russia 2010 above 50000 deaths occurred [1]. A global analysis conducted since 1980 on deadly heat waves and observed that nearly 30% of the population is presently at threat as the heat wave thresholds are increased. Not only daytime maximum temperatures hazardous to human health and life but also warm minimum temperatures during night time also have a great concern on the mortality rate and causing unfavourable conditions to human health during the last few decades across the globe and also durability of heat wave also plays a crucial role for example, one day of extremely hot conditions will not produce severe impacts but if the situation persists for more than two or three days causes a major threat [6]. There are increases in both land and ocean temperatures besides more frequent heat waves in most land regions. The Intergovernmental Panel on Climate Change (IPCC) report also underlined an increase in the frequency and duration of marine heat waves as a consequence of global warming and also the surface mean air temperature has amplified by 0.7 ℃ from 1961 to 2000 [7].

A heat wave is a protracted period of extremely high temperatures or hot weather as generally perceived and scientifically defined as the occurrence of temperatures higher than normal temperatures over the region. Heat waves are known to be responsible for the highest number of human deaths of all-weather related disasters [8,9]. A decreased trend in temperature over Northern India and an increasing trend in temperature over Southern India was observed [10]. Earlier when there is a lack of availability of data trends of both temperatures i.e., maximum and minimum during 1880 to 1950 were studied and consummate that there are no regular changes in both the temperatures [11].

In the20th century the annual mean temperature datasets of 73 stations over India showedan increase of 0.4 ℃ [12]. Heat waves affect human health in many ways, cause hyperthermia when the temperatures are higher than 40 ℃ which leads to heat oedema; heat rash; heat syncope and heat exhaustion, and sometimes death. Reports indicate psychological stress in addition to physical stress due to extreme temperatures [13]. Abnormally high temperatures also have societal impacts such as exacerbating conditions leading to power outages, wildfires, melting of roads, buckling and kinking of rails, bursting of water lines etc. [14]. Three vulnerable zones and heat waves zones were identified over Indian subcontinent [15]. In recent decades, the concern about extreme high temperatures and heat waves had increased due to the observed increased tendency in their frequency and severity since 1950 and an indication of their continued increase in future due to global warming climate change [7]. These are evident from the recent occurrences of long and severe heat waves over western and central Europe in August 2003 and July 2006 that are associated with high human mortality [8,16,17]. The indications of enhanced frequency, intensity, and duration of heat wave conditions from future climate projections raise concerns not only on the human mortalities but also human activities with socio-economic impacts [7,18]. From a statistical point of view, a small change in the mean value of a climate variable (such as temperature) corresponds to large changes in weather, which means a small shift in the mean of temperature distribution imply a sizeable change in the frequency and intensity of temperature extremes [19]. The variations of weather parameters (such as temperature) may be described as a bell-shaped curve, meaning that normal weather is common and weather extremes are rare. In this situation, a small increase in temperature shifts the entire curve toward hotter high temperatures, meaning that extreme heat events become more severe and more frequent.

Heat waves over India are important due to human mortality associated with them and the increase in the mortality rate in recent years [20]. Human deaths in India due to heat waves are noted to be 1425, 1393, and 2500 during 2003, 2013, and 2015 respectively. Indian subcontinent experiences four seasons, namely winter (December to early March), pre-monsoon (summer, March to June), rainy (or monsoon, June to September), and fall (post-monsoon, October-November). Although the highest maximum temperatures are recorded in May, temperatures exceeding 38 ℃ are not uncommon in April associated with heat wave conditions. Summers in India are known for the sweltering heat with temperatures exceeding 40 ℃. Most of the heat waves over India occur in May as the sun rays reach the surface of the earth directly due to the transition of the Sun in the direction of north resulting in the accretion of heat in the north-western parts of the country and the physical patterns of the central plateau and northern plains [21]. Northern India is familiar with heat waves annually but the south-eastern parts of the country experiencing since the decade 1970s [22]. Distribution of temperature during the pre-monsoon season represents that the maximum temperature is located over the north-western parts of the country as the wind blows from Middle East Asia bringing hot and dry air to north-west India through Pakistan and from there the hot air passes to central and south eastern parts of the country representing the advection of temperature [23,24].

The characteristics of heat waves differ from region to region, in terms of the climate conditions describing the maximum temperatures of the region, e.g., the heat wave in Europe during 2003 continued for nearly three months i.e., from June to August [25,26], while in the United States during 1995 and 1999 in July persists only for a few days [27,28]. Different studies were made on heat waves over different parts of the globe and given different threshold to define heat waves for example over Australia [29], USA [30], and Europe [31]. Over India the synoptic features associated with heat wave were studied, and proposed that the reason behind high temperatures and the source of heat is from the Thar Desert and Rajasthan [32–34]. A few studies attempted to describe the characteristics of heat waves over India. Heat wave days over India had been increasing during 1961–2010 and that the increasing trend is more during the warmer decade of 2001–2010 and observed that the highest anomaly of 6–8 ℃ of composite temperatures was seen over coastal Andhra Pradesh reflecting this to be the vulnerable region to heat wave [35]. Heat wave over Karachi, Pakistan during June 2015 recorded a maximum temperature of about 44.8 ℃ and heat index of about 66 ℃ and reported a death toll of about 1200 [36]. A report from the National Disaster Management Authority (NMDA), Government of India [20] stated that the frequency of heat wave days is 5 to 6 over India. The NDMA proclaimed that there is an increasing trend in number of heat waves. The report also added that the deaths due to heat wave during period from 1992–2015 were about 22562.

In India, the occurrence of a heat wave is recognized according to the criteria given by India Meteorological Department (IMD). A heat wave is declared (i) if the mean maximum temperature of a station is ≥ 40 ℃ for plains and hilly areas ≥ 30 ℃ and the departure from the normal maximum temperature is 4–6 ℃ (ii) To be declared as a severe heat wave if the mean maximum temperature of a station is ≥ 40 ℃ and the departure from the normal maximum temperature is greater than 6 ℃ or if the station's normal maximum temperature is ≥ 47 ℃ [37].

The present study is an attempt to describe the statistical characteristics of heat waves over India using gridded temperature data for the period from 1951 to 2019. This study brings out the spatial distributions of the statistical properties such as the arithmetic mean, variability, and trends of temperatures and heat wave days.

2. Data and methodology

2.1. Data

To study heat waves one of the most efficient and high resolution data set established by India Meteorological Department is the daily temperature gridded data set. By using 395 synoptic weather stations which were spread evenly over the Indian subcontinent this data set was developed using daily maximum temperature i.e., during afternoon hours. Shepard's angular distance weighting algorithm was used to interpolate station data into regular grids. Daily maximum temperature anomalies were used instead of absolute values to avoid biases. The climatological normal of maximum temperatures were calculated for every station for the period 1971–2000. This technique of interpolation needs a considerate understanding of the spatial correlation structure of the station data. For this reason, correlations of inter-station were evaluated to examine the distances over which maximum temperature anomalies are connected. The station data was first subjected to primary quality controls such as confirming uniformity and eradicating outliners. Moreover, it was also confirmed that the data length of all the stations should have a similar length to evade errors caused due to inhomogeneity in station density in a gridded dataset. In the beginning, this gridded dataset was established for the period from 1969 to 2005 and later restructured for the period from 1951 to 2019 and for the present study 69 years of a gridded dataset (1951–2019) is considered [38]. Meteorological subdivisions over India as per IMD are given in Figure 1.

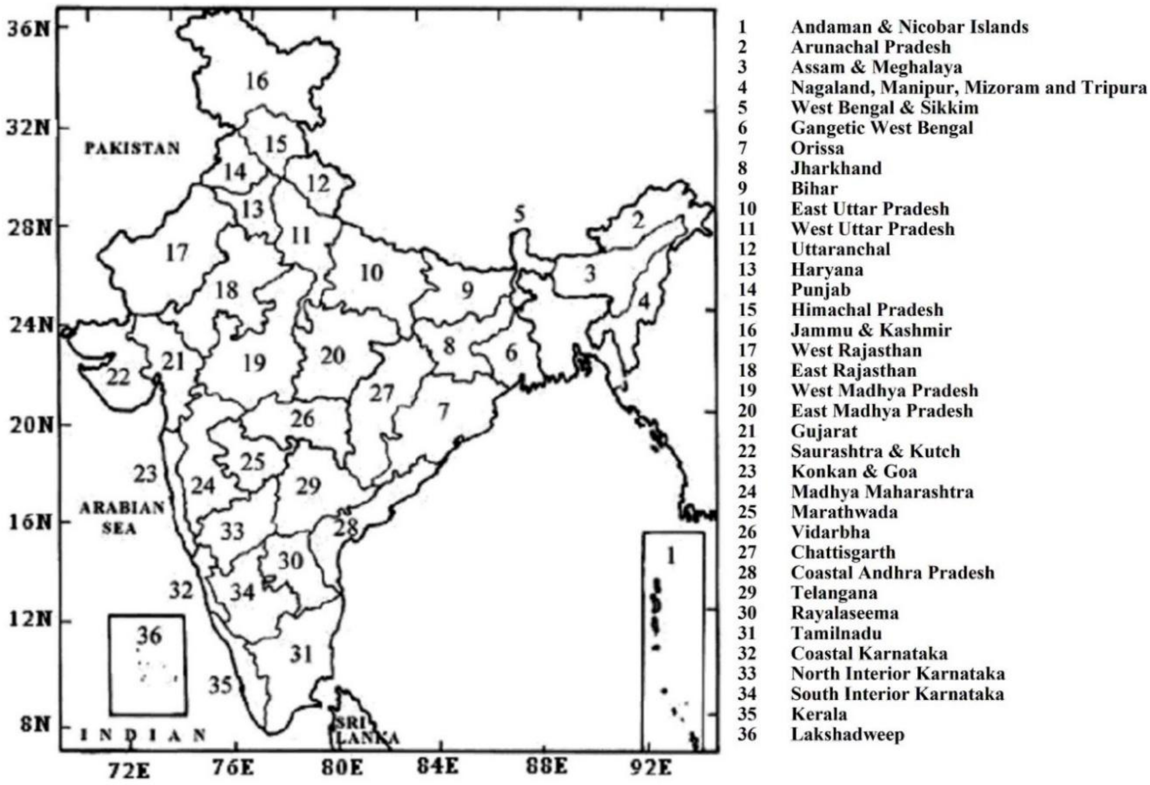

Figure 1. Meteorological subdivisions over India (as per IMD classification).

2.2. Methodology

(i). The Arithmetic Mean (AM), Standard Deviation (SD), and Coefficient of Variation (CV), are calculated for each of the grid points in April and May separately using daily gridded data sets during 1951–2019. The Eqs are

$$Mean\left(\overline{X}\right) = \frac{\sum X}{N} \tag{1}$$

$$\text{Standard Deviation (SD)} = \sqrt{\frac{\sum\left(X - \overline{X}\right)^2}{N}} \ (\tag{2}$$

$$\text{Coefficient of Variation (CV)} = \left(\frac{SD}{\overline{X}}\right) \tag{3}$$

(ii). The number of heat wave days is calculated considering the criterion of greater than mean+4 ℃. The number of days is calculated for each of the grid points and calculated separately for April and May.

(iii). To calculate trend a non-parametric rank based statistical test known as Mann-Kendall test was applied to the long term maximum temperature dataset for the period 1951–2019 to determine the significant trends. It is given as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sig(X_j - X_i) \tag{4}$$

$$V\ (S) = \frac{1}{18}[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\,(t_p - 1)(2t_p + 5)] \tag{5}$$

In the above Eq X_i and X_j are the time series of observations in chronological order; n is the time series length; t_p is the number of values tied for p^{th} value and q represents the number of values tied.

3. Results and discussions

In this section, some statistical parameters are computed and examined to understand thecharacteristics of heat waves over the Indian subcontinent using the currently available gridded daily maximum temperature datasets (Section 2.1).

The first part of the results describes the basic statistical properties (i.e.,) simple arithmetic mean (AM), standard deviation (SD), and coefficient of variation (CV). In the second part, results considering the number of heat wave days are presented. In part 3, trends in the maximum temperature during the 69 years (1951–2019) are presented.

3.1. Distributions of AM, SD, and CV

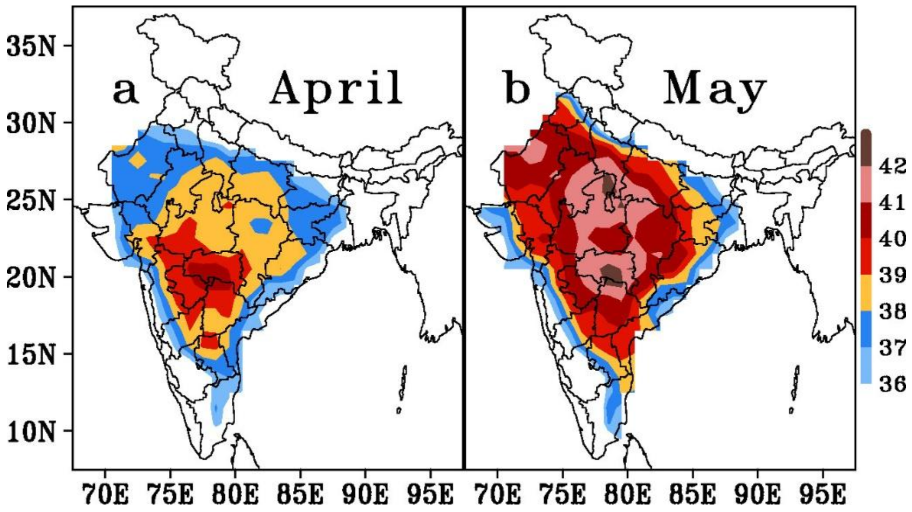

Figure 2. Spatial distribution of monthly mean maximum temperature (℃) over Indian Subcontinent for (a) April and (b) May for the period 1951 to 2019.

The spatial distributions of mean monthly maximum temperature during April and May are presented in Figure 2. During April, the hot region with temperatures exceeding 37 ℃ exists over coastal parts of India with a small core maximum of 40–41 ℃ over Vidarbha (Figure 2a**)**. Temperatures are below 30 ℃ over the west coast, northeast, and north India. During May, the temperature distribution is similar to that of April, except that the temperatures over central India are higher by 2 ℃, and the region of the maximum extent from central India to northwest Rajasthan

(Figure 2b**)**. The core of maximum temperature still maintains the same temperature in May whereas there is an increase in maximum temperature up to 2 ℃ from central India to west Rajasthan, where the temperatures are 40–43 ℃. However, the regions of the west coast, northeast, and north India are cooler with temperatures below 32 ℃.

The distribution of SD shows higher values over the north, decreasing towards the south **(**Figure 3a**)**. During April the northern region has SD of 1.4 ℃ to 2 ℃; the northern parts of central India have 1.2 ℃ to 1.4 ℃; southern parts and central India have 1 ℃ to 1.2 ℃; the west coast and south peninsula having the lowest SD of 0.8 ℃ to 1 ℃. During April SD is higher over NE India in the order of 1 ℃ to 1.4 ℃ whereas it is around 0.8 ℃ to 1 ℃ during the May month. Southeastern parts of India i.e., Andhra Pradesh and Telangana are occupied with higher SD values during May of the order of 1.2 ℃ to 1.4 ℃ whereas it is 0.8 ℃ to 1 ℃ during April. During May the distribution shows a slightly minimum over north decreasing towards the west with comparison to April **(**Figure 3b**)**. The SD over Gujarat has decreased to 0.8 ℃ to 1 ℃ during May while it is 1 ℃ to 1.2 ℃ during April and remained alike over the eastern parts of Jharkhand and Bihar in central India. The coastal areas are cooler and wetter than the inland regions and the center of the continents have a large range of temperatures resulting in temperatures being very high and dry as the moisture from the sea evaporates before it extends to the center of the continent resulting in low mean maximum temperature and standard deviation over the coastal regions.

The distribution of CV shows maximum over north decreasing towards the south (Figure 4a,b). The spatial distribution is mostly similar during April and May except that CV slightly increased over a south peninsula and decreased over northeast parts during May. The CV over northern parts of north India is smaller during May as compared to April.

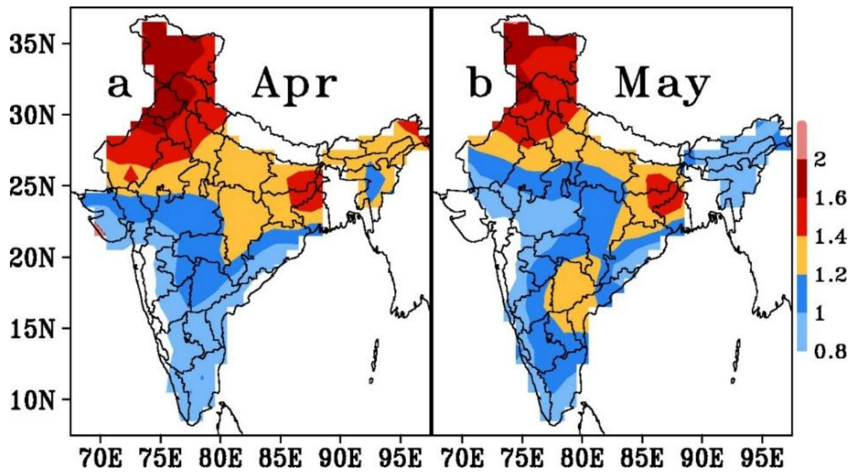

Figure 3. Spatial distribution of standard deviation of maximum temperature (℃) for (a) April and (b) May for the period 1951 to 2019.

The above description of AM, SD, and CV indicate a general pattern of a higher degree of variability over northeastern parts which is cooler; and a slight decrease of CV over the hot region of north central India indicates that hot regions have a lesser CV as compared to higher CV over cooler the region. Most importantly the CV is larger over a south peninsula and southeast coast, specifically over coastal AP which has mean temperatures of 38–40 ℃ during May had SD between 1.2 to

1.4 ℃ thus contributing to higher CV over a small region. This indicates frequent occurrences of hot spells over this isolated coastal region.

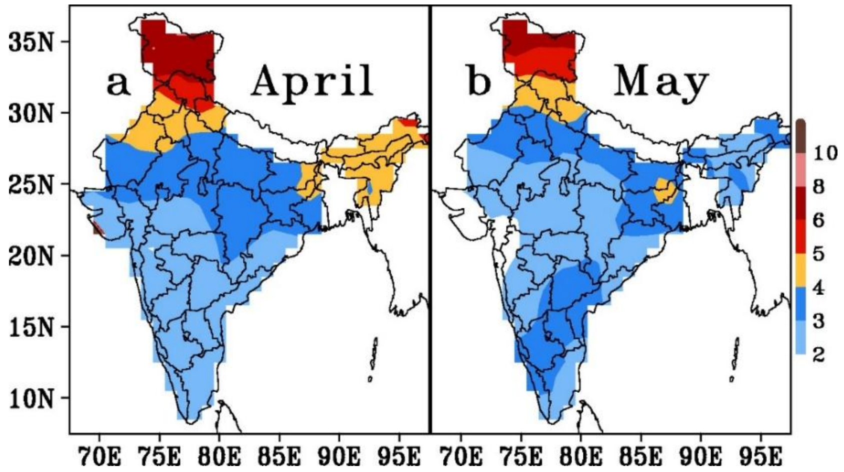

Figure 4. Spatial distribution Coefficient of Variation of monthly maximum temperature (℃) for (a) April and (b) May for the period 1951 to 2019.

3.2. Distribution of maximum temperature days above 42 ℃

Spatial distribution of days with maximum temperatures exceeding 42 ℃ were plotted from 1951–2019 for the hottest months of April and May. In April, a small isolated region over Vidarbha has the highest frequency with more than 6 days/year and it is the hottest region when compared to the rest of the country (Figure 5a). The Frequency of 4–6 days occurs over South Telangana, Marathwada, West Madhya Pradesh, and West Uttar Pradesh. The frequency of 1–2 days is noted over West Orissa, Chhattisgarh, East & West Madhya Pradesh, East & West Uttar Pradesh, East & West Rajasthan, Madhya Maharashtra, South Telangana, Rayalaseema, and Gujarat. During May, the area extent and frequency of days were larger and three hottest temperature zones were observed i.e., West Rajasthan (T1), Northwest Madhya Pradesh (MP) (T2) and Southwest Uttar Pradesh (UP) (T3), and East Maharashtra [15] (Figure 5b). In May, the frequencies are the highest (above 16) over Vidarbha and North Telangana; 12–16 over East Madhya Pradesh, Rajasthan; 1–22 over Chhattisgarh; 16–22 over West Uttar Pradesh; 18–26 days over South Telangana and East Uttar Pradesh; 14–22 over Bihar; 8–16 over Gangetic West Bengal; 6–16 over Coastal Andhra Pradesh; 4–14 over Orissa; and are below 4 over rest of the country (Figure 5b**)**. It is important to note that Vidarbha and Telangana have the highest frequency of above >26 days in May whereas Rajasthan has the frequency of 20–26 days. From the spatial distribution plot, it is clear that higher frequency regions coincide with maximum temperature regions.

The identified maximum temperature region of East Maharashtra is noted as the hottest. Days with a highest average frequency of 14–20 days were noted over the zone of “hot region” during the May month and from the spatial distribution plot, it is clear that the regions of the south-central parts are the warmest when compared to the rest of the Indian subcontinent. This finding of the isolated hot region [39] will be useful to comprehend the occurrence of heat waves over southeast coastal regions. Temperatures over Vidarbha and Telangana are higher than elsewhere, not only because of the remoteness from the sea but also due to the black soil of the area [39–40].

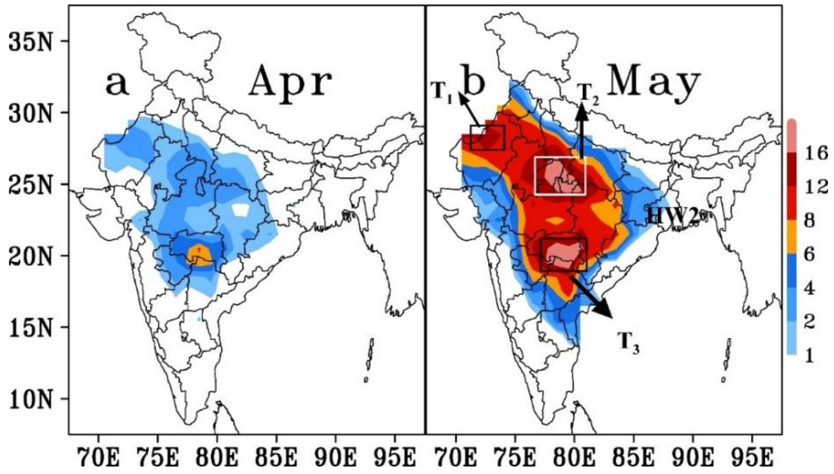

Figure 5. Spatial distribution of the number of days above 42 ℃ days in (a) April and (b) May for the period 1951 to 2019.

3.3. Distribution of heat wave days

Heat wave days as mentioned earlier, are calculated using the criteria that a heat wave day is identified when the maximum temperature exceeds the mean value by 4 ℃. For brevity, it is stated that the maximum temperature of each day of April and May is compared with the respective daily mean maximum temperature and the occurrence of heat wave day is identified. The spatial distribution of the count of heat wave days during April and May is presented in Figure 6 for the period 1951 to 2019. During April, the highest number of heat wave days is observed over north India decreasing towards the south (Figure 6a). The region with heat wave days greater than 20 days is confined to only northern parts at locations higher than 25°N and over east-central India at latitudes higher than 22° N and east of 82° E. The heat wave days were maximum over west Rajasthan, Jharkhand, and Bihar, and no heat wave days were observed over hilly regions, northeast India, west central India. Over peninsular India only, Andhra Pradesh and Telangana are noted to have 5 to 10 heat wave days. Heat wave days are greater in May in a small region of extent (Figure 6b). A remarkable feature that is to be noted is that heat wave days have increased to a higher extent over a small region of Andhra Pradesh and Telangana. The contrastingly located maximum over Andhra Pradesh and Telangana assumes importance as the number of heat wave days rises during May and that took over a region with a maximum temperature at 38–40 ℃. Although not presented here, observations indicate that the highest percentage (80–90%) of heat wave related human deaths over India are in Andhra Pradesh and South Telangana.

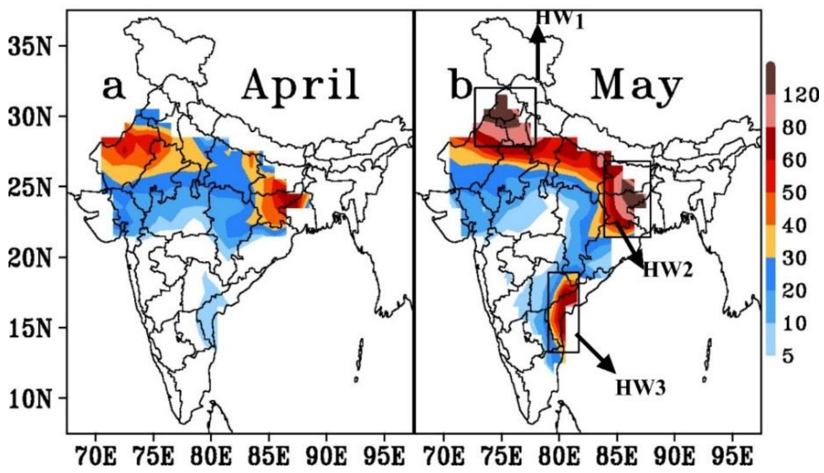

Figure 6. Spatial distribution of heat wave days in (a) April and (b) May for the period 1951 to 2019.

3.4. Spatial distribution of mean minimum temperature

During April, the minimum temperatures above 24 ℃ were observed in the east coastal region, Telangana, and south Vidarbha (Figure 7a). Around 22–24 ℃ were observed in some parts of Gujarat, Saurashtra, Kutch & Diu, Konkan & Goa, Madhya Pradesh and southern parts of Chhattisgarh. The mean minimum temperatures were also showing an increasing tendency in May. It is clear that there are two distinct regions of temperatures exceeding 26 ℃, which are in east central parts of India (Telangana, Andhra Pradesh, Vidarbha, the southern part of Chhattisgarh and Orissa) and north central parts of India (east Rajasthan, west and east Madhya Pradesh, east UP) (Figure 7b).

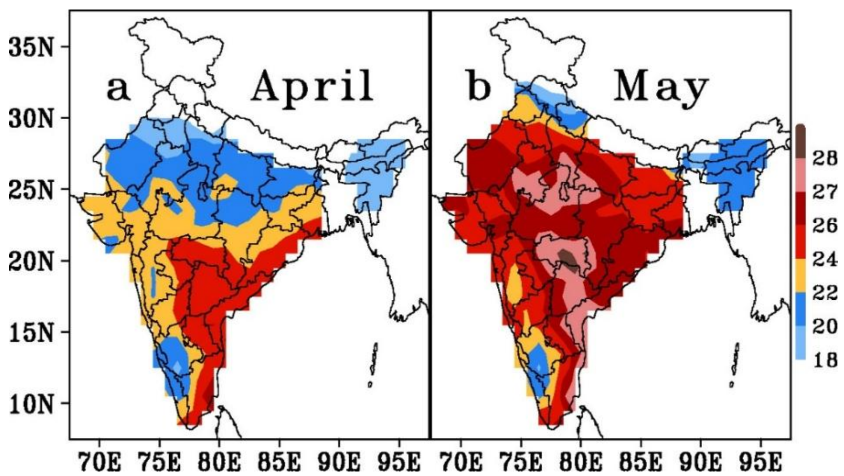

Figure 7. Spatial distribution of monthly mean minimum temperature (℃) over Indian. Subcontinent for (a) April and (b) May for the period 1951 to 2019.

3.5. Climate trends

Trends of maximum temperature, frequency of days with temperatures above 42 ℃, and heat wave days were investigated for a period of 69 years (1951–2019). Secular disparities of maximum temperatures over locations of the small region were also examined.

3.5.1. Maximum temperature trend

As a part of the analysis, trends in the monthly mean maximum temperature during the period the 1951–2019 are computed for each of the grid points and for April & May separately. The spatial distribution of trends is shown in Figure 8.

During April spatial distribution plot of maximum temperature trend indicates an increasing trend all over the Indian subcontinent except for northeast India where the decreasing trend of about −1 ℃/100yr to −2 ℃/100yr is observed. For Northwest India, an increasing trend of about 1.5 ℃/100yr to 3 ℃/100yr, over Jammu & Kashmir, Himachal Pradesh, Uttaranchal, and Central India it is about 1.5 ℃/100yr to 2 ℃/100yr. A higher rate of increasing trend is observed over Peninsular India of the order of about 2 ℃/100yr to 3 ℃/100yr. In May, the increasing trend is observed over Northeast India of the order of 0.5 ℃/100yr to 1.5 ℃/100yr and a decreasing trend is noted over Gangetic West Bengal, Jharkhand, Bihar, East, and West Uttar Pradesh. Overall a large west part of India has the highest temperature increase whereas in some regions like Jharkhand and Bengale-Occidental it decreases. An interesting fact to be noted here are the trends of maximum temperature over Northeast India, where negative trend during April and positive during May are observed. And when compared to both the pre monsoon months increasing trend rate is high for April month than of May month. This analysis brings out the possible reasons for the increase of heat waves over Andhra Pradesh and Telangana leading to higher heat wave related human deaths during the last decade.

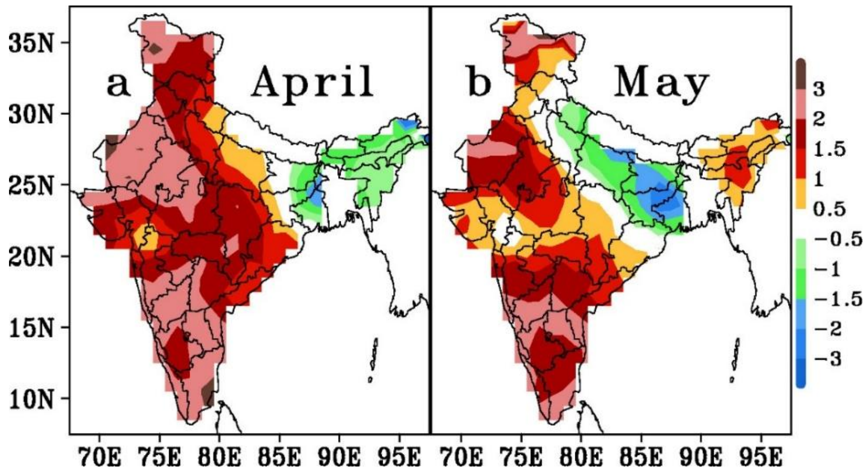

Figure 8. Trends of monthly maximum temperature ℃/100yr (during the 69-year period of 1951–2019) for (a) April and (b) May.

3.5.2. Above 42 ℃ trend

The trends in the frequency of days with maximum temperature above 42 ℃ are given in Figure 9. During the month of April, trends of days above 42 ℃ shows an increasing trend over most parts of central and northwestern parts of India with an elongated area/ geographical regional spread of the heat advection diagonally from north western parts of West Rajasthan (29^{o}N) to the northern part of Telangana (19^{o}N) with three concentrated/ isolated pockets. Some parts of Vidarbha and parts of north Telangana show an increase of ~12days/100yr while major parts of the Vidarbha, Marathwada, Telangana, Chhattisgarh, some parts of North Madhya Pradesh, and West Rajasthan show the highest rate of increase of about 6 to 10 days/100yr in April month (Figure 9a).

During May month, the temperature trends with 42 ℃ days are quite high being a peak month for the hot weather/ pre monsoon season, when compared with April as shown in Figure 9b. A diagonal spread of elongated area of temperature with 42 ℃ days is high with an increasing trend in the north-western Indian states. A large tract of central parts of Rajasthan (>12) (West Rajasthan and East Rajasthan) are experiencing an increasing trend greater than 12 days/100yr. Major parts of Telangana, parts of Marathwada, and a small part of North Interior Karnataka while the remaining parts of central and northwestern parts of the country, parts of Rayalaseema and Coastal Andhra Pradesh recorded about 6 to 10 days/100yr increase in the frequency of days of above 42 ℃. Conspicuously, a negative trend is observed over a major part of Jharkhand, parts of east Uttar Pradesh, parts of Bihar and parts of West Bengal.

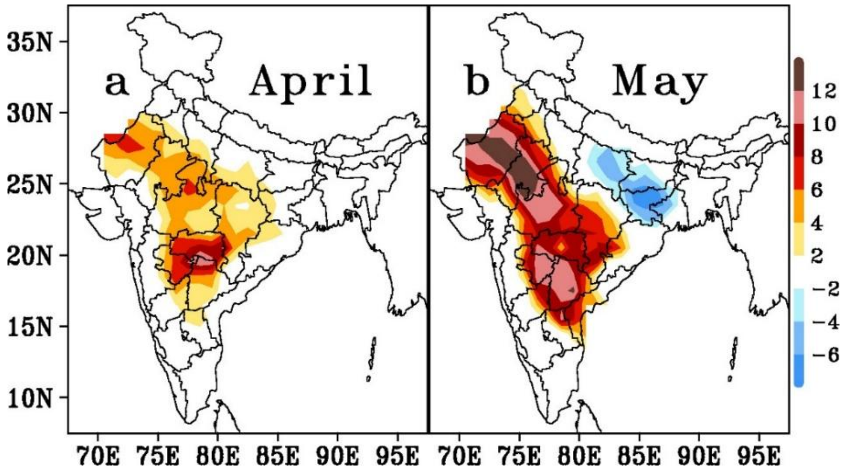

Figure 9. Trends of above 42 ℃ days/100yr (during the 69-year period of 1951–2019) for (a) April and (b) May.

3.5.3. Heat wave days trend

Spatial coverage of heat wave shows increasing trends in the Indian subcontinent during both the pre-monsoon months i.e., April and May (Figures10a,b). It is observed that the spatial coverage of the increasing trend of the heat waves is more in April than during May. During April month, positive trends of the order of 2–3 days/100yr are observed over central and northern parts of Rajasthan; 1 day/100yr over remaining parts of Rajasthan, northwest and East Madhya Pradesh, parts of Jharkhand, Bihar, East UP, Haryana, and Delhi; of the order of 0.5 days/100yr to 1 days/100yr over the remaining parts of the above states, besides small areas of Coastal Andhra Pradesh and Gujarat.

In May, northwest Rajasthan recorded an increase in the trend of heatwaves of 2–4 days/100yr; remaining parts of Rajasthan, Western parts of Punjab, parts of Haryana, and Coastal Andhra Pradesh show an increase of 1–2 days/100yr of heatwaves; parts of Telangana, west Madhya Pradesh, Gujarat, Telangana, and Rayalaseema show an increase of 0.5 days/100yr to 1.0 days/100yr. A negative trend of heat wave days-is observed over the state of Jharkhand, western Bihar, and East Uttar Pradesh.

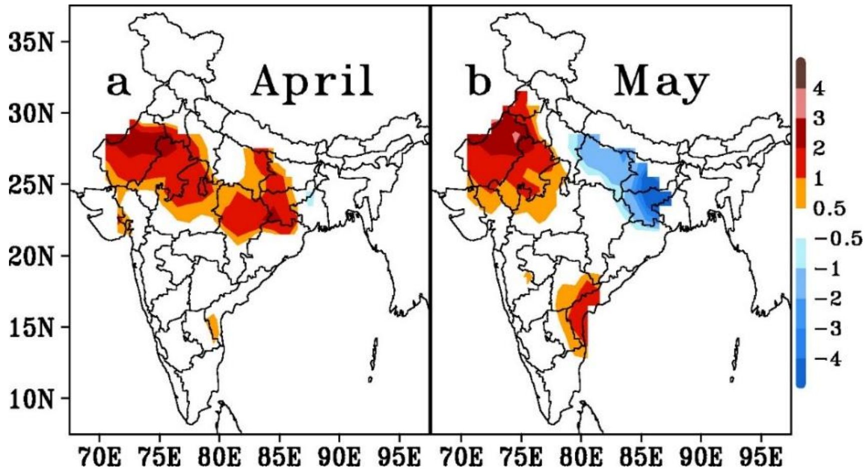

Figure 10. Trends of heat wave days/100yr (during the 69-year period of 1951–2019) for (a) April and (b) May.

3.5.4. Minimum temperature trend

Trends of minimum temperatures were computed for April and May and given in Figure 11. The northern and north-western parts of the country were showing an increasing trend for both the both of April and May and North-Eastern part of the country showing decreasing trend for April and increasing May.

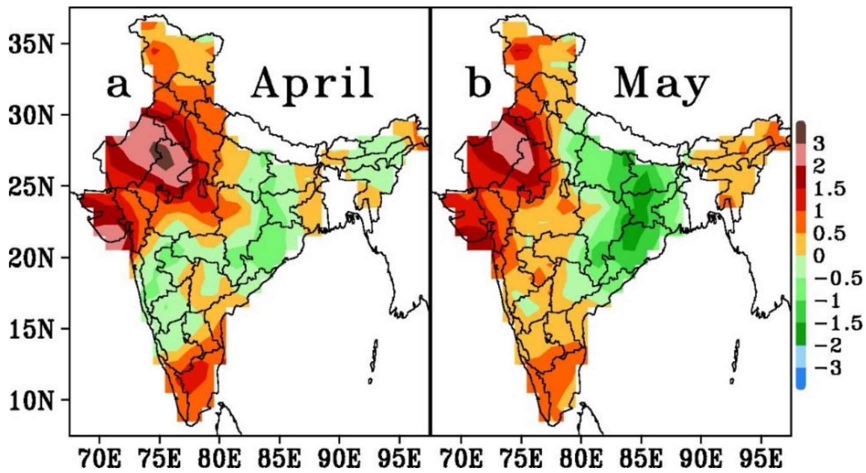

Figure 11. Trends of monthly minimum temperature ℃/100yr (during the 69-year period of 1951–2019) for (a) April and (b) May.

3.5.5. Statistical analysis of mean maximum temperatures for T1, T2 and T3 temperature zones and H1, H2 and H3 heat wave zones

Three maximum recorded temperature zones and three heat wave vulnerable regions were identified over the Indian subcontinent [15]. Statistical analysis was carried out for these three temperature zones T1, T2, and T3and heat wave zones H1, H2 and H3 for the period of 69 years i.e., from 1951–2019 as given in Table 1. The areal maximum value of mean maximum temperature during April and May for T1, T2, and T3 are 38.3 ℃ and 41.3 ℃, 39.3 ℃ and 42.1 ℃, and 40.6 ℃

and 42.5 ℃. From this it is clear that T3 temperature zone is occupied with a higher mean maximum temperature during both the pre-monsoon months of April and May with respect to T1 and T2 (Table 2). The temperature zone T1 is occupied with a lower mean maximum temperature for both April and May w.r.t T2 and T3. This gives clear evidence that East Maharashtra temperature zone i.e., T3 has a higher mean maximum temperature than West Rajasthan. Among the three heat wave zones, the third zone i.e., Southeast India is noted to have higher mean maximum temperatures. In April, positive tendencies over T1, T2, and T3 zones are significant at 2.8 ℃/100yr, 1.8 ℃ /100yr and 1.8 ℃ /100yr (0.01, 0.05 and 0.01 level). During May, the temperatures zone T1 is showing increasing trend (2 ℃/100yr) at 0.01 significant level, T2 zone shows a feeble long-term trend (0.5 ℃/100yr) and T3 zone shows significant increasing trend (1.2 ℃/100yr) at 0.01 significant level. The significant level was tested by using Mann-Kendall test.

For heat wave zones (HW1., HW2 and HW3) during April month, showing positive trend is observed 0.8 (HW1) and 1.7 ℃/100yr at 0.1 and 0.01 significant level; HW2 zones showing a decreasing trend at the rate of −1.2 ℃/100yr is observed for HW2 at 0.1 significant level. In May, the time series of Mean maximum temperature is showing an increasing trend over HW2 (0.2 ℃/100yr) and HW3 (2.0 ℃/100yr) zones at 0.1 and 0.01 significant level. The trend values are presented in Table 2.

Table 1. Details of the domain and the meteorological subdivisions corresponding to the identified maximum temperature and heat wave zones.

Temp. Zones	Regions	Heat Wave Zones	Regions
T1 (27.2–29ºN; 71.5–74ºE)	West Rajasthan	HW1 (27–31.5ºN;72.8–78ºE)	North India (North Rajasthan, Punjab and Haryana)
T2 (23.8–27.5ºN; 75.8–81.2ºE)	Northwest Madhya Pradesh (MP), Southwest Uttar Pradesh (UP),	HW2 (21.2–27.2ºN;83–87.2ºE)	Northeast India (Bihar and Jharkand)
T3 (18.5–21.5ºN; 77–81ºE)	East Maharashtra	HW3 (12–21ºN;79.5–81.2ºE)	Southeast India (Andhra Pradesh and Telangana)

Table 2. Statistical Metrics for Temperature zones (T1, T2 and T3) and Heat wave zones (H1, H2 and H3) for the period of 69 years i.e., from 1951–2019.

S.No.	April			May		
	T1	T2	T3	T1	T2	T3
Mean	38.3	39.3	40.6	41.3	42.1	42.5
SD	1.6	1.5	1.3	1.5	1.3	1.3
CV	4.4	4.1	3.3	3.7	3.4	3.2
Trend	2.8(0.01)	1.8(0.05)	1.8(0.01)	2(0.01)	0.5	1.2(0.05)
Above 42 ℃						
Mean	3.2	3.9	8.3	13	17.4	20.6
SD	3.7	3.9	6.4	7.2	7.1	7.8
CV	1.9	2.4	3.4	0.8	0.8	2.3
Trend	6.2	4.3	7.3	12.2	4.3	8.8
HW days						
	HW1	HW2	HW3	HW1	HW2	HW3
Mean	38.8	39	40.3	42.1	41.1	42.2
SD	1.7	1.5	1.3	1.6	1.6	1.3
CV	5.6	4.4	3.3	4.7	4.2	3.2
Trend	0.8 (0.1)	−1.2 (0.1)	1.7(0.01)	2.1	0.2(0.1)	2.0(0.01)

4. Conclusions

The statistical properties of the maximum temperature, above 42 ℃ days, and heat waves days are evaluated for the Indian subcontinent for the recent 69-year period of 1951–2019.The study assumes importance in the wake of increased heat wave conditions leading to human casualties during the last decade not only over India but all over the world. Spatial distributions of AM, SD, CV, and trends of the monthly maximum temperature field for the two summer months of April and May are evaluated. Important conclusions drawn from the above study are:

(i) Mean maximum temperatures are higher during May, regions higher than 40 ℃ are observed over central parts of India. A Small region with the highest maximum temperature is located over Vidarbha in central India.

(ii) Cooler regions with temperatures below 30 ℃ exist over Jammu and Kashmir of north India; west coast and over Assam, Meghalaya, and Nagaland of northeast India.

(iii) SD values were higher over NE India during April when compared to May month. Higher SD values were observed over Andhra Pradesh and Telangana during May month.

(iv) CV distribution shows higher values over the north decreasing towards the south. CV over the south peninsula is higher during May than April.

(v) Heat wave occurrence days computed based on IMD criterion, show higher values over north, northeast and augmented to a greater extent over southeast parts of India are indicating isolated vulnerable regions.

(vi) Climate trends indicate an increasing trend of 1.28 ℃/decade over Jammu and Kashmir in North and over the south peninsula and decreasing trends over east central India. The Maximum temperature trend is negative over NE India during April and positive during May month. The increase in spatial extent of heatwaves is observed more in April than in May. The increasing trend over the south peninsula assumes importance because the regions above 38 ℃ would become more vulnerable to heat wave conditions. Above 42 ℃ days trend shows negative over Jharkhand, Bihar and East Uttar Pradesh during May month and a higher rate of increase in heat wave days trend is observed during May month over Andhra Pradesh and Telangana.

(vii) A holistic picture of AM, SD, and CV indicates that some selected regions over southeast India with mean temperatures of 38–40 ℃ have a higher heat wave vulnerability than warmer regions with 40–44 ℃ located in the northwest.

This study brings out the basic characteristics of the maximum temperatures and the heat wave vulnerability over India during the summer season.

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Conflict of interest

The authors declare that there is no conflict of interest.

References

1. Coumou D, Rahmstorf S (2012) A decade of weather extremes. *Nat Climate Change* 2: 491–496.
2. IPCC, 2013: Summary for policymakers. Climate Change 2013: The Physical Science Basis, T. F. Stocker et al., Eds., Cambridge University Press, 1–30.
3. Perkins SE, Alexander LV, Nairn J.R (2012). Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geop hys Res Lett* 39: L20714.
4. Perkins SE (2015) A review on the scientific understanding of heatwaves-Their measurement, driving mechanisms, and changes at the global scale. *Atmos. Res* 164–165: 242–267.
5. Mora C, Mora C, Dousset B, et al (2017) Global risk of deadly heat. *Nat Climate Change* 7: 501–506.
6. Nissan H, K Burkart, EC dePerez, et al. (2017) Defining and predicting heat waves in Bangladesh. *J Appl Meteor Climatol* 56: 2653–2670.
7. IPCC, 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the IPCC Fourth Assessment Report. Cambridge University Press: Cambridge.
8. Poumadere M, Mays C, Le Mer S, et al. (2006) The 2003 heat wave in France: Dangerous climate here and now. *Risk Anal* 25: 1483–1494.
9. Sheridan SC, Kalkstein LS (2004) Progress in heat watch warning system technology. *B Am Meteorol Soc* 85: 1931–1941.
10. Srivastava harinarain, BN Diwan, SK Dikshit, et al. (1993) Decadal trends in climate over India. *Mausam* 43: 7–20.

11. Pramanik SK, Jagannathan P (1954) Climatic change in India: II. Temperature. *Indian J Meteorol Geophys* 5: 1–19.
12. Hingane LS, Rupa Kumar K, Ramana Murthy Bh V (1985) Long-term trends of surface air temperature in India. *Int J Climatol* 5: 521–528.
13. Simister J, Cary C (2004) Thermal stress in the U.S.A.: effects on violence and on employee behaviour. *Stress and Health* (International Society for the Investigation of Stress) 21: 3–15.
14. Bell M, Giannini A, Grover E, et al. (2003) Climate Impacts. IRI *Climate Digest (The Earth Institute)*. Retrieved 28 July 2006.
15. Satyanarayana GC, Dodla DV (2020) Phenology of heat waves over India. *Atmos Res* 245: 105078.
16. Filleul L, Cassadou S, Medina S, et al. (2006) The relation between temperature, ozone, and mortality in nine French cities during the heat wave of 2003. *Env Health Persp* 14: 1344–1347.
17. Grize L, Huss A, Thommen O, et al. (2005) Heat wave 2003 and mortality in Switzerland. *Swiss Med Weekly* 135: 200–205.
18. Rusticucci M, Vargas W (2002) Cold and warm events over Argentina and their relationship with the ENSO phases: risk evaluation analysis. *Int J Climatol* 22: 467–483.
19. Gutowski WJ, GC Hegerl, GJ Holland, et al. (2008) Causes of Observed Changes in Extremes and Projections of Future Changes in Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. T.R. Karl, Meehl G.A, Miller C.D, Hassol S.J, Waple A.M, and Murray,W.L, (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.
20. NDMA (National Disaster Management Authority) 2016. Guidelines for Preparation of Action Plan–Prevention and Management of Heat Wave, National Disaster Management Authority, Government of India, 13.
21. Mani A, Chacko O (1973) Solar radiation climate of India. *Sol Energy* 14: 139–156.
22. Ross RS, Krishnamurti TN, Pattnaik Sandeep, et al. (2018) Decadal surface temperature trends in India based on a new high resolution data set. *Sci Rep* 8: 7452.
23. Dodla VB, Satyanarayana CG, Desamsetti S (2017) Analysis and prediction of a catastrophic Indian coastal heat wave of 2015. *Nat Hazards*. 87: 395–414.
24. Yadav RK (2016). On the relationship between Iran surface temperature and north-West India summer monsoon rainfall. *Int J Climatol* 36: 4425–4438.
25. Fink AH, Brucher T, Kruger A, et al. (2004) The 2003 European summer heatwaves and drought—synoptic diagnosis and impacts. *Weather* 59: 209–216.
26. Schar C, Jendritzky G (2004) Hot news from summer 2003. *Nature* 432: 559–560.
27. Kunkel KE, TR Karl DR, Easterling K, et al. (2013) Probable maximum precipitation and climate change. *Geophys Res Lett* 40: 1402–1408.
28. Palecki MA, Changnon SA, Kunkel KE (2001) The nature and impacts of the July 1999 heat wave in the midwestern United States: learning from the lessons of 1995. *B Am Meteorol Soc* 82: 1353–1367.
29. Steffen W, Hughes L, Perkins S (2014) Heat waves: hotter, longer, more often. Climate Council of Australia Limited. http://www.climatecouncil.org.au/uploads/9901f6614a2cac7b2b888f55b4dff9cc.pdf

30. Peterson TC, Heim RR Jr, Hirsch R, et al. (2013) Monitoring and understanding changes in heat waves, cold waves, floods and droughts in the United States, state of knowledge. *Bull Am Meteorol Soc* 94: 821–834.
31. Garcia-Herrera R, Diaz J, Trigo RM, et al. (2010) A review of the European summer heat wave of 2003. *Crit Rev Environ Sci Technol* 40: 267–306.
32. Desai DS (1999) Heat wave conditions during March to June for the year 1972, 1979 and 1987 and their comparison with year 1990–1995. *Mausam* 50: 211–218.
33. Raghavan K (1966) A climatological study of sever heat wave in India. *Indian J Met Geophys* 17: 581–586.
34. Subbaramayya I, Suryanaryana Rao DA (1976) Heat wave and cold wave days in different states in India. *Indian J Met Hydrol Geophys* 27: 436.
35. Pai DS, Smitha AN, Ramatathan AN (2013) Long term climatology and trendsof heatwaves over India during the recent 50 years (1961-2010). *Mausam* 64: 585–604.
36. Chaudhary V (2015) Minister of public safety and emergency preparedness, Canada. *ONCA* 678: 108.
37. Bedekar VC, Dekate MV, Banerjee AK (1974) Heat and cold wave in India. India Meteorological Department, Forecasting Manual FMU Rep. No. IV-6. http://www.imdpune.gov.in/Weather/Reports/glossary.pdf
38. Srivastava A, Rajeevan M, Kshirsagar S (2009) Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. *Atmos Sci Lett* 10: 249–254.
39. Naveena N, Satyanarayana GC, Rao DVB, et al. (2020) An accentuated "hot blob" over Vidarbha, India, during the pre-monsoon season. *Nat Hazards*. 105: 1359–1373.
40. Menon PA (1989). Our Weather. (National Book Trust, India).