



Quantification of heat wave occurrences over the Indian region using long-term (1979–2017) daily gridded ($0.5^\circ \times 0.5^\circ$) temperature data—a combined heat wave index approach

Prabir Kumar Das¹ · Ushashi Podder² · Rituparna Das³ · Chandrasekar Kamalakannan¹ · Goru Srinivasa Rao¹ · Soumya Bandyopadhyay¹ · Uday Raj⁴

Received: 18 June 2018 / Accepted: 13 July 2020 / Published online: 22 July 2020
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Abstract

In the changing climate scenario, the changing heat wave frequency and magnitude have a direct impact on the agriculture, society, economic, and public health. Hence, development of easy and effective tools is essential for quantifying the heat wave incidences for better planning and management towards reducing the impacts of heat waves. In the present study, Climate Prediction Centre (CPC) global daily maximum temperature data along with the long-term normal data for the period 1979–2017 were used for quantification of heat wave conditions. Spatial and temporal sub-setting was carried out to restrict our study within the Indian region and March–July period, respectively. Based on heat wave criteria prescribed by the India Meteorological Department, different heat wave parameters, viz. frequency, magnitude, and extent, were estimated. A new approach, i.e. combined heat-wave index (CHI), was proposed to quantify the impact of heat wave in a profound manner. The efficacy of the overall method of assessing the impact of heat wave had increased by using this new approach. It was found that Rajasthan, Punjab Haryana, and Madhya Pradesh experienced high frequency as well as magnitude of heat wave, while it was lower in north-east, peninsular, and parts of northern India during our study period. The trend analysis for the heat wave parameters along with CHI was carried out over the Indian region during the last 39 years. The increasing trends were found over Rajasthan, Haryana, Punjab, East Madhya Pradesh, and Orissa, while places like Uttar Pradesh, Bihar, Chhattisgarh, Telangana, and Andhra Pradesh showed decreasing trend over the last 39 years. Peninsular and north-east India showed almost no trend regarding heat wave. Further, the month with the maximum contribution towards the seasonal heat wave and its deviation was also estimated. It was observed that the month of May was contributing most over parts of north-western and central India, while it was June in Punjab, Haryana, and western Rajasthan. Hence, the present methodology may be adopted for better planning and management of heat waves.

1 Introduction

The Earth's climate system has been significantly altered since the early days of industrialisation; among several causes, the

anthropogenic activities are the major contributor (Stocker et al. 2013). Consequently, the global climate has changed tremendously with an approximate increase of 0.85°C in surface air temperature (combined land and ocean temperature) during the

✉ Prabir Kumar Das
prabir111@gmail.com

Ushashi Podder
podderushashi@gmail.com

Rituparna Das
rituparna.das@students.teriuniversity.ac.in

Chandrasekar Kamalakannan
kcsekar1368@gmail.com

Goru Srinivasa Rao
gsrao.ad.isro@gmail.com

Soumya Bandyopadhyay
sbanerjee377@gmail.com

Uday Raj
udayraj.isro@gmail.com

¹ Regional Remote Sensing Centre-East, National Remote Sensing Centre, Kolkata, India

² Symbiosis Institute of Geoinformatics, Pune, India

³ Teri School of Advanced Studies, Vasant Kunj, New Delhi, India

⁴ National Remote Sensing Centre, Hyderabad, India

period of 1880–2012 (Stocker et al. 2013; Zhang et al. 2017a). Heat being the leading weather-related killers, the increasing temperature and associated heat waves can have adverse impacts on agricultural, ecological, economic, societal, and public health sector of a nation (Huang et al. 2011; National Weather Service 2014; Johnson et al. 2015; Thamo et al. 2017). The global temperature is likely to increase by 1.4 to 5.8 °C based on the scenario-based projection studies (White 2010), which may lead to a significant increase in heat-related mortality and morbidity (Meehl et al. 2009; Huang et al. 2011; Zhang 2017b). According to the IPCC report, the frequency and duration of warm days have increased since the 1950s and there will be more temperature extremes over most of the parts of Asia (IPCC 2012). The increase in heat wave incidences in last few decades has been recorded in many parts of the globe, specifically over the urban areas with high population density (Sun et al. 2014; Christidis et al. 2015; Mishra et al. 2015; Matthews et al. 2017).

The heat waves are periods with abnormally high temperature with temperature more than its long-term normal (<http://www.ndma.gov.in/images/guidelines/>). In India, the heat waves generally occur typically in the pre-monsoon season, i.e. March–May, covering different parts of the country with varying intensity, duration, and adverse effects (Dunne et al. 2013; Pai et al. 2013a; Smith et al. 2014). The heat waves are very frequent over the Indo-Gangetic Plain, where around 5 to 6 such events are generally recorded over the northern parts of the country. For instance, the heat wave in 1998 over the large area of eastern and southern India resulted in more than 2500 deaths (<https://www.nytimes.com/1998/06/08/world/>). Similarly, the prolonged heat waves in 2015 over the Indian region, specifically covering parts of Andhra Pradesh, Gujarat, Orissa, Gujarat, and West Bengal, lead to more than 2500 deaths (<https://www.britannica.com/event/>). These two incidents ranked among the deadliest weather-related events (Mishra et al. 2017). In addition, heat wave incidences covering different parts of the country during 2002, 2010, and 2013 resulted in deaths of many people (<http://www.business-standard.com/article/>).

Though the overall trends of heat waves are increasing at the global level, the trends are different for different regions (Field et al. 2012; Stocker et al. 2013). Of late, few researches have been carried out to study the trends in heat waves over the Indian region (Pai et al. 2013a; Jaswal et al. 2015; Rohini et al. 2016). Pai et al. (2013a) analysed the trends of heat waves over India using the IMD (India Meteorological Department) station data during 1961–2010. According to the study, except some stations in north, north-east, and central India with a significant increase in heat waves, the rest of the station recorded a significant decrease in heat wave incidences. At the country level, no consistent significant trend was observed. In another study, Jaswal et al. (2015) carried out the trend analyses for hot days exceeding 37 °C threshold (human core body temperature) for entire India. The study showed that there exist increasing trends over north, west, and southern parts of the country, whereas decreasing trends

were observed in north-central and eastern regions. As the normal maximum temperature varies spatially from one part of the country to another, hence fixing a constant threshold of 37 °C may not represent the heat wave/hot day conditions for entire India. In the recent study, Rohini et al. (2016) studied the ‘excessive heat factor’ considering both ‘excess heat index’ and ‘heat stress index’ using gridded dataset for the period of 1961–2013. The results showed that the frequency and duration of heat waves are increasing in limited parts of central and north-western India, whereas in the rest of India, no significant trends were found. Similarly, other studies found varying spatiotemporal trends in heat waves over different parts of the country based on the input datasets, study period, and the criterion (Dash and Marmain 2011; Singh and Patwardhan 2012; Pai et al. 2013b).

The present study aims at detecting the heat wave incidences over the Indian region during the last 40 years (1979–2017) based on the criteria provided by the IMD and using high-resolution gridded data. A new approach has been proposed and adopted towards quantifying the intensity of heat wave at the meteorological sub-division level. The major contributing month towards the seasonal heat wave occurrences was also estimated for improved planning and management to minimise the impact of heat waves. Further, the non-parametric trend analysis will be carried out to characterise different zones based on the heat waves.

2 Study area

India comprises a wide range of weather conditions across a vast geographic area which makes generalisations difficult. India is classified into six major climatic sub-types based on the Koppen’s classification system. According to the Indian Meteorological Department (IMD), India has four climatological seasons. The winter season lasts from December to March, with an average temperature of around 10–15 °C. The summer ranges from April to June, where the mean average of maximum temperature ranges from 32 to 40 °C in most of the regions. Monsoon or rainy season generally extends from July to September. The southwest monsoon dominates this season which strikes the western coast and slowly enters the interiors in late May or early June whereas the northeast monsoon sweeps the southern part of the country at the beginning of October and the season between October and November is generally referred as post-monsoon or autumn.

The summer season experiences some serious hot days which exceeds the normal summer temperature in many parts of the country. For the present study, the analysis has been limited to the Indian mainland which extends from 8° 4′ 28″ to 37° 17′ 53″ N latitude and 68° 7′ 53″ to 97° 24′ 47″ E longitude (Fig. 1). Due to the spatial resolution of the dataset (0.5° × 0.5°), i.e. around 50 km, the study was conducted at the meteorological sub-division level (total 34). Throughout several decades, it has been noticed

that India experiences high temperatures during the summer months which almost starts from the month of March and extends up to July (Mahdi and Dhekale 2016). In the present study, this time period between March and July has been chosen to get detailed information about the heat waves occurring in the country. India mostly experiences heat waves with 5 to 6 days of duration and sometimes even more than 10 days, which again varies from one meteorological sub-division to another. The highest temperatures occur mostly in the month of May or in the beginning of June, before the arrival of the monsoons. During that period, the daily maximum temperatures are found to be very high. In the north-western parts of India, the temperatures often rise to higher than 40 °C in the afternoon. On 19 May 2016, the temperature exceeded 50 °C, over a region near the India-Pakistan border. The temperature even reached 51.0 °C in Phalodi which is India's all-time record (Oldenborgh et al. 2018). Hence, the maximum temperature and heat wave parameters along with the major contributing months are varying across the Indian region. Moreover, due to the changing climate scenario, the heat wave parameters and the heat wave as a whole may have a significant trend across different parts of the country during the past 39 years.

3 Data used and methodology

3.1 Data processing

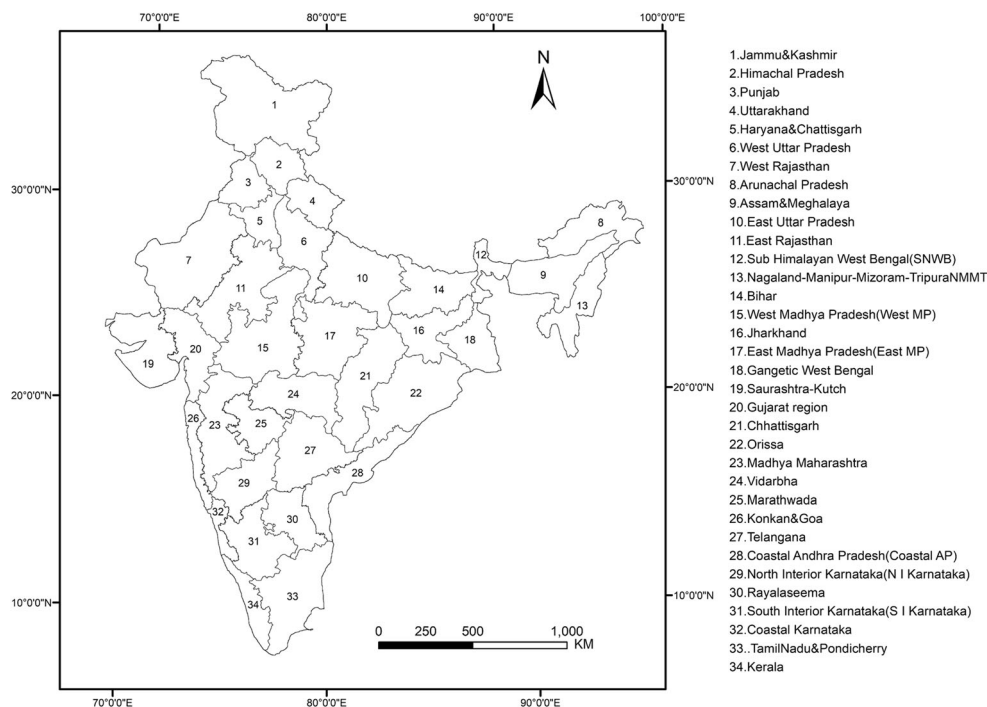
The present study has been carried out using the daily temperature data collected from the Climate Prediction Center

(CPC). The CPC is an organisation which collects and produces daily and monthly data time series, and maps for different climatic parameters, such as precipitation, temperature, degree days, and snow cover for all parts of the globe. CPC global daily maximum and daily long-term mean maximum temperature data (Rachel Lowe et al. 2017) at a grid size of $0.5^\circ \times 0.5^\circ$ were downloaded from the NOAA (National Oceanic and Atmospheric Administration) site (<https://www.esrl.noaa.gov/psd/data/gridded/data.cpc.globaltemp.html>) for the last 39 years (1979 to 2017). These daily gridded maximum temperature (tmax.yyyy.nc) and long-term mean maximum temperature (tmax.day.ltm.nc) data were in the NetCDF format (.nc). These daily global temperature data were sub-setted to confine our study within the Indian region, i.e. the area between latitude ($8^\circ 4' 28''$ to $37^\circ 17' 53''$ N) and longitude ($68^\circ 7' 53''$ to $97^\circ 24' 47''$ E). Further, temporal sub-setting, i.e. for March to July, was carried out to restrict the study within the time period only. Leap year and non-leap years were considered separately. The daily maximum and the mean maximum temperature dataset were prepared at monthly scale (March–July) and for the period of March to July, i.e. for total 153 days.

3.2 Detection of heat wave occurrences

Based on the IMD criteria, heat wave occurrences were detected for the present study (Ratnam et al. 2016). Heat wave occurrence refers to the condition when the IMD criteria are qualified. The following criteria for heat waves (IMD) had been used in the present study:

Fig. 1 Study area with meteorological sub-division boundaries



- i When the actual maximum temperature remains 45 °C or more irrespective of the normal maximum temperature
- j When the normal maximum temperature of a station is less than or equal to 40 °C and the maximum temperature is greater than the normal maximum + 5 °C
- k When the normal maximum temperature is greater than 40 °C and the actual maximum temperature is greater than the normal maximum + 4 °C

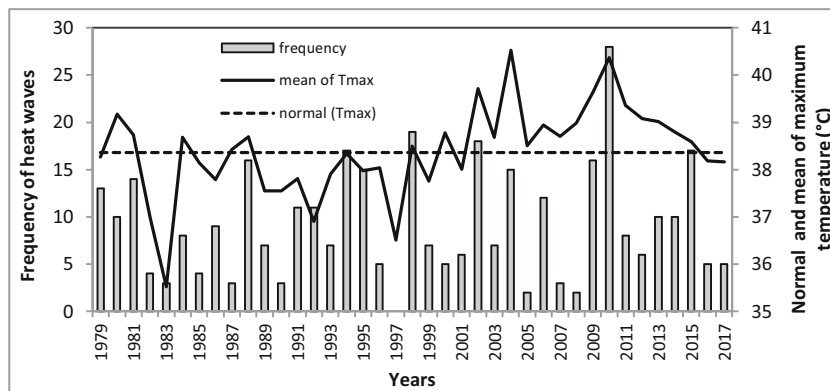
In Fig. 2, the mean maximum temperature for March–July period and the average long-term normal are being depicted along with the resultant heat wave occurrences for a given meteorological sub-divisions. It was observed that with the increase in the mean of maximum temperature above its normal, the number of heat waves was also increasing.

3.3 Heat wave parameters

Based on the IMD criteria, the frequency and magnitude of heat wave occurrence both at month and at period from March to July were detected at the grid level for the last 39 years. The frequency of heat wave occurrences refers to the number of heat wave occurrence in a single grid during each month and cumulative period, separately. The heat wave magnitude represents to the intensity of heat in a given grid. It is defined as the deviation of the daily maximum temperature from the heat wave criteria for the specified grid. For example, if the maximum temperature (T_{\max}) of a place is 44 °C and the normal maximum temperature of that place is 38 °C, then the magnitude of heat wave will be 1 °C, i.e. $[(44 - (38 + 5))^\circ\text{C}]$.

The extent of heat wave was calculated by considering the meteorological sub-divisions as a unit. The extent refers to the percentage of the total geographical area affected by heat wave during each month/period for a given meteorological unit. To capture the spatial distribution of different parameters, i.e. frequency, magnitude, and extent, the temporal mean of all the parameters for the last 39 years was computed.

Fig. 2 Mean maximum temperature (T_{\max}), normal maximum temperature, and frequency of heat wave during May–July months for a given grid over West Rajasthan during 1979–2017



3.4 Generation of combined heat wave index

All the three parameters, viz. frequency, magnitude, and extent, for each year were brought into a single spatial domain by calculating their mean at the meteorological sub-division level. A combined heat wave index (CHI) had been developed by combining all the three parameters. This index quantifies the incident of heat waves by considering all the three parameters, as the interpretation of the individual parameters does not truly depict the actual impact of heat wave. For a particular sub-division, the heat wave extent, duration, and magnitude may differ for two consecutive years, with one parameter signifying a higher value in 1 year and the other signifying a higher value in another year. But after combining the parameters, we can quantify heat wave more efficiently and assess the overall impact of heat wave in a particular place. In the present study, the combined heat wave index (CHI) was computed using the following equation:

$$\text{CHI} = \frac{i_d - \min_d}{\max_d - \min_d} + \frac{i_m - \min_m}{\max_m - \min_m} + \frac{i_e - \min_e}{\max_e - \min_e}$$

where i_d , i_m , and i_e are duration, magnitude, and extent of heat wave for individual sub-division (i) for a given year, respectively. The \min_d , \min_m , and \min_e are the global minimum duration, magnitude, and extent, respectively, whereas \max_d , \max_m , and \max_e are global maximum duration, magnitude, and extent, respectively.

Figure 3 represents the annual variability of different heat wave parameters along with the proposed CHI for East Madhya Pradesh meteorological sub-division. It can be observed that for the years 2009 and 2010, the heat wave extent values were 0.981 and 0.942, durations were 9 and 14, and magnitude values were 17.494 and 11.021, respectively. But after combining the above three parameters, it was found that the combined heat wave index (CHI) for those years were 1.884 and 1.809, respectively, which helps in understanding that the comparative heat wave impacts for both the years.

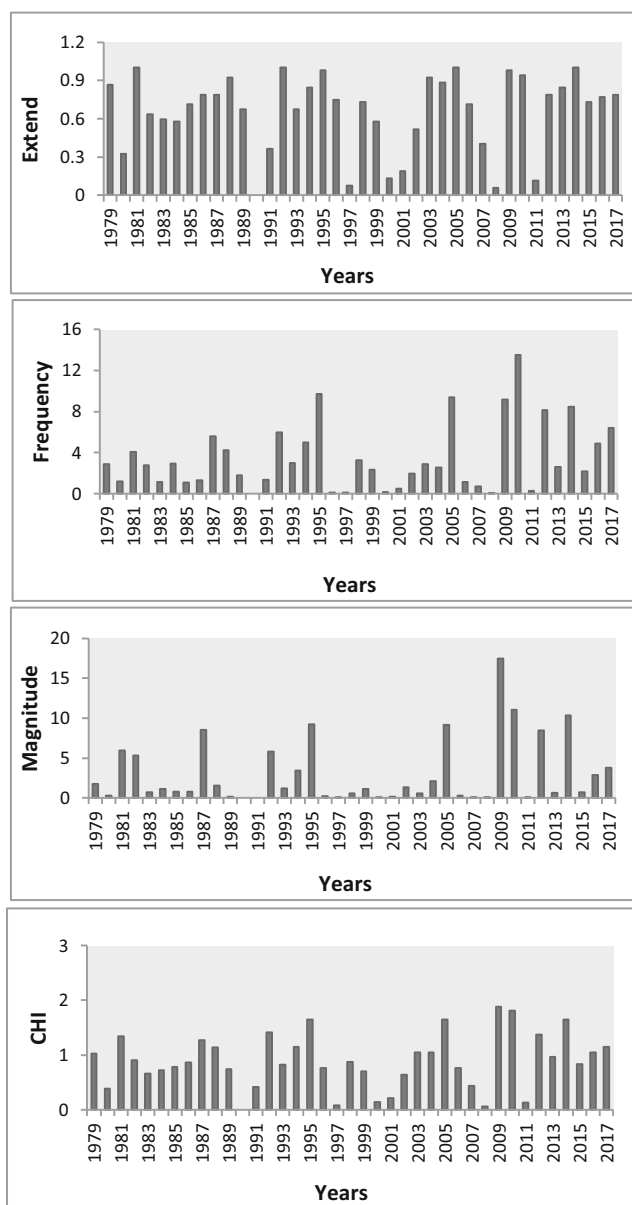


Fig. 3 The heat wave parameters and CHI values for east Madhya Pradesh meteorological sub-division

3.5 Trend analysis of heat wave parameters

Trend analyses were carried out for the heat wave frequency and magnitude at each grid level, whereas for extent of heat waves and CHI at meteorological sub-division wise, using the Mann-Kendall test and Sen's method. The trend analyses were performed on the long-term anomalies of heat wave frequency, magnitude, extent, and CHI, from their long-term normal.

The direction of the trend of heat wave parameters during each of the months and entire period, i.e. March to July, was estimated using the non-parametric Mann-Kendall test. Further, Sen's method (Sen, 1968) was used to estimate the magnitude of the trend for each parameter. The significant

trends with more than 95% confidence level (at $p = 0.05$) were also computed. For the details of the techniques and advantages, Das et al. (2014) may be referred.

3.6 Probability analysis

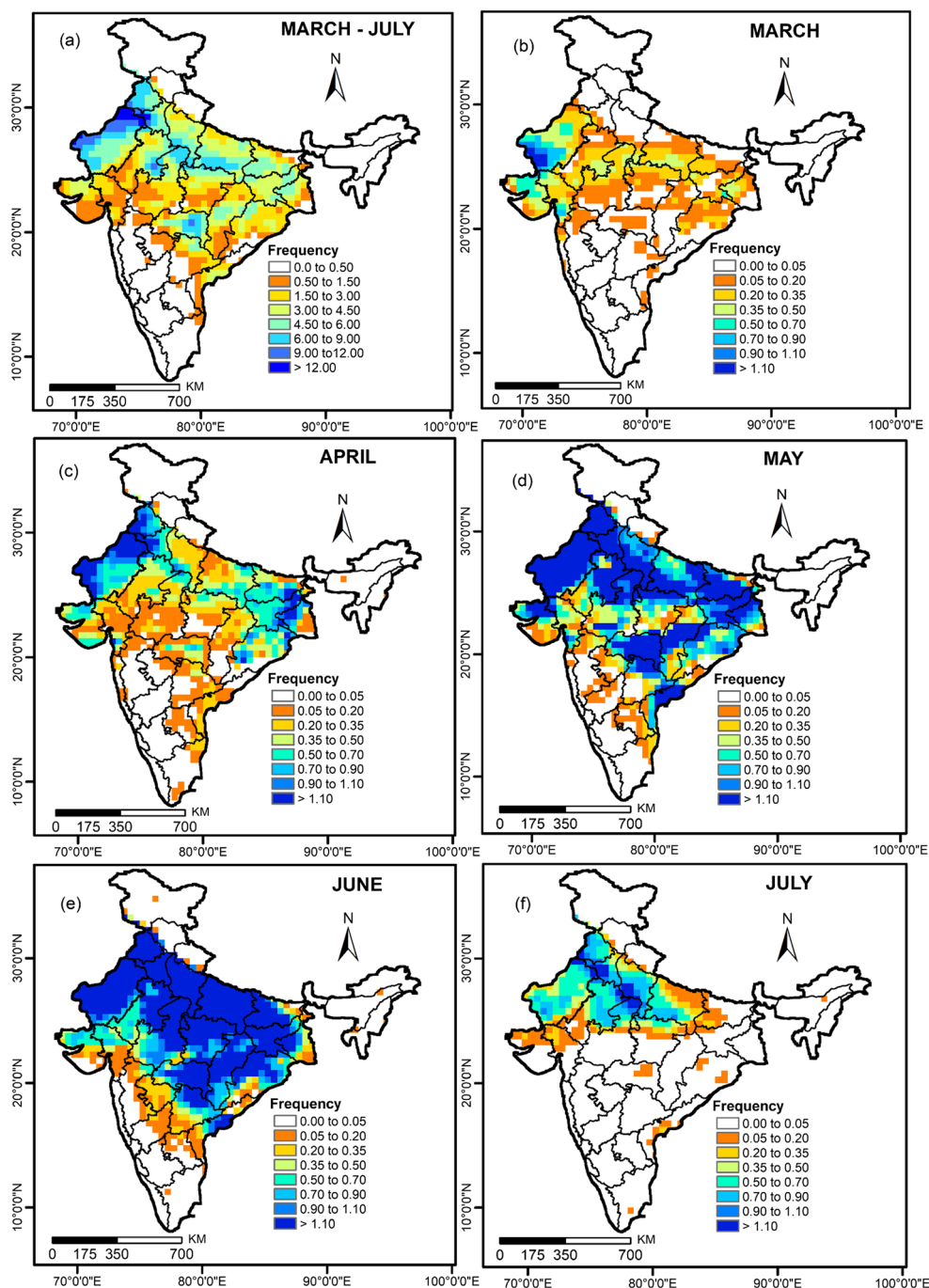
The information regarding the month contributing maximum towards the heat wave for a given meteorological sub-division may be important for planning and management to minimise the adverse effects of heat wave incidences. Hence, probability analysis was carried out to find out the month with a maximum contribution towards heat wave during the period of March–July. The deviation from the maximum heat wave contributing month was also estimated, followed by the trend analysis using Sen's method and the Mann-Kendall test to find out whether there was any significant shift in the contributing month over the last 39 years.

4 Results and discussion

4.1 Heat wave frequency

Heat wave frequency refers to the number of heat wave incidents occurring over a particular region. The present study has been carried out using daily gridded data ($0.5^\circ \times 0.5^\circ$). The number of heat wave incidents for the last 39 years was calculated over the meteorological sub-divisions of India at both monthly and March–July period. The average number of heat wave days over the entire region varies from less than 0.5 days to more than 12 days (entire period or month). Over the cumulative period, it has been observed that parts of western Rajasthan, eastern Rajasthan, Punjab, and Haryana as well as some parts of central India experienced more than 6–12 days of heat wave on an average (Fig. 4). Western Rajasthan tops the list where heat wave on an average was found to be more than 12 days during the March to July period. Maximum heat wave occurrence had thus been found in the north-western portion of the sub-divisions (Rohini et al. 2016), whereas in the eastern part of the country, the number of heat wave incidents was found to be lesser than that in the western part (Fig. 4). West Bengal, Orissa, Bihar, Jharkhand, and Chhattisgarh showed 0.5–6 days of heat wave on an average. The entire Gujarat region experienced 0.5–3 days of heat wave, whereas the Saurashtra-Kutch region witnessed up to 4 days of heat wave. Peninsular India as well as Northern India was affected very less by this extreme temperature conditions; the number of days on an average was found to be less than 0.5 (Fig. 4). Thus, for the entire period, i.e. March to July, the heat wave incidents varied widely across the meteorological sub-divisions of India. As western Rajasthan experienced the greatest number of heat waves, Fig. 2 represents the frequency of heat waves in a particular grid of that region. It was

Fig. 4 Mean frequency of heat wave occurrences for **a** the March–July period, **b** March, **c** April, **d** May, **e** June, and **f** July during 1979–2017



interesting to find that the specific grid experienced total 29 days of heat waves during 2010.

The heat wave frequency had also been analysed on a monthly basis (March–July) for the past 39 years. Some parts of western Rajasthan witnessed more than 1 day of heat wave on an average in the month of March while most of peninsular and northern India witnessed no heat wave at all. A slightly different picture was observed in the month of April, where majority parts of western Rajasthan and some parts of West Bengal, Bihar, and Jharkhand witnessed more than 1 heat

wave day on an average, whereas central India and Uttar Pradesh experienced even lesser frequency (Fig. 4). Majority of the regions experienced more than 1 day of heat wave in the month of May and June. This includes the entire western Rajasthan, Punjab, and Haryana and parts of Bihar, Jharkhand, West Bengal, Uttar Pradesh, Madhya Pradesh, Vidarbha, Chhattisgarh, and Andhra Pradesh. Heat wave frequency of less than 1 day on an average was observed in few meteorological sub-divisions. The number of heat wave days decreased in the month of July; only few parts of Uttar

Pradesh and Punjab experienced higher heat wave incidences (Fig. 4), whereas in the rest of India, the values were lower. Thus, heat wave occurs for the maximum number of days in the month of May or June.

4.2 Heat wave magnitude

Magnitude of heat wave is the amount of deviation of maximum temperature from the heat wave criteria, cumulated over a period of time, i.e. at the month or cumulative period level. It tells us the intensity of hotness of a place. The magnitude of heat wave was seen to be varying over the Indian region for the past 39 years during March–July. Most parts of Punjab and western Rajasthan have witnessed more than 8 °C of heat wave magnitude, while the values were around 4–8 °C for most parts of Uttar Pradesh, Bihar, and West Bengal (Fig. 5). On the other hand, Gujarat and Madhya Pradesh experienced an average heat wave magnitude of 0.3–2.5 °C. Majority of the portion of southern India, north-eastern sub-divisions, and northern India experienced less than 0.3 °C heat wave magnitude; only few isolated areas with 0.3–1.5 °C magnitude were also observed (Fig. 5).

In case of monthly level analysis, only few parts of western Rajasthan were seen to have experienced more than 1.5 °C magnitude in the month of March, while most of the central and eastern sub-divisions felt a surge of temperature by 0.05–0.30 °C from the heat wave criteria. North-eastern sub-divisions, northern India, and peninsular sub-divisions hardly witnessed any surge (Fig. 5). A more or less similar picture was noticed in the month of April over the north-western sub-divisions covering western and eastern Rajasthan, Punjab, and Haryana and some parts of the eastern sub-divisions where the increase in the values ranges more than 0.95 °C. In Uttar Pradesh, Madhya Pradesh, Chhattisgarh, Telangana, and parts of Andhra Pradesh experienced a heat wave magnitude of 0.05–0.30 °C (Fig. 5). The month of May was found to be hotter in some places over the north-western and eastern parts of the country, where the average heat wave magnitude was found to be more than 1.5 °C. The central part witnessed a surge not more than 0.5 °C on an average, whereas peninsular India, northern India, and the north-eastern sub-divisions witnessed a surge less than 0.05 °C. June was found to be another crucial month when the cumulative temperature soared to more than 20 °C from the heat wave criteria in the year 1995 in a particular place over Punjab. Overall, both north-western and eastern India witnessed a very hot weather. In the past 39 years, the magnitude was more than 1.5 °C in these places. In few parts in peninsular India, the values were ranging between 0.05 and 0.3 °C rise (Fig. 5). July was a much cooler month due to onset of monsoon over most of the parts of India giving a respite from the abnormally high temperature. However, parts of Uttar Pradesh and Punjab experienced

a surge by 1.5 °C while most of the sub-divisions felt a meagre surge from the heat wave criteria.

4.3 Extent of heat wave

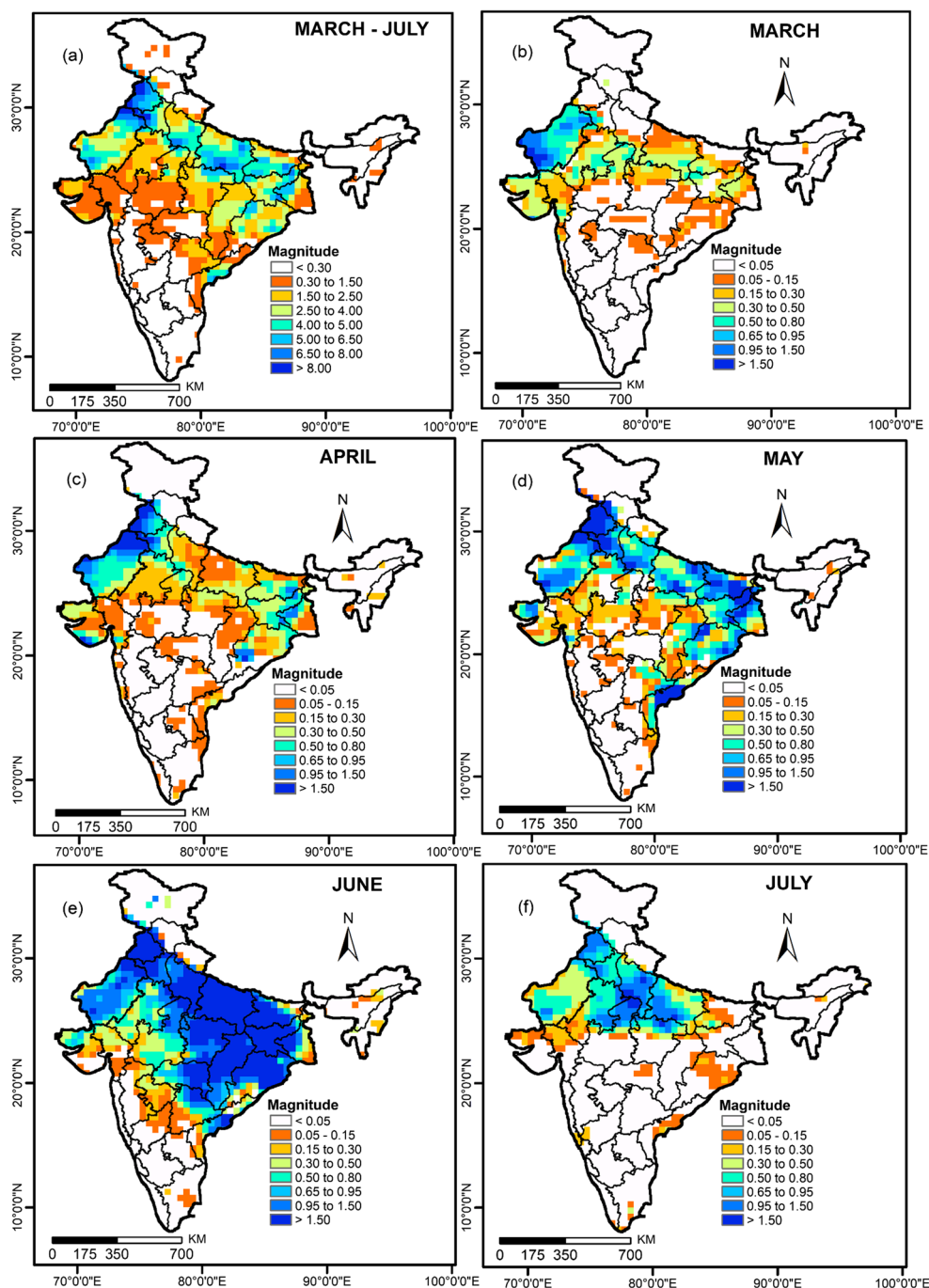
The percentage area covered by heat wave varies across places. The extent helps us in identifying the places covered by heat wave. It has been observed that in both western Rajasthan and Punjab, more than 85% area had been covered with heat wave in the entire period, i.e. March–July. Around 75–85% of area had experienced heat wave over east Uttar Pradesh. The central sub-divisions comprising west Uttar Pradesh, east Rajasthan, west Madhya Pradesh, east Madhya Pradesh, Vidarbha, and Jharkhand had 60–75% of area covered up by heat wave, whereas the value was around 45–60% in the eastern part of the country (Fig. 6). Madhya Maharashtra and Marathwada had 15–30% of area affected under heat wave, while north interior Karnataka, south interior Karnataka, Konkan and Goa, and Tamil Nadu had very few areas covered by heat wave during the entire period, whereas north-eastern India, northern India, and few areas of peninsular India experienced very little heat or no heat wave at all (Fig. 6).

On a monthly level, around 0–5% of area in the entire country was under heat wave in the month of March. On the other hand, in the month of April, about 30–45% area of western Rajasthan had felt the heat wave. The north-western sub-divisions and the eastern sub-divisions had 15–30% of area covered by heat wave while 5–15% of central India had experienced this sweltering heat (Fig. 6). In the month of May, the percentage of area affected by heat wave increased. Western Rajasthan had 60–75% of area under heat wave while sub-divisions like Punjab, Haryana, Jharkhand, and Vidarbha had 45–60% of area experiencing heat wave. Most of central India, Uttar Pradesh, Bihar, Orissa, West Bengal, and Telangana had 30–45% area under heat wave. The values were within the range of 15–30% in Gujarat, Saurashtra-Kutch region, Chhattisgarh, and Andhra Pradesh. In three meteorological sub-divisions, namely, Madhya Maharashtra, Marathwada, and Rayalaseema, 5–15% of areas were affected by heat wave (Fig. 6). Almost similar results were observed in June month also. In the month of July, the area under heat wave was significantly lower than in the previous months. Western Rajasthan had 30–45% of area under heat wave; eastern Rajasthan, Punjab, Haryana, and western Uttar Pradesh had 15–30% of area under heat wave while the values were 5–15% in Madhya Pradesh and Eastern Uttar Pradesh (Fig. 6).

4.4 Combined heat wave index

For planning and management point of view, it is essential to come out with a single index to quantify heat wave for a given

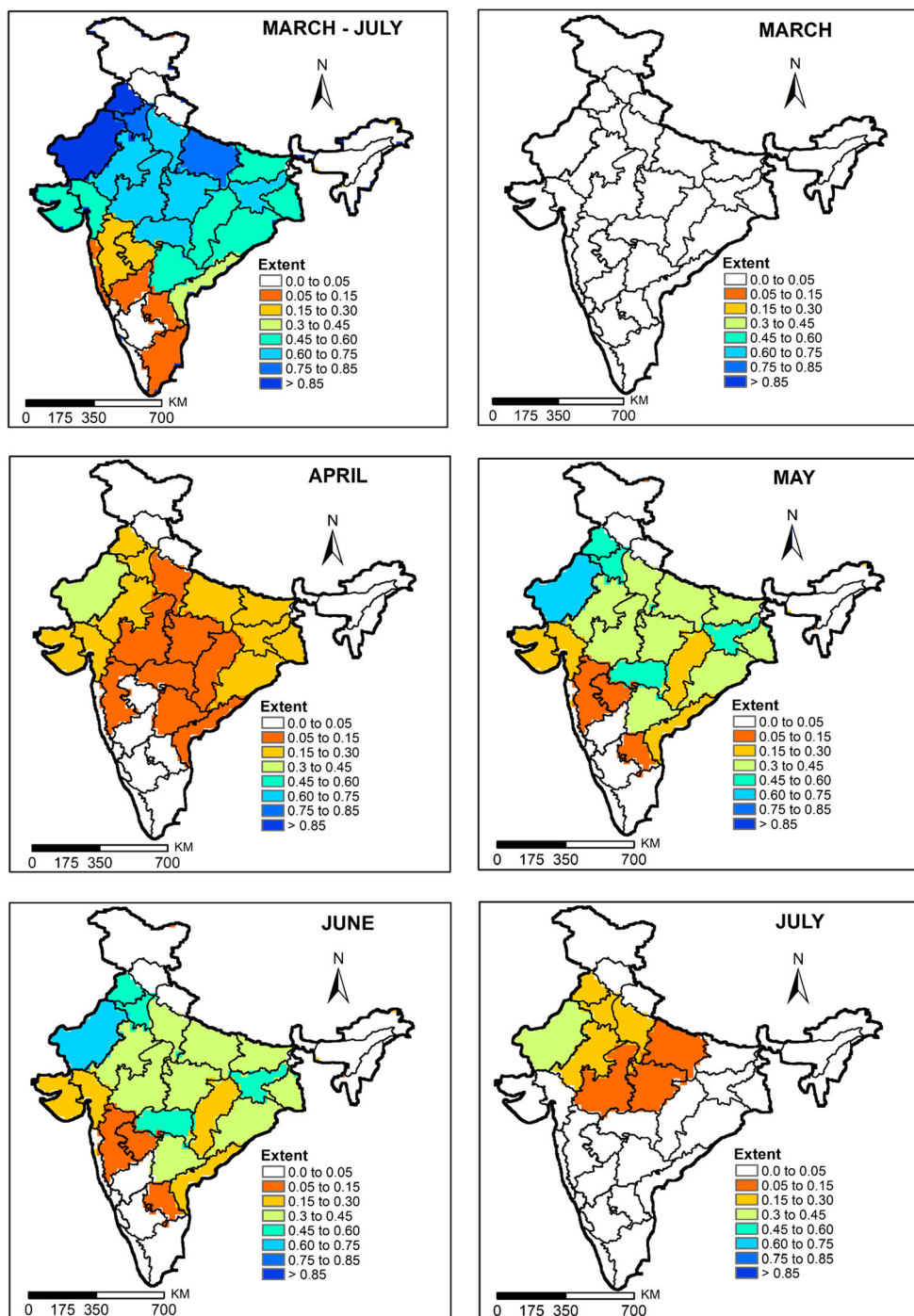
Fig. 5 Mean magnitude of heat wave occurrences for **a** the March–July period, **b** March, **c** April, **d** May, **e** June, and **f** July during 1979–2017



meteorological unit. A new approach has been proposed and adopted to estimate the impact of heat wave during our entire study period (1979–2017). This index provides combined information of all the heat wave parameters, namely, frequency, magnitude, and extent, and their impact as a whole in quantifying heat wave over a region. CHI may be useful in quantifying the hotness across the meteorological sub-divisions of India. It was been observed that west Rajasthan and Punjab had a CHI value of more than 1.70 for the period of March to July. This signified that these meteorological sub-divisions

showed higher area, frequency, and extent of heat waves. The sub-divisions comprising Haryana, east Rajasthan, east Madhya Pradesh, west Madhya Pradesh, west Uttar Pradesh, east Uttar Pradesh, Vidarbha, and Jharkhand had CHI values between 1.20 and 1.70 (Fig. 7a). The values were around 0.80–1.20 over eastern sub-divisions and Gujarat region. Saurashtra and Kutch, Andhra Pradesh, Madhya Maharashtra, and Marathwada had CHI values of 0.30 to 0.80, while the northern India and north-east and peninsular India witnessed CHI of less than 0.3, which signified lower

Fig. 6 Mean extent of heat wave occurrences for **a** the March–July period, **b** March, **c** April, **d** May, **e** June, and **f** July during 1979–2017



values of all the three heat wave parameters towards the CHI (Fig. 7a).

The deviation of CHI has mainly been observed in the north-western, central, and eastern sub-divisions of India. Saurashtra-Kutch and Marathwada had deviations of 0.3 to 0.4 CHI (Fig. 7b). The southern parts of India had lesser deviation of 0.2–0.3. Konkan and Tamil Nadu had CHI deviation of 0.1–0.2, whereas northern, north-east, and few sub-divisions of peninsular India had deviation less than 0.1.

The varying degree of heat waves over different parts of the country may be attributed to alterations in pre-monsoon rainfall amount and distribution. Similarly, the impacts of deficit summer monsoon on heat waves of succeeding years were also reported (<https://ndma.gov.in/>). Moreover, the studies by Ratnam et al. (2016) explained that the heat waves over north and central India may be due to anomalous blocking over North Atlantic Ocean, whereas it is the anomalous cooling of Pacific which impacts the heat waves over eastern

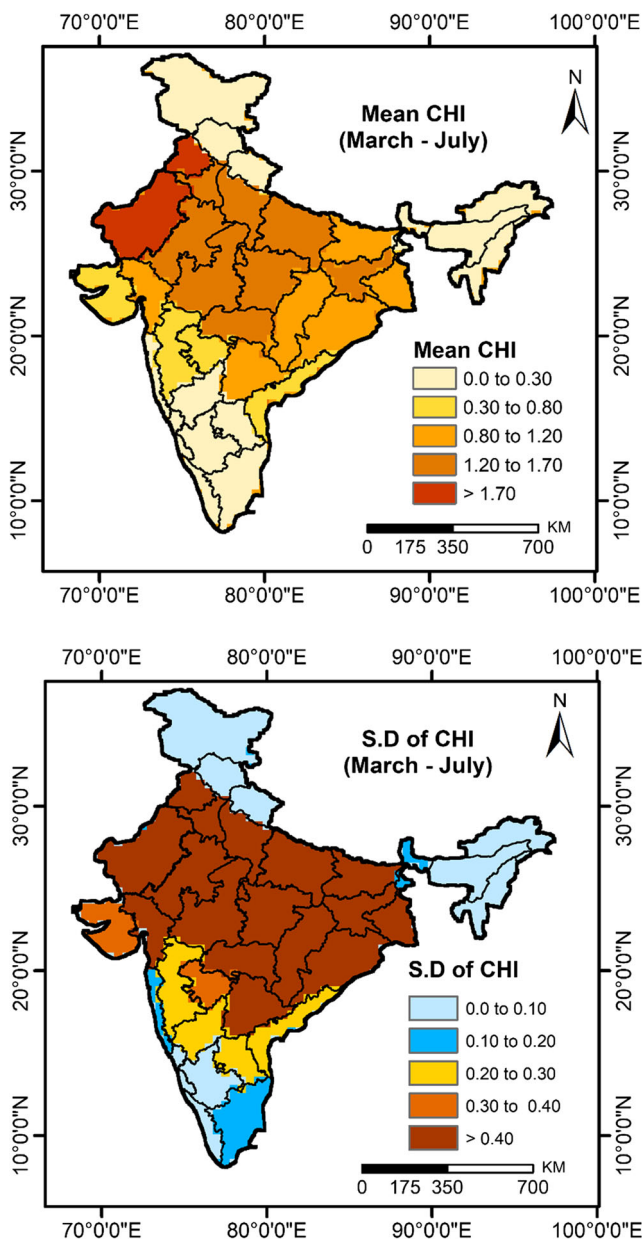


Fig. 7 a Mean and b standard deviation of combined heat wave index (CHI) over the period of 1979–2017 over the Indian region

Indian coast. Some of the studies have also analysed the relationships between heat wave and El Niño (De and Mukhopadhyay 1998).

4.5 Trend analysis of heat wave parameters

4.5.1 Frequency

A positive trend is defined as the increase in the number of heat wave incidents from the mean frequency. The positive trend was observed in the north-western, central, and eastern sub-divisions of the country (Oldenborgh et al. 2018), while a negative trend was seen in Uttar Pradesh, Bihar, few parts of

western Rajasthan, and Telangana for the entire period (Fig. 8a). In the rest of the country, no trend was found, which signified that the heat wave incidents had not deviated much from the normal and had remained almost similar over the study period. Maximum positive trend was seen in some selected parts of western Rajasthan (more than 0.3 days/year) while the rest of the areas experienced a positive trend, having 0–0.3 days per year, on an average. A significant trend had been observed in parts of western and eastern Rajasthan, Madhya Pradesh, Jharkhand, Orissa, West Bengal, and Vidarbha (Fig. 8a).

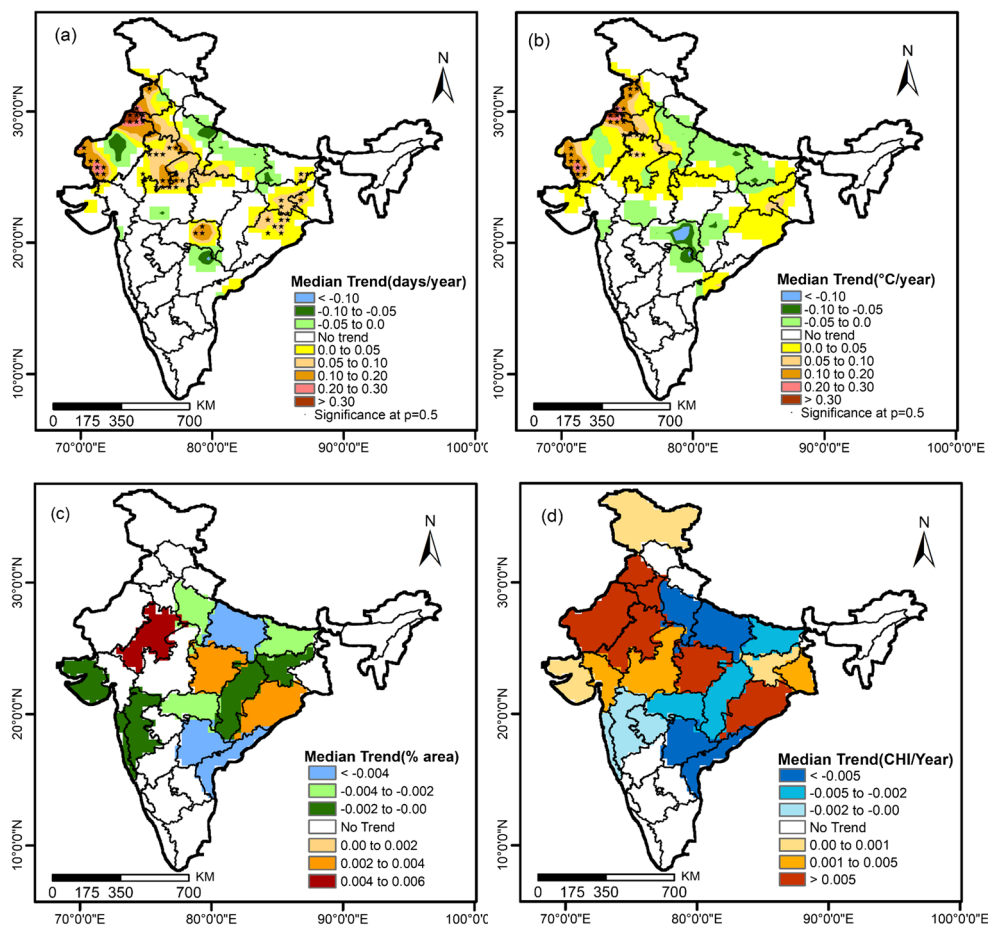
Monthly trend had also been analysed, where in the month of March, no trend was observed, whereas in the month of April, a low positive trend of 0–0.05 days was found over western Rajasthan. The month of May witnessed both positive and negative trends. Positive trends up to 0.3 days of heat wave frequencies were observed in parts of west and east Rajasthan and Bihar, while negative trends up to less than 0.1 days were observed in some parts of Madhya Pradesh, Chhattisgarh, Vidarbha, and Bihar. A significant trend was observed in a small pocket of west Rajasthan. In the month of June, the trend is more negative in places like western Rajasthan, small parts of Punjab, Haryana, and Madhya Pradesh (–0.05 to 0.00 days on an average). However, in most of the regions, no trend of heat wave occurrences was observed in the month of June (figures not provided).

4.5.2 Magnitude

The trend of magnitude of heat wave was found to be varying across space and time. North-western India comprising Punjab, Haryana, and Rajasthan and the eastern sub-divisions including Orissa, Bihar, Jharkhand, and some parts of Andhra Pradesh witnessed positive trends (Fig. 8b). In west and east Uttar Pradesh, Bihar, Chhattisgarh, Vidarbha, Telangana, Madhya Pradesh, Gujarat, and small parts of west Rajasthan, negative trends were observed. The sub-divisions of Punjab and western Rajasthan had more than 0.05 °C per year of positive trend on an average. The rest of the regions had positive trends of around 0–0.5 °C per year. Less than –0.10 °C of trend was found in the meteorological sub-division of Vidarbha. A significant trend of magnitude was observed only in the north-western part consisting of Punjab, Haryana, and western Rajasthan (Fig. 8b).

Monthly trend was analysed for each of the summer months. In the month of March and April, no trend was observed, while in the month of May, north-western sub-divisions and small parts of Bihar witnessed positive trends up to 0.2 °C per year on an average. Mostly negative trends were observed in Vidarbha, Chhattisgarh, eastern Rajasthan, and Uttar Pradesh. June mainly witnessed negative trends in the north-western sub-division ranging from –0.05 to 0 °C, while positive trends were witnessed over small parts of Uttar

Fig. 8 Trends of heat wave **a** frequency, **b** magnitude, **c** extent, and **d** combined heat wave index for the period of March–July during 1979–2017 over the Indian region>



Pradesh and Madhya Pradesh. No trend was found in July month during the entire study period (figures not provided).

4.5.3 Extent

The trend analysis of heat wave extent showed the change in the percentage area covered by heat wave during the last 39 years. Eastern Rajasthan, with positive trends of 0.004–0.006 per year, observed the maximum change in the area affected by heat wave (Fig. 8c). Two more sub-divisions, namely, Orissa and east Madhya Pradesh, had positive trends of 0.002–0.004. Saurashtra-Kutch region, Konkan and Goa, Madhya Maharashtra, Jharkhand, and Chhattisgarh observed negative trends of -0.002 to 0 , whereas west Uttar Pradesh, Bihar, and Vidarbha observed negative trends of -0.004 to -0.002 . A negative trend of less than -0.004 was observed in east Uttar Pradesh, Telangana, and Andhra Pradesh. In the rest of the parts of India, no trend was found during the cumulative period of March to July (Fig. 8c).

No trend was observed during the month of March, while the month of April witnessed positive trends in western Rajasthan, Jharkhand, and West Bengal. The month of May witnessed the highest positive trend of 0.004–0.006 per year in Punjab, Haryana, Rajasthan, and Madhya Pradesh. Trends

with 0.002–0.004% area per year were observed in Vidarbha and Orissa. A negative trend was observed in Saurashtra, Bihar, and Andhra Pradesh. A similar trend was observed in the month of June while during the month of July, no trend in the percentage area affected by heat wave was observed (figures not provided).

4.5.4 Combined heat wave index

The trends of CHI provided an idea on the impact of the three heat wave parameters, i.e. frequency, magnitude, and extent, over different meteorological sub-divisions during the study period. During the period of March–July, the CHI had the highest positive trend of greater than 0.005 in west Rajasthan, east Rajasthan, Punjab, Haryana, east Madhya Pradesh, and Orissa. West Bengal, Gujarat, and West Madhya Pradesh also observed positive trends with 0.001–0.005 value, while northern India and Jharkhand had witnessed very low positive trends (Fig. 8d). West and east Uttar Pradesh, Telangana, and Coastal Andhra Pradesh showed the most negative trends which were less than -0.005 . Bihar, Chhattisgarh, and Vidarbha exhibited a negative trend of -0.002 to -0.005 . The least negative trends were observed over Konkan and Goa, Madhya Maharashtra, and

Marathwada, Peninsular India, north-east India, and parts of Uttarakhand and Himachal Pradesh showed no trend in CHI values (Fig. 8d).

Monthly CHI trend was also analysed across the study period. In the month of March, only positive trends were observed with maximum values over western Rajasthan and Punjab. A relatively lower trend was observed in most of central and eastern India, whereas very lower trend values were recorded in west Uttar Pradesh, Madhya Maharashtra, Telangana, and Coastal Andhra Pradesh. Majority of the subdivisions had no CHI trend in the month of April, except in places like west Rajasthan, Jharkhand, and West Bengal (Fig. 8d). The month of May showed the highest positive trend of greater than 0.005 in north-western and some sub-divisions of central India. Orissa and Jharkhand had witnessed trends of 0.001–0.005, while Saurashtra-Kutch had observed negative trends with values -0.005 to -0.002 . The Coastal Andhra Pradesh and Bihar also observed negative trends. In June, almost similar trends were observed with few more sub-divisions. West Uttar Pradesh, Vidarbha, and West Bengal were added to the list of positive trends, whereas Telangana and east Uttar Pradesh were in the list of negative trends. During July, no trend in CHI was found. Thus, north-western subdivisions witnessed the most fluctuations in CHI (figures not provided).

The increasing trends of heat waves over parts of north-western India and decreasing trends over parts of the Indo-Gangetic Plain were reported by Mukherjee and Mishra (2018). The study inferred that the increasing trends may be due to anthropogenic emissions, whereas it was irrigation and local cooling for decreasing heat waves. The recent studies showed that there was an increase in six heat wave days per year in major parts of India, covering north-western, eastern, central regions (Mandal et al. 2019). The lower or no trends in heat wave over north-eastern and south-eastern regions were also reported.

4.6 Decadal changes in CHI

The mean CHI values for the last four decades, i.e. 1979–1988, 1989–1998, 1999–2008, and 2009–2017, were computed separately to capture the decadal changes in the overall heat wave characteristics. It was interesting to find that in most of the meteorological sub-divisions, except northern, north-eastern, and southern parts of India, the mean CHI values were changing over the decades. In Himachal Pradesh, Uttarakhand, Kerala, southern and coastal Karnataka, and north-eastern meteorological sub-divisions, the CHI values were less than 0.1 in all the decades, whereas in Gujarat, Telangana, and Andhra Pradesh, the values were between 0.4 and 0.8 during the entire study period, irrespective of the decades (Fig. 9).

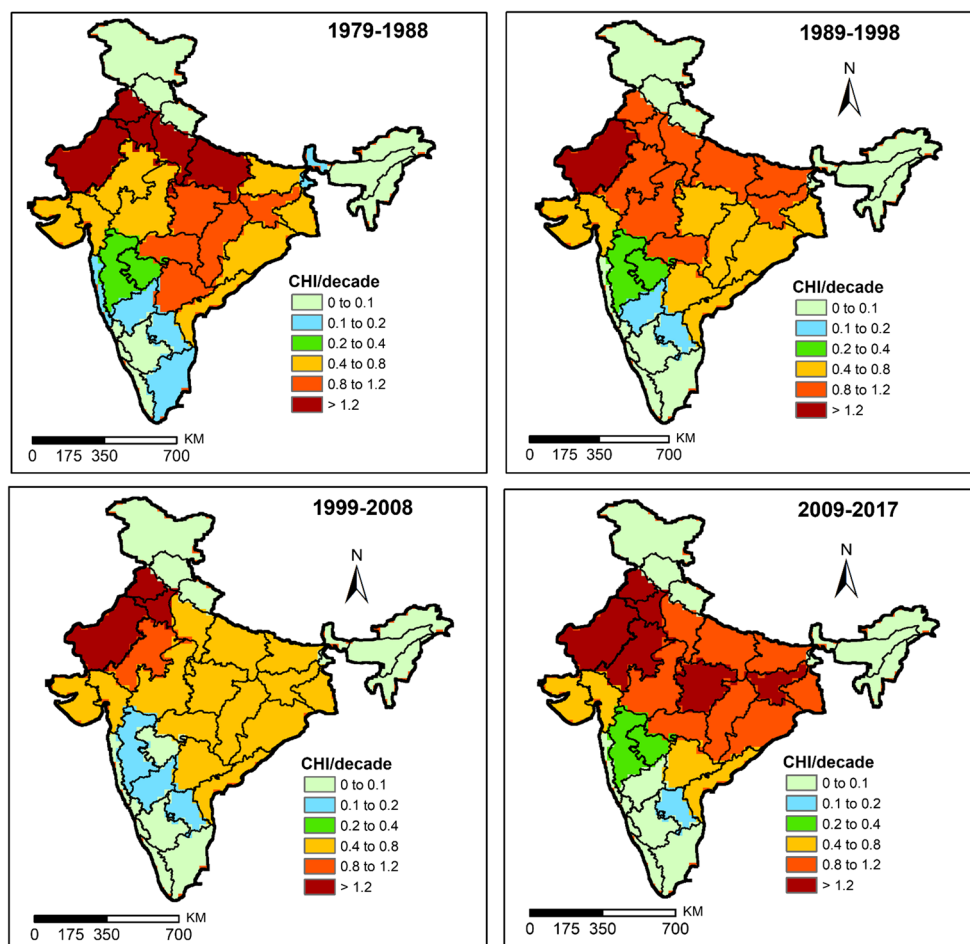
During 1979–1988, very high CHI values of more than 1.2 was found over western Rajasthan, Punjab, Haryana, and Uttar Pradesh, whereas over Tamil Nadu, Rayalaseema, northern Karnataka, and Maharashtra, the values of CHI were relatively lower, i.e. less than 0.4. Intermediate CHI values were mainly found over central and eastern India (Fig. 9). During 1989–1998, the CHI values were found to be increased over eastern Rajasthan, western Madhya Pradesh, and Bihar, whereas it was decreased over Punjab, Haryana, Uttar Pradesh, eastern Madhya Pradesh, and Chhattisgarh. It was interesting to record that during the next decade, i.e. 1999–2008, the decadal mean CHI values became moderate over almost the entire study area except the western Rajasthan, Punjab, and Haryana. However, during 2009–2017, almost opposite results were observed, where the CHI values were found to be increasing over the entire Indo-Gangetic Plain, Maharashtra, and eastern and central India (Fig. 9). Hence, it can be inferred that during the third decade, i.e. 1999–2008, the CHI values were decreasing, representing lesser impacts of heat wave, whereas the impacts of heat waves were maximum during the last decades, i.e. 2009–2017.

4.7 Major contributing month

The contribution of each month to the total number of heat wave occurrences in the entire study period, i.e. March–July, was calculated. It provides information about the month with maximum heat wave incidents. It was seen that the entire of Uttar Pradesh, Bihar, Jharkhand, parts of Vidarbha, Chhattisgarh, and Rajasthan experienced majority of the heat waves in the month of May (Fig. 10). The month of June mainly contributed to the total number of heat waves in subdivisions like western Rajasthan, Punjab, and Haryana. In some areas over Gujarat, Madhya Pradesh, West Bengal, Orissa, and Chhattisgarh, the heat wave was maximum during the month of April, whereas during the month of March, it contributes to the total number of heat wave occurrences majorly in the peninsular India, parts of north-east India, and isolated parts of north India (Fig. 10). It can be inferred that the month of May contributed the maximum heat wave occurrences across the meteorological sub-divisions of India.

The month with major contribution towards heat wave occurrence during cumulative period, i.e. March–July, varies from year to year. The deviations of the major contributing month were computed and presented in Fig. 10. Uttar Pradesh, Bihar, parts of west Rajasthan, east Rajasthan, Madhya Pradesh, Chhattisgarh, Vidarbha, Jharkhand, Orissa, West Bengal, and parts of Telangana may experience heat wave before or after 1.5–2 months from the month generally affected by heat wave, whereas the occurrence may deviate by 1–1.5 months from the general contributing month in few parts of west Rajasthan, Marathwada, Gujarat, and Punjab (Fig. 10).

Fig. 9 Decadal mean combined heat wave index (CHI) values over the Indian region during **a** 1979–1988, **b** 1989–1998, **c** 1999–2008, and **d** 2009–2017



Northern Karnataka, Rayalaseema, Konkan and Goa, Madhya Maharashtra, Tamil Nadu, and Pondicherry may experience heat wave in a buffer period of 0.5–1 month from the normal month. In northern and north-eastern India, southern Karnataka and Kerala experience heat wave in less than 0.5 month from the month affected in general. Thus, this analysis may provide unique information about the time of heat wave occurrences in different sub-divisions of the country.

The analysis of trend of anomaly in major contributing month (i.e. the deviation of heat wave occurrences from its long-term normal) showed that in major parts of the meteorological sub-divisions, it was negative. This signifies that the time of occurrence of heat wave during the past 39 years has been preponed than the normal time of occurrence in those places (Fig. 10). Few parts of the country also showed a positive trend and it was mainly confined in northern, peninsular, and north-eastern parts of India.

The present study involves temperature as the main component for characterisation of Indian heat wave. However, the future research may incorporate the role of humidity in intensification of heat wave, by addressing the adverse impacts of co-occurrence of hot and humid days

during heat wave incidences. Earlier studies have already reported the negative effects of heat wave accompanied with humidity in terms of human comfort index. Researchers have mentioned that humidity can play a significant role towards intensifying heat waves, and the phenomena are becoming more regular. Coffel et al. (2018) have projected that in many regions, the severe impacts of humidity might increase in this century. Similarly, other researchers have also mentioned that the severity of a heat wave may be underestimated by only considering the role of temperature, as the effect of extreme heat waves may be amplified due to high humidity during consecutive hot days in humid regions (Fischer and Knutti 2013; Davis et al. 2016; Hass et al. 2016). Due to increase in both specific humidity and temperature at the global level, the intensification of heat stress is being projected for the entire twenty-first century. More specifically, the densely populated regions are most susceptible due to co-occurrence of both heat and humidity. It is also projected that there is a potential for widespread exposure to adiabatic saturation temperatures, which in some cases might exceed postulated theoretical limits of human tolerance by mid to late century (Coffel et al. 2018).

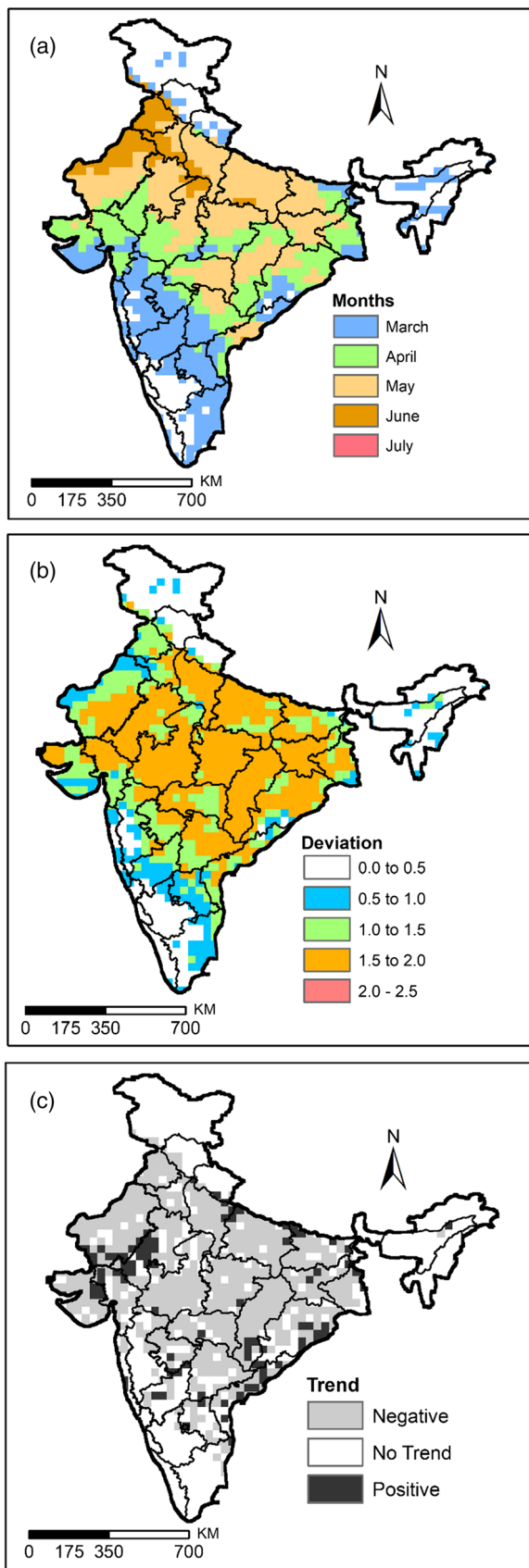


Fig. 10 **a** Major heat wave contributing month, **b** its deviation, and **c** trends during 1979–2017 over the Indian region

5 Conclusion

The present study proposed a new index, i.e. combined heat wave index (CHI), by combining different heat wave parameters, like magnitude, occurrence, and extent. The varying values of these parameters have different implications on the overall heat wave characteristics. Hence, a methodology has been developed to combine all these three parameters in quantifying the heat wave. It was observed that the CHI was able to properly characterised and quantify the heat wave conditions across different parts of the Indian mainland; moreover, its capability in addressing the inter-annual variations in heat wave was also evident. The study revealed that persistent heat waves with higher magnitude were frequent over north-western India, covering Rajasthan, Punjab Haryana, and Madhya Pradesh, whereas the values of heat wave magnitude and frequency were quite lower over eastern India. The long-term trend analysis showed that the trends of heat waves were increasing in parts of north-western Indian and some parts over eastern India, whereas it was lower in Uttar Pradesh, Bihar, Chhattisgarh, Telangana, and Andhra Pradesh. The present study revealed that the month of May had maximum contribution in seasonal heat wave over parts of north-western and Central India, whereas it was June in Punjab, Haryana, and western Rajasthan. It was interesting to find that contribution of March was maximum over the peninsular India. The decadal changes in heat wave characteristics were evident; however, persistent higher heat waves were also observed over parts of north-western Indian and the Indo-Gangetic Plain. The varying significant trends in heat waves over different parts of Indian mainland may be due to alterations in amount and distribution of pre-monsoon rainfall. Moreover, the studies on climate change and associated impacts on global circulations, like southern oscillation and Indian Ocean dipole, along with the increasing aerosol due to crop residue burning need to be attempted before drawing any conclusions on causes of varying trends in heat waves over parts of the country.

Acknowledgments We express our sincere thanks to Shri. Santanu Chowdhury, Director, National Remote Sensing Centre (NRSC), for his constant encouragement and suggestions. Guidance received from Dr. C. S. Jha (CGM, RCs) and Dr. D. Dutta (GM, RRSC-East) is duly acknowledged. We are also thankful to Climatic Prediction Center (CPC), NOAA, for providing gridded temperature data and India Meteorological Department (IMD) for providing the heat wave criteria. The authors are grateful to those anonymous reviewers for their constructive suggestions.

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