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RESEARCH ARTICLE

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Changing spatio-temporal trends of heat wave and severe heat wave events over India: An emerging health hazard

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Abstract

Heat wave (HW) and severe heat wave (SHW) events are the manifestations of extreme temperature causing an array of impacts on health, ecosystem, and economy. Since the mid-20th century, an increasing trend in the characteristics of heat waves has been observed over India causing an increased rate in human mortality. Our study aimed to analyse monthly, seasonal, and decadal variations along with long-term trends of HW and SHW events for pre-monsoon (March–May) and early summer monsoon (June–July) season during 1951–2016. HW and SHW events were identified using revised criteria given by the India Meteorological Department (IMD) using daily gridded maximum temperature data at $0.5^\circ \times 0.5^\circ$ resolution from IMD. The study found a Spatio-temporal shift in the occurrence of HW events with a significantly increasing trend in three prominent heat wave prone regions that is northwestern, central, and south-central India, the highest being in West Madhya Pradesh (0.80 events/year), while a significantly decreasing trend was observed over an eastern region that is Gangetic West Bengal (−0.13events/year). SHW events showed a southward expansion and a spatial surge during the decades of 2001–2010 and 2010–2016. Tri-decadal comparative assessment shows a decadal increase of around 12 HW and 5 SHW events post the 1980s. State-wise Pearson's correlation between HW/SHW events and observed mortality reveals that the eastern coastal states that are Odisha and Andhra Pradesh show a significant positive correlation of 0.62 and 0.73, respectively. This significantly increasing trend in HW and SHW events may pose a grave risk to human health, predominantly on the vulnerable sections of the society. Heat waves need to be recognized as a potential health risk and demand further study, robust preparedness, and policy intervention.

KEYWORDS

heat waves, long term trends, mortality, severe heat waves

1 | INTRODUCTION

India, the second-most populous and seventh-largest country of the world is also the sixth most vulnerable country to the extreme events (Eckstein *et al.*, 2017; Mall *et al.*, 2019). The dynamics of climate-dependent mechanisms are changing at a great pace due to the rise in global mercury. Both man-made and natural ecosystems are at a risk to climate-related extreme events such as heat waves, extreme precipitation, droughts, wildfires, and so forth (Field et al.2014; Mall *et al*., 2011). Multi-model projection studies have established that the global mean surface temperature and its characteristics are very likely to change (increase) in the future (Kharin *et al*., 2007; IPCC, 2013; Sillmann *et al*., 2013; Lewis and King, 2017). This rise in the mean temperature will trigger more intense extreme temperature events (high confidence) with significant global impact (Field *et al*., 2014). In such a scenario, it is extremely important to understand the characteristic of extreme temperature events and their impact on different ecosystems, probable interaction with other climatic variables, and their altered behaviour under different climatic conditions (Perkins and Alexander, 2012; Ching *et al*., 2019).

Heat waves are understood as prolonged episodes of extreme temperature over any region (Pai *et al*., 2013). These episodes are defined based on temperature threshold, which may vary with the physiography and climate of the region and different durations considered. Apart from temperature, humidity is an important parameter that is considered for declaring heat-related stress (Fischer and Knutti, 2013). In the wake of the rising global mean temperature of 0.85°C during 1880–2012, India has also experienced an increasing trend of 0.66°C/100 in annual mean temperature during 1901–2017 with a significant increasing trend of 1.06°C/100 years in the maximum temperature (IMD, 2017). Ross *et al*. (2018) did a comprehensive trend analysis of decadal mean, maximum, and minimum surface temperature from 1951 to 2016 for India and found the evolution of warming pattern over the northwestern and southern India while a progressive cooling phase over northeastern and southwest region of the country.

Heat waves are observed as a common seasonal episode in Indian climatology occurring during the hot weather season for March–July (Pai *et al*., 2013; Mishra *et al*., 2017). Studies in the past have used different indices to reflect on the severity imposed by recurring incidents of heat waves with a statistically significant increasing trend of their spatially wide occurrence (SE Perkins and Alexander, 2012; Russo *et al*., 2015). Long term trend of HW and SHW events analysed for the hot weather season (March–July) during 1961–2010 showed the highest numbers of HW days experienced over the northwestern, northern, central, and eastern coastal regions with an average of ≥8 HW days 1–3 SHW days for the season. An increasing trend of HW and SHW days was observed in the decade of 2001–2010 as compared to previous decades (Pai *et al*., 2013). Rohini *et al*. (2016) observed a significant increasing trend of 0.23, 1.3, and 0.76 days per decade in the frequency, duration, and maximum duration of heat waves during April–June based on the 90th percentile of maximum temperature over a five-day window and excess heat factor (EHF). An undenied influence of post-1980s global warming has been confirmed by Panda et al. (2017) in both day time and nighttime heat waves and warm spells as they increased significantly during 1981–2013.

Future projection studies show an unprecedented rise of heat waves over India (Murari *et al*., 2015; Mishra *et al*., 2017; Rohini *et al*., 2019). Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model simulations reported an increase in intensity, frequency, and duration of severe heat waves 2070–2099 under 4.5 and 8.5 scenarios, the eastern and western coast, which are currently unaffected, will be severely impacted by severe heat waves in future (Murari *et al*., 2015). An increase of 3–9 severe heat wave events by the mid-century, which further rise to 18–30 events by 2071–2100 for CMIP5 and community earth system model simulations (Mishra et al. 2017). Mukherjee and Mishra, 2018 studied events of the concurrent hot day and hot night (CHDHN), which increased by 1–3 days under current scenario after 1984 in the present scenario, will increase up to four times for Representative Concentration Pathway (RCP) 4.5 while a 12-fold increase noted under 8.5 scenario by the end of the century. Rohini *et al*. (2019) reported an increase of 1.5–2.5 heat wave events and an increase in the average duration of 12–18 days during 2020–2064 using CMIP5 simulations.

Heat waves have a direct impact on human health causing commonly felt discomfort, heat cramps, exhaustion, dehydration, heat strokes, and increasing risk for patients of cardiovascular and respiratory diseases to severe instances of mortality (Basu, 2009; Chen *et al*., 2015; Mall *et al*., 2017; Singh *et al*., 2019). The presence of humidity in the environment prevents the thermoregulatory mechanism of evaporative cooling of the body through sweating and perspiration giving rise to conditions of heat stress (Fischer and Knutti, 2013). An increase in night-time temperature exacerbates the impact of daytime heat wave due to the absence of heat discharge at night (Gosling *et al*., 2009).

India has become a hotspot for heat-related mortality, an increasing toll of deaths due to heat waves recorded a spur in recent decades from a cumulative of 5,330 deaths reported during 1978–1999 to extreme cases of 3,054 and 2,248 deaths in 2003 and 2015, respectively (Chaudhury *et al*., 2000; Ratnam *et al*., 2016). An increase of 0.5°C in mean summer temperature can cause an increase of heat-related mortality from 2.5 to 32% while for an increase in heat wave duration from 6 to 8 days, the probability of mortality shows a 78% increase (Mazdiyasni *et al*., 2017). Projections on conditions of heat stress over India state that areas near Chota Nagpur Plateau, northeastern India, and eastern coast of India may approach the 35°C threshold in the business as usual scenario while large urban centres such as Lucknow and Patna housing large population shall reach the critical wet bulb temperature(TW_{max}) of 31°C under RCP 4.5 scenario (Im *et al.*, 2017). Densely populated northern India is prone to extreme heat stress conditions by the mid and end of the century (Im *et al.*, 2017).

Apart from health, increasing temperatures have a substantial impact on agriculture in terms of a decrease in the yield of major crops for every degree rise (Mall *et al.*, 2006; Zhao *et al.*, 2017; Chakraborty et al., 2019; Sonkar *et al.*, 2019; Sonkar *et al.*, 2020). Spells of heat extreme are a risk to the agriculture sectors as well, particularly the northern Indian rice-wheat crop system (Lobell *et al.*, 2012; Mall *et al.*, 2016; Mall *et al.*, 2018; Singh *et al.*, 2018; Bhatt *et al.*, 2019). Interaction of rainfall anomalies and prevailing extreme temperatures may strengthen the impact and occurrence of droughts (Wreford and Neil Adger, 2010). Sharma and Mujumdar, (2017) found an increasing trend in the concurrent extreme events of the heat wave and droughts over India and noted the episodes of simultaneous severe and long duration heat waves and droughts occurring in Gujarat, Peninsular, and Central India.

The impact of extreme events is aggravated due to high vulnerability, lower resilience, and adaptive capacity (Im *et al.*, 2017). In such a scenario, it is necessary to study long-term trends of HW/SHW events over India for understanding its climatological characteristics and suggesting adequate mitigation and adaptation measures for the country. The objectives of our study were to analyse (a) the monthly, seasonal, and decadal trends and variations of heat wave and severe heat wave events over India; (b) the shifts in occurrence of HW/SHW events in post-1980s warming era through a comparative assessment of occurrence between 1951 and 1980 and 1981 and 2016; and (c) the impacts of HW/SHW events on human mortality over India.

2 | MATERIALS AND METHODS

2.1 | Data and Methodology

The study area extends over entire India for the period of 66 years from 1951 to 2016 targeting pre-monsoon and early monsoon season (March–July) (Figure 1). Daily gridded maximum temperature data were obtained from the India Meteorological Department (IMD) at a resolution of 0.5° latitude × 0.5°longitude (Subash and Sikka, 2014). The high resolution daily gridded temperature data were originally developed by Srivastava *et al.*, 2009 employing modified Shepard's angular distance weighting algorithm for interpolation of maximum temperature (Tmax) and minimum temperature (Tmin) data available from 395 meteorological stations into 1° spatial resolution throughout 1969–2005.

To obtain high-resolution homogenous temperature dataset for the entire study period (1951–2016) Tmax data available at 1° × 1° resolution for the period 1951–1979 was gridded to 0.5° × 0.5° using the bilinear interpolation method. HW and SHW events have been estimated at 0.5° × 0.5 resolution for each of the 1,156 grid points all over India.

In the study, HW and SHW events were defined according to the criteria given by IMD, which is based on maximum temperature threshold anomalies that are

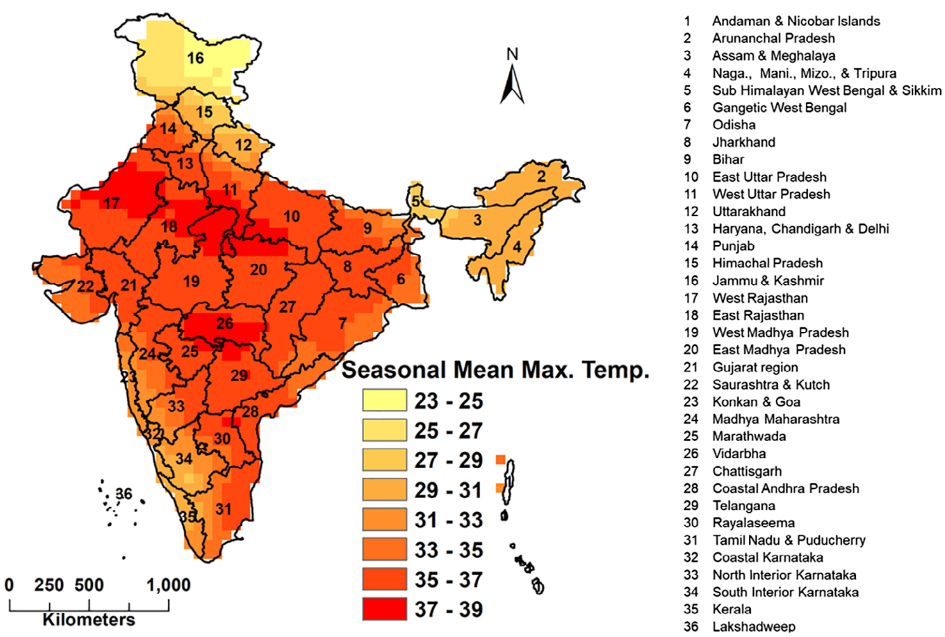

FIGURE 1 Seasonal mean maximum temperature (°C) over India for March–July (1951–2016) [Colour figure can be viewed at wileyonlinelibrary.com]

departure relative to the long-term climatological mean of maximum temperature that is normal for each grid. Considering the spatial and climatological heterogeneity of the Indian region IMD has categorized the HW and SHW declaring thresholds separately for coastal, plains, and hilly regions. The definition and criteria for HW and SHW given by IMD (2018) are as follows:

Heat wave is considered if the maximum temperature of a station reaches at least 40°C or more for Plains, 37°C or more for coastal stations and at least 30°C or more for Hilly regions. Following criteria are used to declare heat wave (IMD, 2018):

(a) Based on departure from normal

1. Heat wave: Departure from normal is 4.5 to 6.4°C.
2. Severe heat wave: Departure from normal is >6.4°C.

(b) Based on actual maximum temperature (for plains only)

1. Heat wave: When actual maximum temperature ≥ 45°C.
2. Severe heat wave: When actual maximum temperature ≥ 47°C.

To declare HW/SHW, the above criteria should be met in at least two stations in a meteorological subdivision for at least two consecutive days and the HW/SHW will be declared on the second day.

For the study, quality controlled maximum temperature data for 1,156 grid points at a resolution of 0.5° latitude × 0.5° longitude was used for the study period 1951–2016. The daily mean of maximum temperature (Tmax) for each grid was obtained using 1981–2010 as the climatological normal (standard) period during March–July (1951–2016). To observe long-term trends and variability in the occurrence of HW events and SHW events daily maximum temperature anomaly (departure) was obtained. The study area has been categorized as coastal region according to the coastal area information given by Centre for Coastal Zone Management and Coastal Shelter Belt, Environmental Information System (EnvIS)) and hilly region according to hilly districts as designated under Hill Areas Development Programme/ Western Ghats Development Programme (HADP/ WGDP) (Planning Commission, 1997) and the remaining area was considered a plain region. The criteria given by IMD for each of the hilly, coastal, and plain regions was followed to declare heat waves in the respective regions to declare heat wave, and each day after consecutive 2 days are considered a heat wave event.

To understand the Spatio-temporal variability of HW and SHW events over India monthly, decadal, and seasonal frequencies of HW/SHW events for each grid point during 1951–2016 (March–July) was estimated. Following the criteria, HW and SHW events were computed separately for each grid and SHW events do not include HW events in them.

2.2 | Trend analysis

Heat waves are observed as a period of extreme temperatures occurring in any region, these extreme values lack a uniform normal distribution. Thus, to determine any possible long-term upward or downward trend in the occurrence of HW/SHW events, non-parametric Mann-Kendall trend test at a 95% confidence level was used. Mann-Kendall trend test is widely used in trend detection against random order in climate studies (Subash and Sikka, 2014; Kumar *et al*., 2016; Srinivas et al. 2020).

The Man Kendall trend statistics (S) was calculated as:

$$S=\sum_{k=1}^{n-1}\sum_{j=k+1}^{n} a_{ij} \tag{1}$$

Where,

$$aij=\operatorname{sgn}(x_i-x_j)=\begin{cases}1\,x_j<x_i\\0\,x_j=x_i\\1\,x_j>x_i\end{cases} \tag{2}$$

x_i and $x_j$in (2) are the values of heat wave events in the time series.

For n > 10 the statistic S has a normal distribution and the mean = 0, the variance of S statistics was computed as:

$$\mathrm{VAR}(S)=\frac{n(n-1)(2n+5)-\sum_{i=1}^{m}t_i(t_i-1)(2t_i+5)}{18} \tag{3}$$

Where m is the number of tied groups (set of sample data having the same values) and $t_i$is the number of values in ith group. The standardized test statistic Z was computed as follows:

$$Z=\begin{cases}\frac{S-1}{\sqrt{\mathrm{VAR}(S)}}\ if\ S>0\\0\ if\ S=0\\\frac{S+1}{\sqrt{VAR(S)}}\ if\ S<0\end{cases} \tag{4}$$

If Z is not statistically significant the null hypothesis H_0 is accepted and is rejected in case of Z being statistically significant. An upward or downward trend is indicated by a positive or negative sign of Z.

To study the correlation between the occurrence of HW/SHW events and mortality, Pearson's correlation coefficient was calculated as state-wise during 2001–2015. The observed mortality data were obtained from the death records reported in Mausam journal during pre-monsoon and monsoon season due to heat waves from 2001 to 2015, the journal is quarterly published by IMD (IMD, 2002).

3 | RESULTS AND DISCUSSIONS

3.1 | Heat wave events

3.1.1 | Monthly and Seasonal occurrences of heat wave events

The monthly climatology of HW events over India shows that HW events are more frequent and pronounced during April–June, while in March and July they are less frequent and are spatially limited to only the regions experiencing maximum HW events over the season (Figure 2).

In March, the average number of HW events remained ≤1 per year for the study period. The frequency of HW events in the northern, northwestern, western coastal, and northeastern region of the country was greater than those occurring in central and southern region while absent in Jammu and Kashmir during March. The analysis shows that most of the HW events in March occurred during the decade 2001–2010 that was also the warmest decade over the century as also reported by Pai *et al.* (2013). The spatial occurrence of HW events increased during April covering most of northern India and also saw a threefold increase in the frequency of heat wave post-1980s with a cumulative number of events rising from 1,101 HW events during 1951–1980 to 3,130 HW events during 1981–2016 over India during April.

May and June are the warmest months of the year, showing the maximum spatio-temporal distribution of HW events where the frequency reaches an average of 1–2 events per year. The analysis shows that Vidarbha, Telangana, Bihar, West Bengal, and northern parts of Madhya Pradesh are the worst hit by HW events in May while in June heat wave approaches and covers most of the country apparently, northern India.

The frequently affected regions due to HW events are parts of northern (Jammu and Kashmir) northwestern (West Rajasthan), central (East and West Madhya Pradesh), eastern (Bihar and Jharkhand), and south-central (Vidarbha and Coastal Andhra Pradesh) India. With approaching southwest monsoon, heat waves begin to retreat, so in July an average of less than one event/year were observed confined to the parts of the northern and northwestern region. Importantly, the northwestern

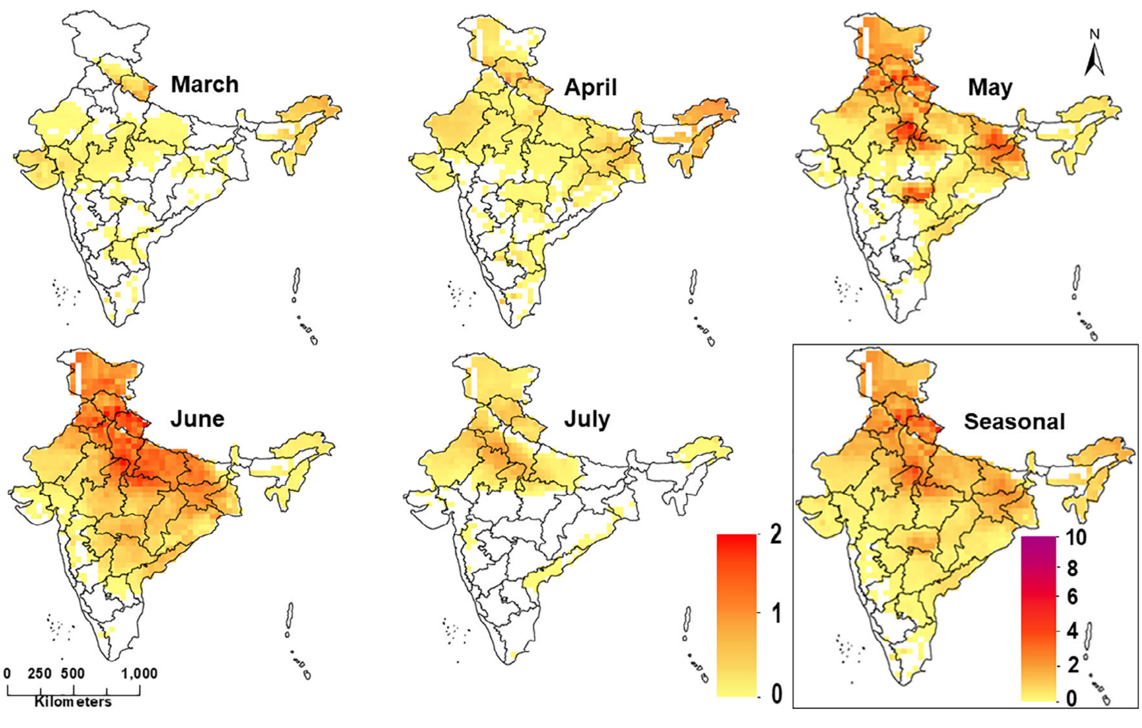

FIGURE 2 Monthly and seasonal average number of HW events over India during 1951–2016 (March–July) [Colour figure can be viewed at wileyonlinelibrary.com]

region has shown a sustained HW event during the months included.

Figure 3 shows the variation in the distribution of monthly HW events for the decades during 1951–2016 in which the month of May and June records the maximum number of HW events and March the lowest.

Seasonal climatology of occurrence of HW events for March–July as pre-monsoon and early monsoon season during 1951–2016 report an average of 4–5 events per season per year (Figure 2). The spatio-temporal distribution of HW events during pre-monsoon and early monsoon indicates northern, northwestern, central, and southeastern regions as the heat wave zones and experienced a continuous increase in frequency.

3.1.2 | Decadal heat wave events

Decadal variations in the frequency of HW events provide an opportunity to determine the trend in HW (Spatio-temporal increase or decrease). The decadal analysis performed for all of the decades from 1951 to 2016 indicates a rise in both frequency and spatial occurrence of HW events from 1951 to 2016 (Figure 4). During 1951–1960 and 1961–1970, on an average, 2–3 HW events were observed over most of the country while the north, northwestern and eastern part of the region observed a higher frequency of 4–5 events with rare extremes of 8–9 were observed in some grids of Uttarakhand. A shift in the spatial occurrence of HW events from the eastern region in West Bengal and Bihar to northwestern and central India over the period observed an increase of 3–5 HW events. The shift further extends to the south-central region, making these three zones a new hotspot of intense HW events starting in the 1981–1990s. This shift is explained by a warming trend orienting towards northwestern India and South-Central region after the 1970s as observed in the trend analysis of maximum temperature over India by Ross *et al.* (2018).

The post-1980s consistent increase in HW events was found. In the decade 1991–2000, the total number of heat wave events observed over central India has shown a marked increase from 2 to ≥5 events. However, heat wave events in the northeastern part of the country can be seen receding clearly (Figure 4). Heat wave events have found to have a severe impact over the eastern coastal region manifesting in the highest number of deaths over the region. Moreover, the decade 1991–2000 reported a significant spatial variation and decline in frequency over the eastern coast particularly in Odisha. Although a drop-in HW event was observed over the decade (1991–2000), the year 1998 reported the highest frequency of HW events, which is quite evident in terms of huge mortality reported from heat waves in Odisha. The reason behind this adversity can be traced to the synoptic conditions associated with prevailing high temperatures, particularly instances of the north–south wind discontinuity and recurving of cyclonic storms over the Bay of Bengal towards the east (Jenamani, 2012).

These events disrupt the pressure distribution system followed by the movement of the N-S trough towards the sea resulting in cut-off of sea breeze and also strengthen the intense pressure system causing persistent high temperatures leading to heat waves (Jenamani, 2012).

In the decade 2001–2010 an average of 4–6 heat wave events was observed over Central India while a lesser 2–4 events were observed over the northern, northwestern, northeastern, and south-central region of the country, similar were the observations during 2011–2016 wherein the entire Rayalaseema and some parts of Karnataka and Tamil Nadu also observed heat wave events, which in the previous decades showed no or very less heat wave events. The two decades 2001–2010 and 2011–2016 marked the beginning of an even warmer global climate.

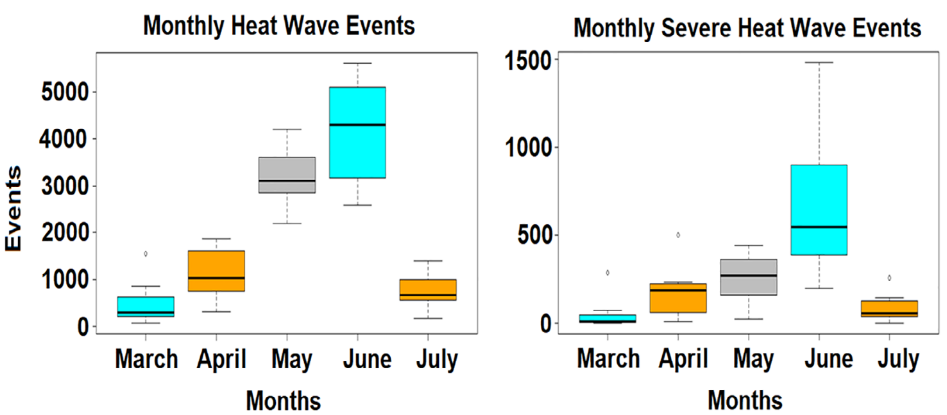

FIGURE 3 Boxplot showing the monthly distribution of the total number of heat wave and severe heat wave events for March–July (1951–2016) [Colour figure can be viewed at wileyonlinelibrary.com]

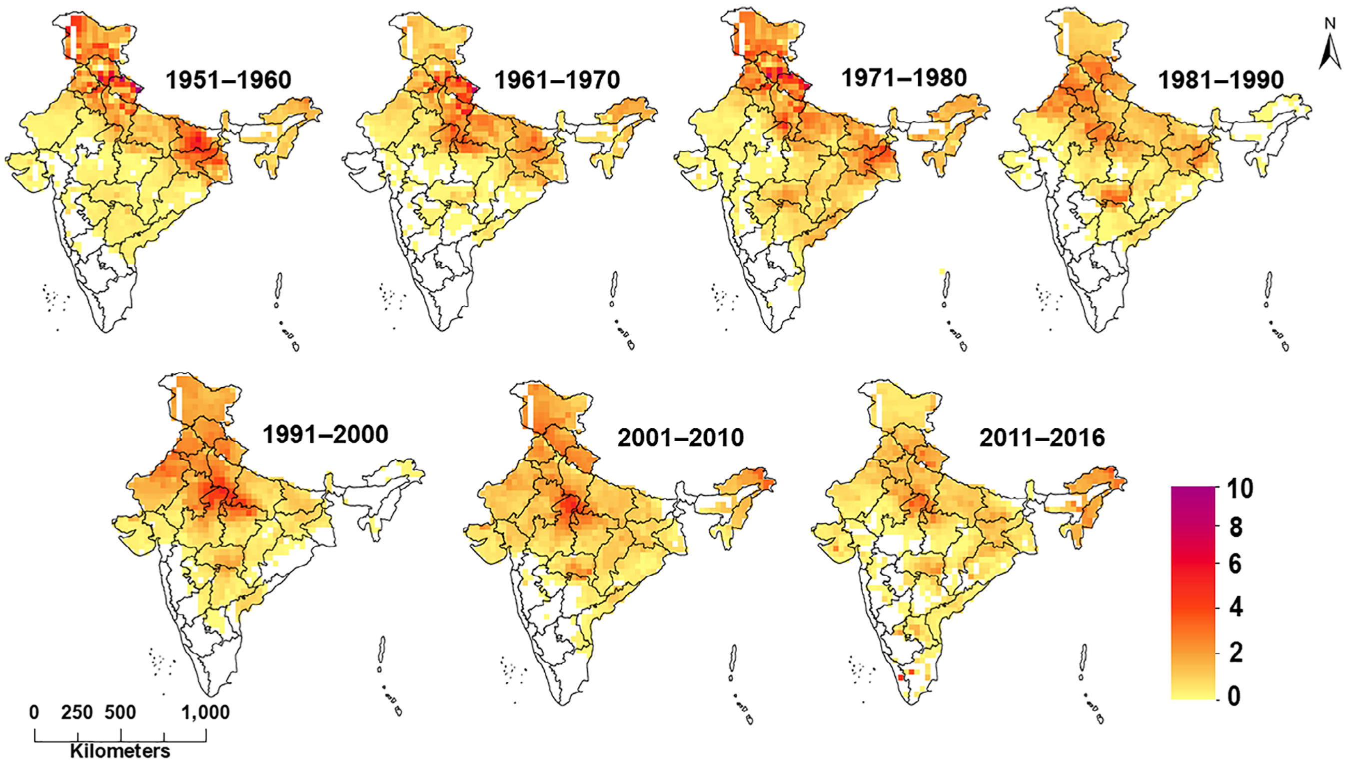

FIGURE 4 Decadal average number of heat wave events during 1951–2016 (March–July) [Colour figure can be viewed at wileyonlinelibrary.com]

The meteorological subdivisions of Jammu and Kashmir, Himachal Pradesh, Punjab, West Rajasthan, East Rajasthan, East UP, West UP, East MP, West MP, Vidarbha, Odisha, and Coastal Andhra Pradesh recorded the most frequent heat wave events while the eastern region constituting West Bengal and Bihar reported less heat wave events (≤ 2/year) during 2010–2016 from 6 to 8 events observed in the decade of 1951–1960 showing an evident decline in the occurrence of HW events over 66 years (1951–2016). The decrease in these regions can be attributed to a decreasing trend of maximum temperature from 1950 to 2016 as reported by Ross *et al*. (2018). Mukherjee and Mishra (2018) also observed a similar significant decrease and stated that the decrease/cooling may be due to synergy between evaporative cooling induced by increased latent heat flux because of the rise in intensive irrigation in the Indo-Gangetic region and increased atmospheric aerosol loading over the region. The evaporative cooling and aerosol loading influence the surface energy budget thereby decreasing the observed surface temperature. Following decreasing maximum temperature over the latter half of 20th century the eastern region as reported by Ross *et al*. (2018) do not report frequent heat waves and hence is not a prominent heat wave region as also reported by Ratnam *et al*. (2016) and Rohini *et al*. (2016).

3.2 | Severe heat wave events

3.2.1 | Monthly and seasonal severe heat wave events

The monthly climatology of SHW events shows a similar pattern in Spatio-temporal occurrence as March, April, May, June, and July show a significant spatial variation in SHW. SHW events were observed over the northwestern and northern region of the country at an average of ≤1 event/year in March, which follows a trail of expansion through the north, central, and eastern region, reaching a maximum frequency of an average ≥ 1 event/year in May and finally become most widespread in June (Figure 5) between 1951 and 2016. SHW events start retreating in July with some parts of Jammu and Kashmir, Uttar Pradesh, Madhya Pradesh, and Himachal Pradesh witnessed the events (≤ 1 events/year). However, both the frequency and spatial spread of SHW were substantially lesser than the HW events.

The monthly analysis shows that the northern and northwestern and eastern regions of the country observed more frequent SHW events while at least to no SHW event observed in the southern region. High humidity moderates the temperature of the southern coastal region because of which they do not experience very extreme temperatures but are vulnerable to heat stress.

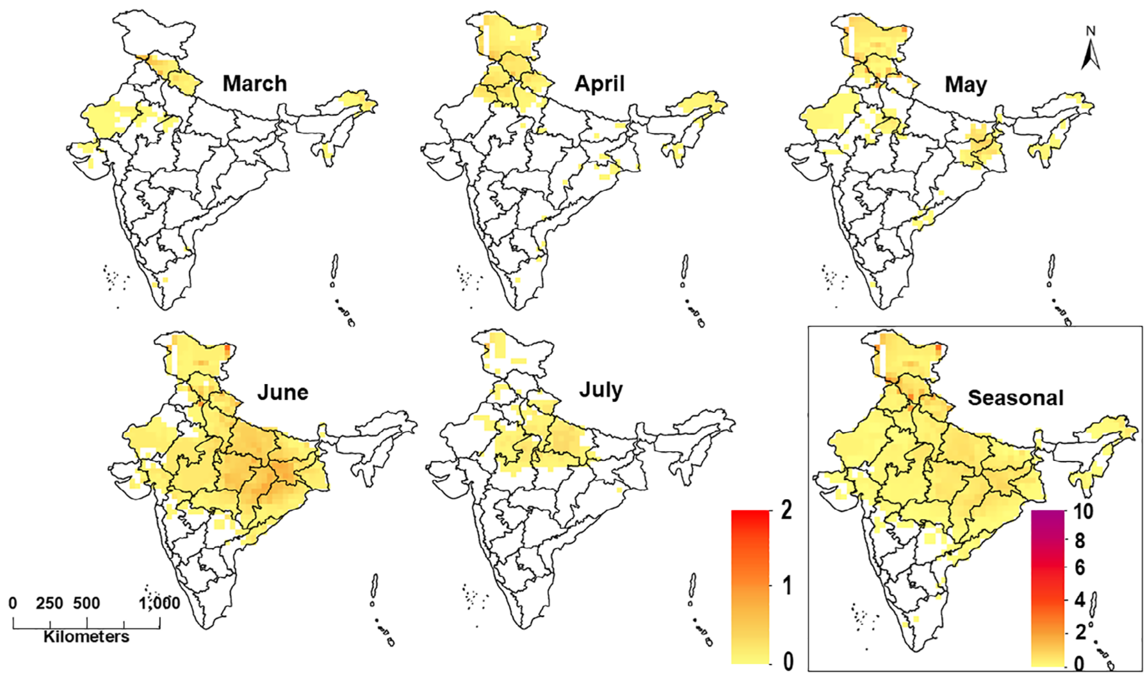

FIGURE 5 Monthly and Seasonal average number of severe heat wave events over India during 1951–2016 (March–July) [Colour figure can be viewed at wileyonlinelibrary.com]

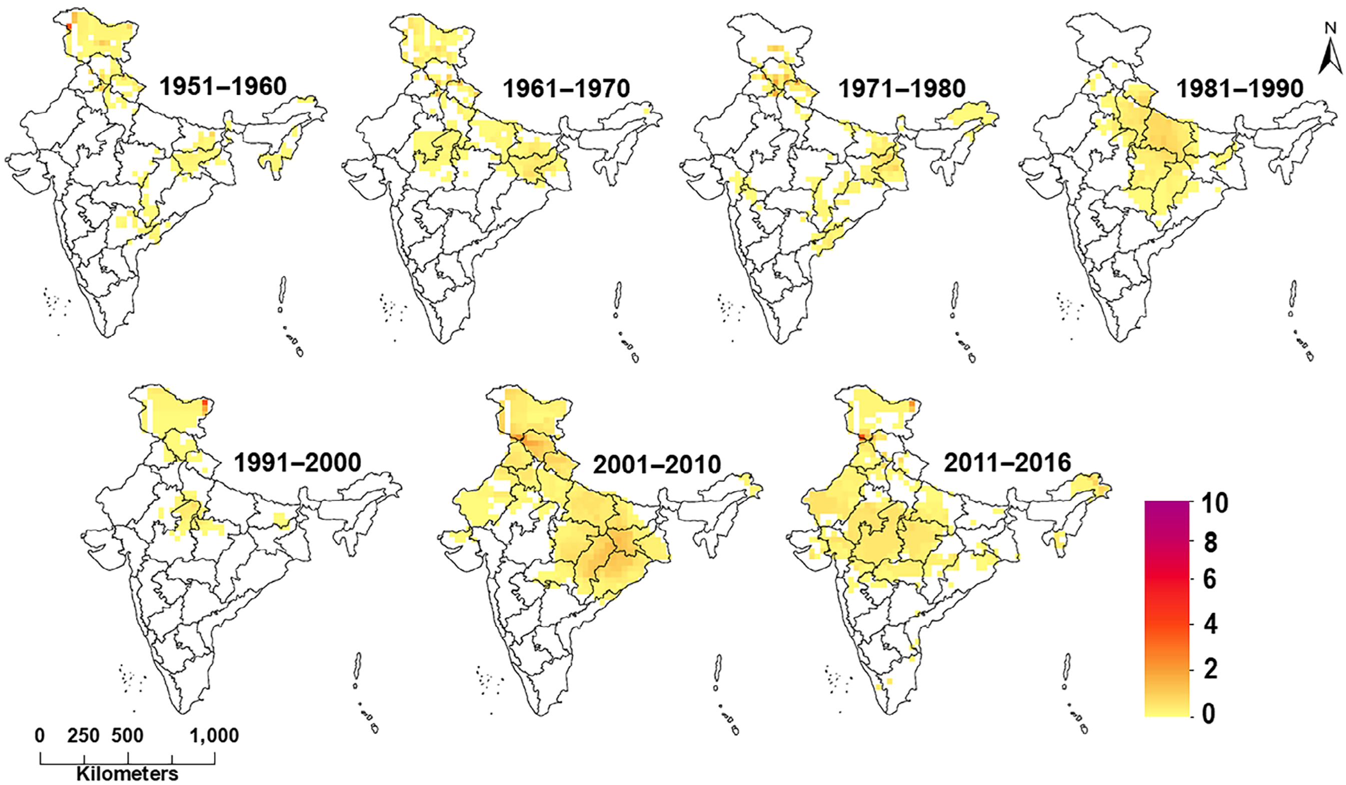

FIGURE 6 Decadal Average number of severe heat wave events over India during 1951–2016 (March July) [Colour figure can be viewed at wileyonlinelibrary.com]

The seasonal analysis SHW events during March–July (1951–2016) shows the occurrence of an average of <1 SHW events per season over the northern, north-western, central, eastern, and south-central region except for north-east and south-western region. The analysis indicates that SHW events are less frequently occurring over most parts of the country.

3.2.2 | Decadal severe heat wave events

Figure 6 shows the spatial distribution of decadal average SHW events. In the decade 1951–1960 SHW events were very pronounced over Jammu and Kashmir (2–3 events/year), Bihar (<1 event/year), some parts of Uttarakhand, and Haryana (<2 events/year) and less widely distributed

TABLE 1 Heat wave and severe heat wave event trend for meteorological subdivisions of India

	Heat Wave events		Severe Heat Wave events	
Meteorological Subdivision	**Kendall's tau**	**Sen's slope**	**Kendall's tau**	**Sen's slope**
Arunachal Pradesh	0.05	0.00	0.07	0.00
Assam and Meghalaya	0.04	0.00	–	–
Bihar	−0.21	−0.33[a]	−0.02	0.00
Chhattisgarh	0.08	0.00	0.01	0.00
Coastal Andhra Pradesh	0.11	0.00	0.03	0.00
East Rajasthan	0.25	0.75[a]	0.13	0.00[a]
East Madhya Pradesh	0.15	0.27	0.06	0.00
East Uttar Pradesh	−0.02	0.00	0.09	0.00
Gangetic West Bengal	−0.17	−0.13[a]	0.01	0.00
Gujarat region	0.19	0.00[a]	0.06	0.00[a]
Haryana, Chandigarh, and Delhi	0.02	0.00	−0.11	0.00
Himachal Pradesh	−0.02	0.00	−0.06	0.00
Jharkhand	−0.21	−0.42[a]	−0.02	0.00
Jammu and Kashmir	0.000	0.00	−0.03	0.00
Kerala	0.03	0.00	0.03	0.00
Konkan and Goa	0.00	0.00	–	–
Madhya Maharashtra	−0.02	0.00	0.03	0.00
Marathwada	0.08	0.00	0.05	0.00
Naga., Mani., Mizo., and Tripura	0.06	0.00	0.03	0.00
North Interior Karnataka	0.01	0.00	–	–
Odisha	−0.04	0.00	−0.03	0.00
Punjab	0.06	0.04	−0.01	0.00
Rayalaseema	0.04	0.00	–	–
Saurashtra and Kutch	0.29	0.00[a]	0.05	0.00
South Interior Karnataka	0.03	0.00	–	–
Sub Himalayan West Bengal and Sikkim	−0.14	0.00[a]	−0.02	0.00
Telangana	0.14	0.00	0.00	0.00
Tamil Nadu & Puducherry	0.04	0.00	0.03	0.00
Uttarakhand	−0.16	−0.56	−0.11	0.00
Vidarbha	0.18	0.03[a]	0.02	0.00
West Rajasthan	0.24	0.79[a]	0.10	0.00[a]
West Madhya Pradesh	0.24	0.80[a]	0.12	0.00[a]
West Uttar Pradesh	0.00	0.00	0.08	0.00

[a]Significant increase/decrease at 95% confidence level.

over Manipur and Mizoram. The occurrence of SHW events became more spatially wide over the next decade (1961–1970) covering East and West UP, Eastern Rajasthan, Western MP, Bihar and Jharkhand, and Jammu and Kashmir. However, a sharp decline in SHW events was observed during 1971–1980 while in the same decade HW events were most frequent and spatially wide (Figure 6). In 1981–1990 SHW events were profound over Uttar Pradesh, eastern Madhya Pradesh, Uttarakhand, and Chhattisgarh. The 1991–2000 decade saw the least number of SHW events over the entire study period seen only over Jammu and Kashmir, Himachal Pradesh, and some regions of Madhya Pradesh and Uttar Pradesh. However, SHW events saw a tremendous rise both in frequency and intensity during 2001–2010 covering the northern and eastern parts of the country except for the northeastern region.

A marked increase in the frequency of SHW events was observed over the northern region (≥ 2) followed by the eastern coast particularly over Odisha (1–2), which is among the most severely impacted heat wave prone regions of the country. An interesting northwestern shift

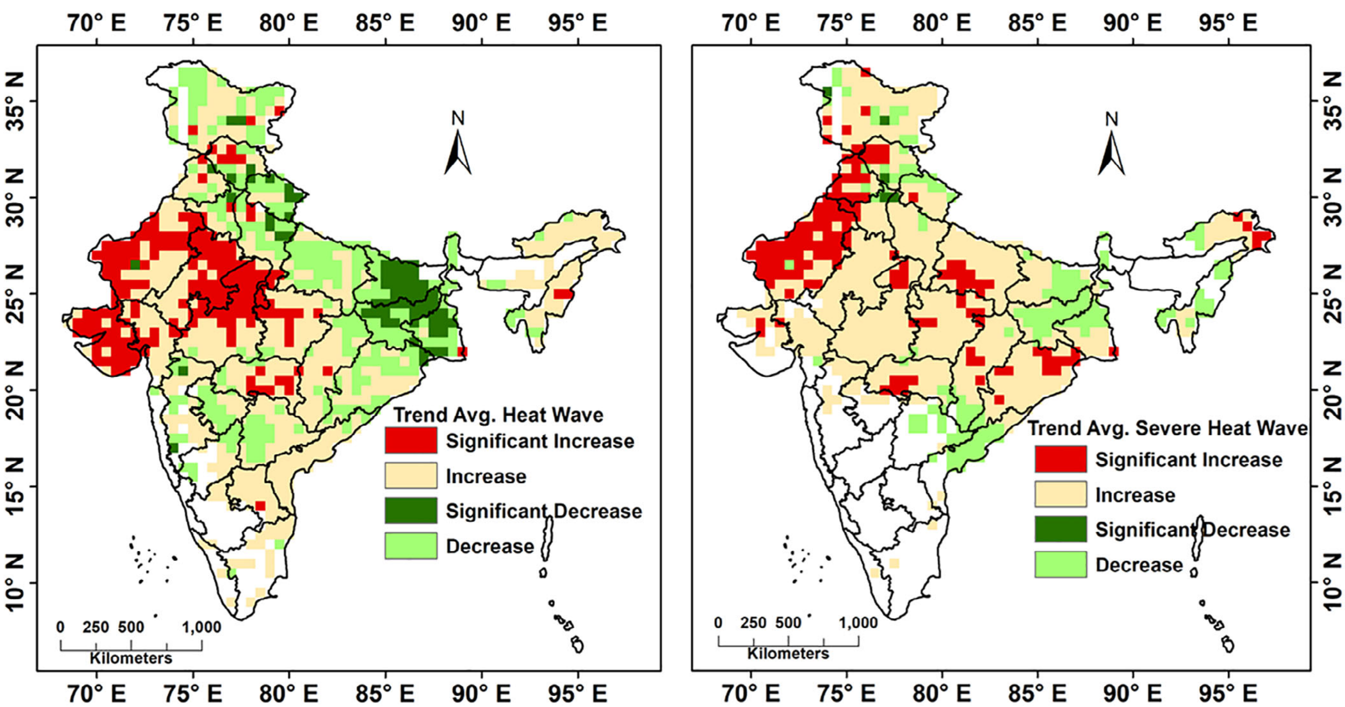

FIGURE 7 Long term trend in seasonal heat wave and severe heat wave events during 1951–2016 (March–July) [Colour figure can be viewed at wileyonlinelibrary.com]

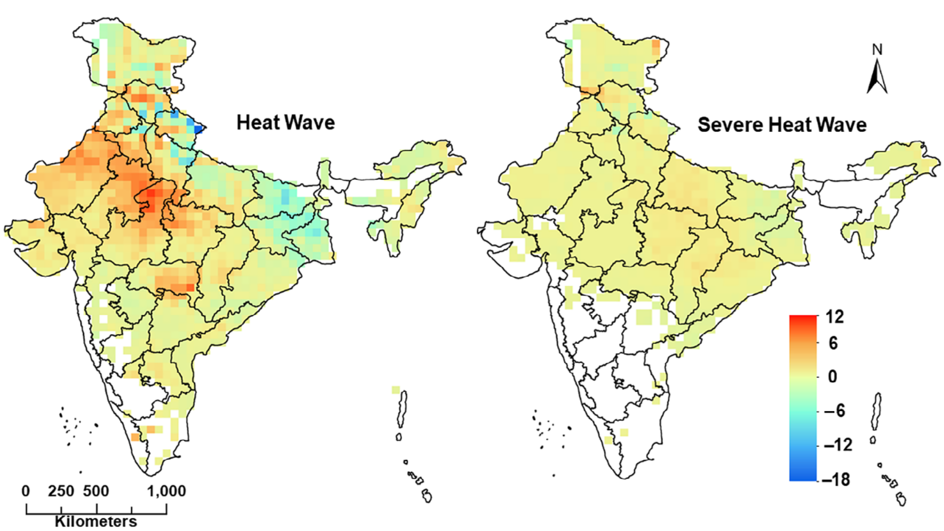

FIGURE 8 Difference in heat wave and severe heat wave events from 1951–1980 to 1981–2016 (March–July) [Colour figure can be viewed at wileyonlinelibrary.com]

in SHW events was observed in 2011–2016 over northern, northwestern, and central India, and also a southward expansion covering Madhya Maharashtra, north-interior Karnataka, and some parts of Rayalaseema, Tamil Nadu, and Kerala. The occurrence of SHW events in the region where previously they had not been occurring indicates potential future risk. The decadal analysis shows that SHW events have increased over time, becoming more frequent and widespread particularly after the 2000s. However, unlike HW events, SHW events did not indicate a clear changing spatial pattern of occurrence. There is a need to study the behaviour of severe HW from a meteorological point of view.

3.3 | Trend analysis

Non-parametric Mann-Kendall trend test at 95% confidence level was employed for each grid point (1156) to analyse the trend of seasonal occurrences of HW and SHW events during March–July (1951–2016). Results of spatiotemporal trend analysis show that out of 1,156 grid points distributed over the country 1,013 grid points reported the occurrence of HW events and 819 grid points observed SHW events.

3.3.1 | Heat wave events

A significant increasing trend has been observed in the northwestern, western, and central India, the highest being in the subdivisions of West Madhya Pradesh observing an increase of 0.80 events/year followed by East Rajasthan with 0.75 events/year and West Rajasthan of 0.79 events/year. Similarly, an increase in Eastern Madhya Pradesh, Vidarbha, Gujarat, Saurashtra, and Kutch region (Table 1) and some regions of Eastern Uttar Pradesh has been noticed (Figure 7).

HW events in the northwestern region are associated with an anti-cyclonic circulation developing due to a quasi-stationary anomalous Rossby wave train generated at North Africa (Ratnam *et al*., 2016). These waves are generated due to stretching of vorticity by divergent winds, which propagates along with westerly jet streams over northwestern India causing a sinking motion that causes positive outgoing longwave radiation (OLR) and hence heat waves (Ratnam et al.2016; Sandeep and Prasad, 2018).

Moreover, the eastern region observed a significantly decreasing trend with a decline of −0.13 events/year in Gangetic West Bengal, −0.42 events/year in Jharkhand and − 0.33 events/year in Bihar (Table 1), which is consistent with findings of Ross *et al*. (2018) .

There is significant spatial variation within some subdivisions such as some regions of Himachal Pradesh showed a decreasing trend while areas in the north observed a significant increase, similarly, northern Eastern Uttar Pradesh reported significant increase while

TABLE 2 State-wise Pearson's correlation between heat wave and severe heat wave events to observed mortality from 2000 to 2015

State	HW/mortality correlation (r)	SHW/mortality correlation (r)
Arunachal Pradesh	–	–
Assam	−0.14	−0.08
Meghalaya	–	–
Nagaland	–	–
Manipur	–	–
Mizoram	–	–
Tripura	–	–
Sikkim	–	–
West Bengal	0.11	0.47
Odisha	0.22	0.62[a]
Jharkhand	0.54[a]	0.5[a]
Bihar	0.2	−0.08
Uttar Pradesh	−0.05	−0.28
Uttarakhand	–	–
Haryana	0.08	−0.11
Chandigarh	0.08	−0.25
Delhi	0.18	−0.16
Punjab	−0.02	0.24
Himachal Pradesh	–	–
Jammu and Kashmir	–	–
Rajasthan	0.46	0.42
Madhya Pradesh	0.3	−0.06
Gujarat	0.19	0.23
Goa	–	–
Maharashtra	0.73[a]	0.35
Chhattisgarh	0.74[a]	0.48
Telangana	0.06	−0.1
Andhra Pradesh	0.12	0.73[a]
Tamil Nadu	−0.05	0.08
Karnataka	–	–
Kerala	–	–

[a]Significant at 95% confidence level.

other regions decreased. Jammu and Kashmir, Uttarakhand, and Haryana also show such variation. A non-significant increase in HW events has been observed over some parts of the northeastern and southeastern regions of the country while parts of eastern Uttar Pradesh, Telangana, Marathwada, and Odisha observed a non-significant decrease.

3.3.2 | Severe heat wave events

Severe heat wave events observed an increasing trend over the north, northwest, central, western, and northern portion of the eastern coastal part of the country (Figure 7). A significant increase has been observed over East and West Rajasthan, Gujarat, and Western Madhya Pradesh meteorological subdivision (Table 1) while some regions of Eastern Uttar Pradesh, Haryana, northern Madhya Pradesh and some parts of Odisha, Chhattisgarh, and Vidarbha while a non-significant decrease was observed over some parts of Jammu and Kashmir, Chandigarh, Delhi, and Haryana, Punjab, Bihar, Jharkhand, Sub Himalayan West Bengal and Sikkim, Himachal Pradesh, and so forth. A non-significant yet spatially wide increasing trend was observed over most of the region of the country indicating an increased frequency of SHW events. SHW events are showing an increasing trend in most heat wave prone parts of the country suggesting a future increase in these events.

3.4 | Comparative assessment of heat wave and severe heat wave events between events during the 1950s and 1980s

The period from 1951 mark the beginning of a warmer period with the 1980s observing a greater increase in temperature with a higher frequency of heat waves for India (Sharma and Mujumdar, 2017). A difference between the occurrence of HW/SHW events is performed to identify the region where the HW/SHW events have increased/decreased in the recent decades of 1981–2016 as compared with 1951–1980. An increase in HW events can be seen over the northwestern and central region of the country, which has recorded a decadal average increase of 12 events in recent decades similarly SHW events also show an increase of up to five events in these regions. A decrease of around 1–3 events was observed in the western coastal region in HW. The eastern and northeastern region have observed a decline of 3–9 events in HW and a maximum of 3 SHW events following the decreasing trend of annual maximum temperature given in Figure 8. A decrease in HW events over some region of the Indo-Gangetic plain can be attributed to increased evaporative cooling and aerosol effect during recent decades (Mukherjee and Mishra, 2018). The analysis shows the episode of HW events over India has become more frequent in the last 3–4 decades (Table 2).

3.5 | Heat wave and mortality

A simple Pearson's correlation was performed to find a possible correlation between observed seasonal HW/SHW events and mortality due to HW/SHW events for all the states of India from 2001 to 2015 as per records from IMD. Figure 9 shows that observed mortality in Jharkhand is significantly positively correlated with both heat wave and severe heat wave events while Maharashtra and Chhattisgarh show a significant positive correlation with heat wave events. A higher non-significant positive correlation between heat wave event and mortality was observed in Rajasthan.

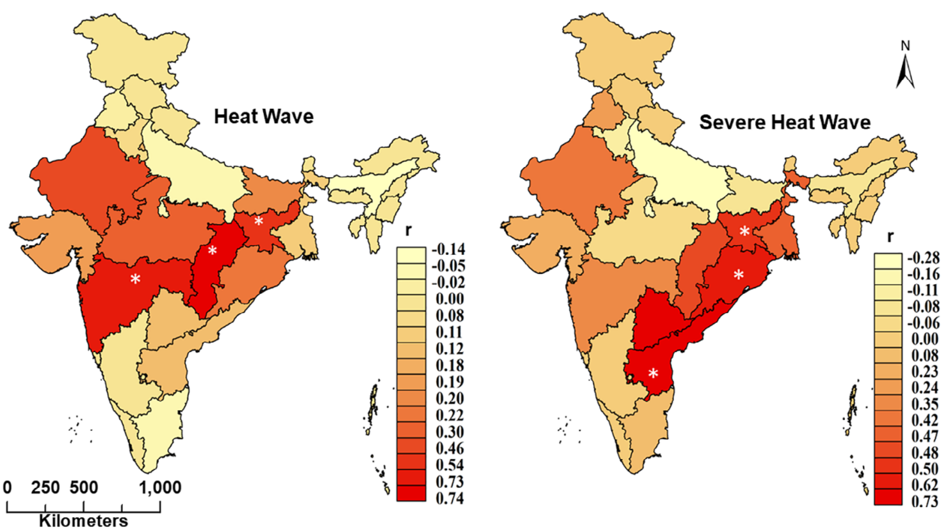

FIGURE 9 State-wise Pearson's correlation of heat wave and severe heat wave events with observed mortality. A statistically significant correlation ($p < .05$) is denoted by an asterisk (*) symbol in the map [Colour figure can be viewed at wileyonlinelibrary.com]

Severe heat wave events show a significant positive correlation with observed mortality in Andhra Pradesh (0.73) and Odisha (0.62). These two states have experienced the highest casualties from heat wave events in 1998, 2003, 2007, and 2015.

Assam did not observe deaths despite the occurrence of HW and SHW events. A weak positive correlation of mortality 0.08 with SHW in Tamil Nadu suggests that although heat wave events are more frequently observed but mortality is reported in case of occurrence of SHW events. Mazdiyasni *et al.*, 2017 reported that with an increase of HW events from 6 to 8 days there is a probability of an increase of 78% in heat-related mortality over India. Singh *et al.*, 2019 found an increase of 5.61% (95% CI:4.69, 6.53%) in all-cause mortality in summers due to extreme temperatures observed over Varanasi. Whereas, other regions have shown negative to no correlation with either of HW or SHW events. Prevailing synoptic conditions such as recurving of cyclones, increased sensible heat flux, local accumulation of heat as a result of land-atmosphere coupling also played a greater role in increasing the mortality (Ghatak *et al.*, 2017; Neethu *et al.*, 2019).

4 | CONCLUSION

As discussed above, the study shows a significant increase in heat wave and severe heat wave events over India indicating possible escalation in the future. The characteristics of heat wave events have markedly changed over the years, becoming more frequent and expanding in areas where previously there was no or very less heat wave events occurred.

Northwestern, Central, and South-central region of the country have been identified as most heat wave prone regions posing a direct health risk to the population inhabiting those areas. At the district level Bhind, Morena, Gwalior, Jalaun, Etawa, Ganganagar, Bikaner, Churu, Pithoragarh, Chamoli, Sirmaur and Jaisalmer, Gadchiroli, Yavatmal, Amravati, Chandranagar, and Adilabad are some of the districts that have recorded the highest frequency of heat wave events in the analysis and hence most vulnerable to extreme temperatures.

In case of delay of monsoon, the probability of increased sensible heat flux and accumulation of heat wave for a sustained period can cause dire consequences. Another alarming finding to be considered is the southward spread of heat waves, which are relatively more prone to heat stress given the presence of high humidity that may have a severe impact on the health of the population leading to mortality.

The frequency of heat wave and severe heat wave events have become more frequent in recent decades following the warming trajectory and so is expected to increase with increasing temperature in the absence of mitigation strategy. A significant positive correlation between HW/SHW events and mortality implies the severity of the risk associated with these events. As HW events over India are directed by the synoptic conditions, a detailed study on the influence of increasing temperature on these phenomena and hence over Indian heat wave are a must to get a clear picture of future heat wave over India. Although many multi-model-based studies have been done for future projections of heat waves, it is necessary to consider the dynamics of global circulations also as they play a major role.

The densely populated northern region experienced a significant rise in both HW and SHW events posing serious implications on the health of its inhabitants. Increasing urbanization, diminishing green cover, rising humidity due to increasing irrigation altogether may aggravate the impact of HW events over the region. India, where the majority of the population is involved in outdoor activities, increasing exposure to heat wave and severe heat wave events insinuate the necessity to recognize heat wave as a major health risk. The way ahead to decrease the impact of heat extremes is to develop effective heat action plans. Efficient early warning systems, mapping vulnerable population, awareness about providing proper health care in case of heat-related health issues are some major concerns that need urgent consideration. The course of adaptation and mitigation measures over the country should be taken seriously and immediately as the increasing global temperatures will have disastrous consequences.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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