Heat Waves over India

Venkata Bhaskar Rao Dodla[1] and G. Ch. Satyanarayana[2]
[1]Foremerly in Andhra University, Visakhapatnam
[2]Center for Atmospheric Science, K L Deemed to be University, Andhra Pradesh
Email: dvbrao@gmail.com

ABSTRACT

This paper presents a review of the studies on heat waves over India. A brief summary of the characteristics of maximum temperatures and the heat wave impacts is presented in the first section. A brief discussion of heat wave vulnerability, specifically for humans, is outlined. The availability of temperature data for the Indian subcontinent is portrayed. A chronological review of scientific studies on the characterization of heat waves over India based on observations and model simulations is provided. The scientific studies on the understanding of heat wave characteristics in conformity with the improvements in observation network and analysis methodologies have been illustrated. A brief description of the "heat action plan" initiated by the Government of India to mitigate heat wave vulnerability as a part of disaster management is given. Finally, scientific studies on heat waves in India is summarized.

Keywords: *Heat waves, Indian subcontinent, Characterisation, Prediction, Vulnerability and Atmospheric teleconnections.*

1. Introduction

Heat waves, at the present time, are recognized as a weather disaster all over the world, because of the causation of human deaths. Heat waves mean the occurrence of higher-than-normal temperatures for a several consecutive days that would impact human health system. A research study by Zhao et al. (2021) reported that ~0.5 million people across the world died because of extreme temperatures during the recent 20-year period of 2000-2019. A modest estimate of heat wave related human deaths are ~166,000 during 1998-2017, of which notable heat wave events in recent decades are the U.S. heat wave of 1988 with ~10,000 deaths; the European heat wave of 2003 with ~30,000 mortalities; Russian heat wave of 2010 with ~55,000 deaths (McGregor et al., 2015). In India, with vast expanse of ~3.3 million sq.km and a population of ~1.3 billion, of which 80 million live below the poverty line, the impact of heat waves is enormous. Heat waves are recognized as an important weather-related disaster in India, which had been responsible for several human deaths during the last few decades, estimated at 25,716 during the 15-year period of 1992-2016, 3058 in 1998 and about 2040 in 2015.
(https://ndma.gov.in/sites/default/files/IEC/Booklets/HeatWave%20A5%20BOOK%20Final.pdf).
Since cold waves also cause human mortalities much higher than of heat waves, extremities of temperatures are known to impact the human health sometimes leading to death.

Heat waves identification or recognition varies with region or country as the heat wave impacts are dependent not only on the high temperatures but also on the temperature variability and adaptation. Thus, a definition of a heat wave signifies temperature related heat stress extending for several consecutive days that would affect human health. As such, the impacts of a heat wave are to be assessed considering both the maximum and minimum temperatures as related to their climate variability of the region concerned along with the effect of duration. Although several atmospheric variables such as temperature, humidity, wind speed, turbulence, and radiation are important for assessing heat wave stress on human health, humidity along with temperature plays key role. For this reason, several of the heat wave indices include both the temperature and humidity as appropriate for the assessment of heat wave status. The World Meteorological Organization (WMO, https://www.

britannica. com /science/heat-wave-meteorology) defines a heat wave period, when the daily maximum temperature is higher than the average by 5°C or more for at least 5 consecutive days. However, many nations configured their own criteria to define a heat wave. In Netherlands, Belgium and Luxembourg, a heat wave is recognized when the maximum temperature exceeds 25°C for at least five consecutive days, of which the maximum temperature records higher than 30°C on any 3 days. In Denmark, a heat wave is recorded if the average maximum temperature across more than fifty percent of the country exceeds 28°C for a period of at least 3 consecutive days. In Sweden, a heat wave is declared when the daily maximum temperature exceeds 25°C for a minimum of five consecutive days. In the United States of America, heat wave definitions vary by region; in the Northeast parts (southwest parts of California) heat wave is declared when the temperature exceeds 32.2°C (37.8°C) for three or more consecutive days. In South Australia, a heat wave is reported when the maximum temperatures are above 35°C (40°C) or five (three) consecutive days. In Greece, a heat wave is identified when the maximum temperatures are above 39°C for three consecutive days along with minimum temperatures above 26°C. The United Kingdom Met Office declares heat wave occurrence when the maximum and minimum temperatures exceed predefined thresholds for a particular region, and at 4 severity levels that depend on the duration of extreme temperatures. A more general definition of heat waves as applicable for all regions was proposed by Russo et al. (2015), which considers the heat wave when the maximum temperatures exceed the daily threshold for at least 3 consecutive days, where the daily threshold is the 90th percentile of the daily maximum temperature computed using a 31-day window and with the reference period as 1981–2010. In contrast, India Meteorological Department uses the following criteria to recognise the existence of a heat wave at any location or region:

(i) normal heat wave is confirmed if the maximum temperature at a station reaches ≥ 40^{0}C for plains and ≥ 30^{0}C for hilly regions, and the departure from normal is 4-6^{0}C;

(ii) severe heat wave is declared if the mean maximum temperature is ≥ 40°C and temperature departure from normal is above 6^{0}C or if the actual maximum temperature is ≥ 47^{0}C or if the actual maximum temperature is ≥ 6.5^{0}C above normal.

The criteria for heat waves over coastal stations are that the maximum temperature exceeds 37°C along with departure from normal are ≥ 4°C.

Further, the occurrence of a heat wave is confirmed if the heat wave criterion persists continuously for a minimum of 3 days.

2. Heat Wave Vulnerability

Heat waves, meaning occurrence of anomalous high temperatures for a considerable period, are not only detrimental to human health, but also are noted cause social and community vulnerability through causation of psychological stress, wild fires, power outages, damages to roads etc. Extreme heat is harmful, and sometimes fatal to human health. Exposure to extreme heat leads to "hyperthermia" (heat stroke), heat cramps and exhaustion, cardiovascular and respiratory disorders in humans. Hyperthermia occurs when the human body cannot regulate the exposure to heat whereby the body temperature gradually rises and when the body temperature is above ~40°C, hyperthermia sets in leading to health disorder. Hyperthermia may gradually manifest as psychological stress, dizziness and fainting; cramps or rash; oedema; and finally as a heat stroke. Heat waves are known to cause psychological stress, that affect to reduce the physical activity and performance levels, and is also connected to increase of crime. High temperatures are recognised to be connected with increased interpersonal and societal level conflicts; increased crime rate, particularly violent crimes such as assault, murder, and rape (Hsiang et al. 2015).

Abnormal high temperatures lead to increase of electricity consumption due to increased air conditioning use, which often lead to electricity spikes and power outages. For e.g., during the summer of 2009, the city of Melbourne, Australia experienced major power disruptions as the heat wave temperatures caused blow up of transformers that led to power grid failure, which left over half a million people without power. Heat waves are noted to have caused damage to infrastructure facilities such as buckling and melting of roads on highways; buckling and kinking of rail lines; and bursting of water lines. Extreme high temperatures during night may affect agriculture, as some crops may not cool off enough affecting crop productivity; and animals that do not cool off enough cause reduction in milk production. Heat waves with high temperatures, when associated with low humidity, low rainfall- drought conditions are conducive to increase the probability of wildfire occurrences.

3. Temperature Data over India

India Meteorological Department (IMD) has the mandate to make observations of all meteorological variables at the surface and specified upper levels that include surface temperature. Surface temperature data from observatories are available since 1875 (https://mausam.imd.gov.in/ahmedabad /docs/data-procedure.pdf). At the current time, surface temperature data is available from ~550 observatories and these data were the source of several studies on the characterization of temperatures over the Indian subcontinent. IMD has generated daily gridded temperature data comprising of maximum, minimum and mean temperatures at 1^0 longitude x 1^0 latitude over the Indian subcontinent for the period starting from 1969 till 2005 (Srivastava et al. 2009), which is being updated at regular intervals. The daily gridded temperature data are being used by several researchers and scientists for characterisation of temperature variability and heat waves and for validation of numerical model simulations and predictions over Indian subcontinent.

4. Heat Waves over India

This section presents a review of the analysis and prediction of heat waves over India. The physical mechanism for the occurrence of a heat wave over a region may be elucidated based on thermodynamics and dynamics. Since heat wave is defined as sudden spurt in the temperatures beyond a threshold of its climate normal sustained for a few days, both the local thermodynamic and synoptic scale dynamic processes are important. Seasonal heating due to insolation contributes to the location of the relative warm regions over the continental part, primarily because of the heat absorption and retention capabilities of the soil. Direct heating at the surface from insolation cause the near surface temperatures to rise, but this rise beyond a point leads to thermodynamic instability and subsequent neutral atmosphere. Basic physics denote that the temperatures at any location will increase because of the two important processes of heat advection and subsidence-warming, and both arise due to dynamical processes related to synoptic scale circulation changes. This grief description helps to understand the development of understanding the occurrence and characterization of heat waves over India in this paper. Since heat waves imply the occurrence of anomalous high temperatures, firstly an overview of the seasonal variations of temperatures is presented followed by a description of the chronological sequence of temperature studies over the Indian subcontinent.

The Indian subcontinent, as per the terminology of the India Meteorological Department, features four seasons namely winter (January-February), Pre-Monsoon (March-May), Southwest Monsoon (June-September) and Post-Monsoon (October-December) (http://imd.gov.in/ section/nhac/ wxfaq.pdf) whereas the climate seasons of winter, spring, summer and autumn prevail over the other parts of the northern hemisphere. In this paper, the pre-monsoon season is referred to as "summer season" for brevity of understanding the heat wave characteristics as the usage of "pre-monsoon" may not reflect the reference to temperature. During this season, the temperatures gradually rise connoting the transition from winter to summer. A figure of the spatial distribution of monthly mean maximum temperatures prepared using the IMD daily gridded temperature data for the period 1951-2015 for the 4 months of March-April-May-June (June is also shown as hot season prevails over north till ~1 July, the onset of southwest monsoon covers the entire India) are presented in Figure 1. Indian subcontinent extending meridionally from ~6°N to 37°N latitudes, with the "Tropic of Cancer" situated approximately along the central parts, display large meridional variations of temperature, with the

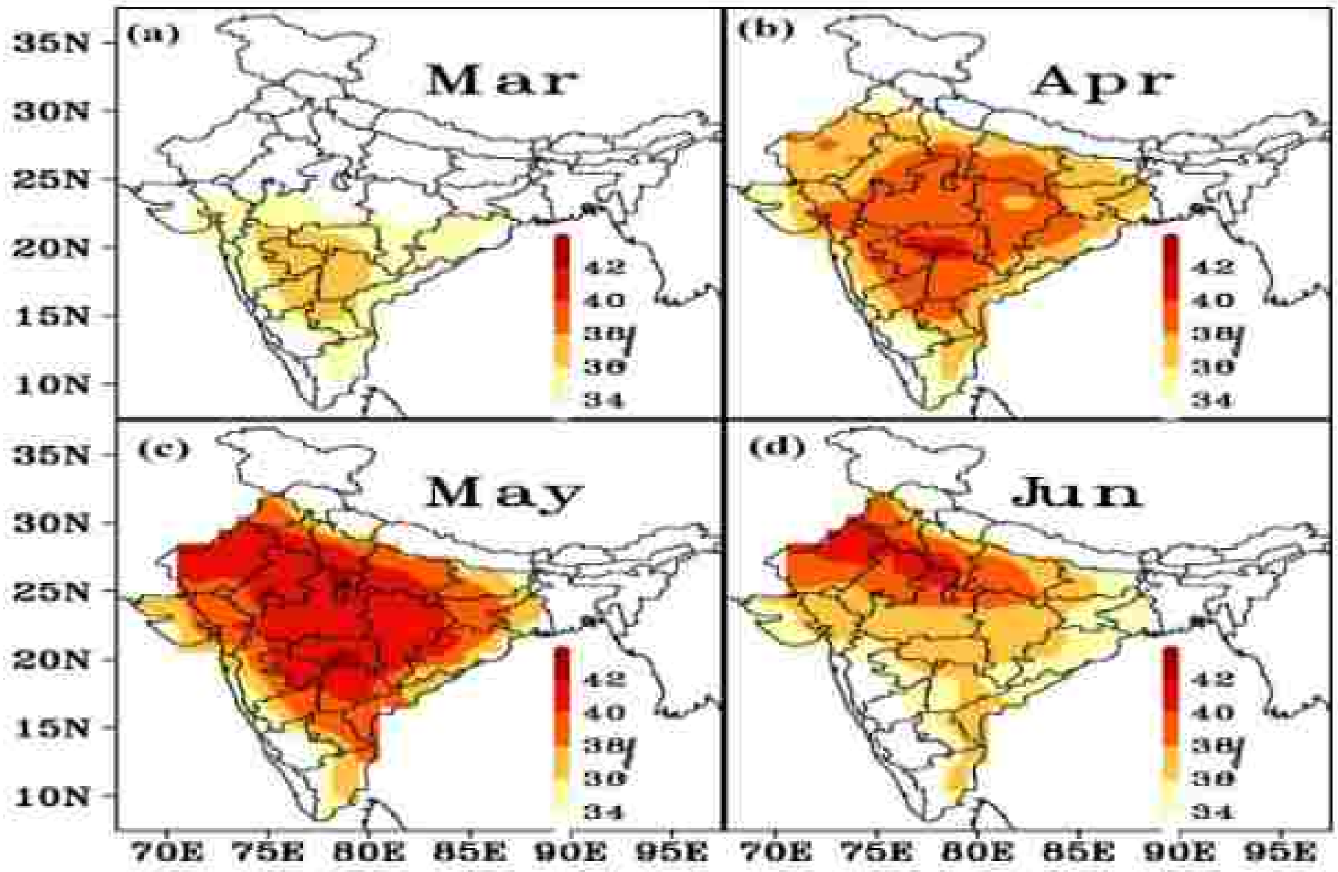

Figure 1: Spatial distributions of mean maximum temperatures (°C) for the months of (a) March (b) April (c) May and (d) June.

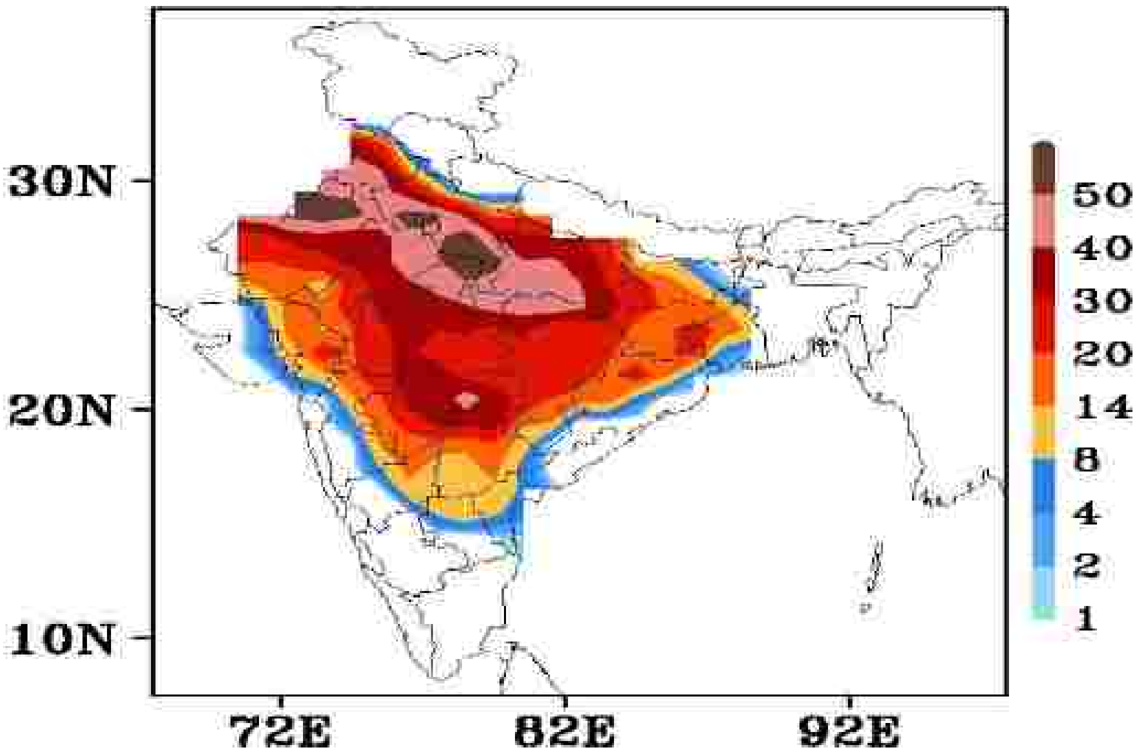

Figure 2: Spatial distributions of average number of days (per year) with maximum temperatures exceeding 40°C.

southern parts recording moderate high temperatures throughout the year whereas the northern parts exhibit low (high) temperatures during winter (pre-monsoon) (Jain et al. 2007). Apart, the coastal regions of peninsular India feature smaller temperature variations due to the influence of oceans. Because of the apparent movement of the Sun towards the north, the southern parts experience the hot weather season in March-April-May whereas the northern parts experience the hot season during April-May-June. It is observed that temperatures gradually rise from March onwards, reaching highest surface temperatures over large parts in May, although high temperatures continue over North India till June. In May, highest temperatures often exceeding 40 ^{0}C are observed over a wide area extending from northwest to central and south-central parts of India. The distribution of the number of days/year with temperatures exceeding 40 ^{0}C (Figure 2) broadly coincide with the region of maximum temperature, with the highest magnitude of ~40 days/year over the north-central parts. The summer season is characterized by a steady increase of temperatures due to increasing insolation in conjunction with the transition of Sun into the northern hemisphere from the spring equinox. Consequentially, temperatures gradually rise from south to north, reaching highest in May wherein the occurrence of thunderstorms is also higher (Normand 1921; Koteswaram and De 1959; Umakanth et al. 2021). The hot season ends around 1 June over Kerala (southernmost part of India) with the onset of monsoon rain and the temperatures gradually recede as the monsoon current advances northward around 1 July. As such, the temperatures may hover around 45 °C in mid-May over most parts of the northern plains, and sometimes exceed 45 °C in the northwest parts of India. Along the coastal regions, the temperatures vary around 36 ^{0}C, with east coast parts to be slightly warmer by a few degrees than the west coast and the coastal regions possess higher humidity than the inland parts. This description shows that the pre-monsoon (summer) season is the warmest over the largest part of South Asia, and the abnormal high temperatures during this season sometimes lead to heatwave conditions (Kothawale et al. 2010). A review of the literature shows that the studies on heat waves were initiated as far back as 1960s, although studies of temperatures over India were available ever since meteorological observations had been initiated in the last quarter of the 19th century.

Raghavan (1966) studied the time and spatial variations of temperatures using observations from all over India and reported that heat waves over India occur during March to June, with highest frequencies over north, northwest, central and the east coast parts of India. Ramamurthy (1972) performed a case study of the heat wave during 2-11 July, 1966 using temperature data from meteorological observatories during July, 1966 that corresponded with severe heat conditions over South as well as North parts of India. Normally, temperatures over the Indian subcontinent would reduce as the monsoon rains set-in all-over India by 1 July, but break monsoon conditions led to the occurrence of a severe heat wave over East peninsular India during the 1st week, later over North during the 2nd week of July, 1966. The author considered the IMD criterion of higher-than-normal maximum temperatures of 6-7 (>8) ^{0}C to define moderate (severe) heat wave. The analysis of maximum temperatures during July, 1966 have shown that maximum temperatures higher than normal by 10-12 ^{0}C have persisted for several days and with temperatures exceeding 40 ^{0}C at several stations. The authors have identified that the four periods of 3-5; 6-8; 9-11; 12-13 July had corresponded with (i) heat wave onset over East peninsula (South Coastal Andhra Pradesh, Telangana, East Vidarbha); (ii) shift of heat wave to Central parts covering Telangana, Marathwada, East parts of Madhya Maharashtra, Vidarbha and west parts of Madhya Pradesh; (iii) severest period of heat wave over West Madhya Pradesh and adjoining East Rajasthan and covering nearly two-thirds of India; and (iv) cessation of heat wave conditions respectively. The author confirmed that a heat wave of this magnitude and extent had not occurred in the prior 70 hears. An analysis of synoptic conditions revealed that the built-up of break monsoon conditions, which rarely manifest in July, had caused the occurrence of prolonged heat wave conditions for a continuous period of 10 days from 2-11 of July, 1966. This study is important as it emphasizes the impact of break monsoon conditions to trigger heat waves over India during the monsoon rainy season, although this type of heat wave conditions are unlikely as per the results of Raghavan (1966), which had indicated only 10% probability for heat waves to occur in July. Bedekar et al. (1974) provided a statistical analysis of the heat waves over India considering the temperature data from different meteorological observatories for the period 1911-1961. A month-wise frequency of heat waves for each of the political states of India had been estimated along with the mean monthly pressure and wind patterns. A case study of severe heat wave during 7-12 June, 1966 had been made and reported that increased lower tropospheric thickness and abnormal northwest winds were associated with the heat wave. Subbaramayya and Suryarao (1976) have analysed maximum temperature data from 170 stations in India to assess the characteristics of heat waves. The authors grouped all stations into 16 divisions and determined the occurrence of a heat wave over a division in terms of percentage that is based on the number of stations that have recorded higher than 100^0 F (~37.8 ^{0}C). The authors have reported that widespread heat wave conditions occur during April, May and June and that their frequency is higher over Madhya Pradesh, Rajasthan, Punjab and Telangana. The heat wave occurrences are noted to be higher in April and May, but reduce in June over southern parts of India due to rains associated with the onset of southwest monsoon. Ramachandran et al. (1988) studied the temperature data from 14 Meteorological observatories in Karnataka state for the period of 1964 - 1983 to identify the occurrence of heat waves over the Karnataka state. The occurrence of a heat wave or severe heat wave is considered when the temperature anomalies above the climate normal at a station is between 6-7 ^{0}C and >8 ^{0}C respectively. Their study revealed that highest number of 21 severe heat waves had occurred in Belgaum district; and highest (lowest) number of 95 (21) heat wave days in Bellary (Mysore) district. Further, the results have shown that larger part of the Karnataka state experiences heat waves till the onset of the monsoon and that the heat waves persist for the highest duration of 6-7 days in June. Poornachandra Rao and Prabhakar (1999) have made a case study of a heat wave that occurred over Andhra Pradesh during 19-26 May, 1980, using temperature and other meteorological variables data from several observation stations in Andhra Pradesh. The criterion of at least 8 ^{0}C above the normal temperature is considered to recognize a severe heat wave as per IMD definition. The authors have identified severe heat wave conditions to exist at the coastal stations of Kakinada on 19 May; at Machilipatnam on 20, 21, 23, 24 and 25 of May and during all the days of 19-26 May at Ongole. A synoptic analysis over the parts of South India during 19-26 May, had shown that the onset of sea breeze was either delayed or did not set in at the three coastal stations during the heat wave period, which was attributed to a low pressure area that moved from Karnataka and situated over central parts of coastal Andhra Pradesh during 17-26 May. This study had shown cessation of sea breeze to be one of the plausible reasons for the dryness and heat increase. Bhadram et al. (2005) have analysed temperature data of pre-monsoon months for the period 1901-2002 from the IMD observation stations in Andhra Pradesh. Their study had identified May and June to be the hottest months and also that the frequency and duration of heat wave spells had shown an increasing trend. The authors have computed some of the heat indices namely "Heat Index, Thom's Discomfort Index and Webbs Comfort Index" and reported that these indices reflect the severity of heat waves. Pai et.al (2013) have made a comprehensive study of the heat waves during Mar-July for the 50-year period 1961-2010 using temperature observations from 103 stations over the Indian subcontinent. Several aspects of the heat waves such as long term climatology, decadal variations and long term trends and teleconnections were studied. The authors have considered the definition of IMD for the identification of moderate and severe heat waves. The authors had reported that the average frequency of heat waves is 8 days, they occur mostly over North, Northwest; Central and Northeast peninsula, and with maximum occurrences during May and June. The authors have also notified that the duration of moderate heat wave spells varies from 10 to 15 days whereas severe heat wave spells have duration of ~7 days. Interestingly, one station (Nellore) from coastal Andhra Pradesh was identified to be most prone to heat waves in respect of both frequency and duration. Their analysis of the decadal variation of heat waves indicated that the areas with higher than 8 heat wave days was relatively higher during the two recent decades of 1919-2000 and 2001-2010 as compared to the previous three decades during 1961-1990; and also that the number of severe heat wave days had increased during 2001-2010 as compared to the prior four decades during 1961-2000. Their results notified that heat waves over North, Northwest, Central India, Tamil Nadu, and Andhra Pradesh had increasing trends whereas stations in Orissa, West Bengal, Punjab and Uttar Pradesh had shown decreasing trend. The authors' analysis of heat wave days in relation to ENSO (El Nino Southern Oscillation) events had indicated that the heat wave events have relatively increased during El Nino phase and more during El Nino +1 year whereas the heat wave days were noted to decrease during the La Nina +1 year. This study had not only estimated the heat waves over India, but also provided the linkage to Pacific Ocean temperature variations denoted by El Nino and La Nina.

Ratnam et al. (2016) studied the spatial occurrence of heat waves over India and their causation related to certain climate modes. The authors have analysed IMD daily gridded maximum temperature data for the period March-June for the years 1982-2013 to identify heat wave vulnerable regions. Analysis of empirical orthogonal functions indicated two dominant patterns, the first mode to correspond with the heat maximum over North and Central India and the second over East coast regions of India. In this study, heat waves were identified, considering anomalies of daily maximum temperatures and the IMD criterion, for the two representative box regions of North and Central India (71-80E, 21-30N) and East Coast region (79-83E, 15-19N). The results have shown the occurrence of 19 heat wave events over North and Central India with temperature anomalies higher than 3 ^{0}C in contrast to 13 events over East coast regions where the temperature anomalies were below 3 ^{0}C, and that the heat wave vulnerable regions coincide with the regions having larger standard deviation in the maximum temperature. The authors have attempted to understand the global teleconnections with respect to the two identified heat wave patterns. Their analysis have indicated that heat waves over North and Central India were caused by the presence of an anomalous anticyclone over India depicted in the 200 hPa stream function analysis that is related to a quasi-stationary wave train extending from Northwest Africa to the Indian subcontinent, which is triggered by an anomalous anticyclone blocking pattern over North Atlantic Ocean. Their results also indicated that the maximum temperature anomalies over India have occurred with a lag of 2 days to the geopotential anomalies over North Atlantic. Further, the authors conjectured that the East coast heat waves were related to anomalous cooling over the Pacific Ocean as the cooling generates two anomalous anticyclonic patterns at 200 hPa level over the West Pacific and as a result of Matsuno-Gill response extending to lower levels leading to two cyclonic cells at the 850 hPa level across the equator over the West Pacific. These cyclonic circulations generate anomalous anticyclone circulation at lower levels over South India, and as the westerlies on the northern side of the anticyclone transport moisture away from the east coast, and this anomalous transport of moisture lead to dry and hot conditions that trigger heat waves over Southeast coast India. The authors have made a case study of the heat wave during 21-31 May, 2015 over North India that caused more than 2000 human deaths and have shown that their hypothesis of anomalous anticyclone over North Atlantic that generated Rossby wave train pattern was responsible for anomalous northwest winds that advected dry air from northwest parts leading to the noted heat wave. This study had identified two types of heat waves, over North-central and East-coast India, and hypothesized two different teleconnection mechanisms emanating from North Atlantic Ocean and North Pacific Ocean that trigger the noted heat waves over Norht-central and East coast respectively.

Basha et al. (2017) studied the changes in surface temperature over India using 109 CMIP5 multi-model simulations generated for the 20th century climate to understand the role of greenhouse gases and land-use and analysed the 21st century CMIP5 future climate projections with different RCP emission scenarios to estimate future characteristics of heat waves. The CMIP5 simulated surface temperatures were validated by comparison with monthly gridded data from Climate Research Unit for the period 1901-2005 and with IMD daily gridded temperature data for the period 1969-2005, and reported good concurrence over major parts of India, except West Coast western Ghats, Northeast and Himalayan regions where the bias is larger, which is due to complexities in the inclusions of orography in numerical models. Analysis of the trends during the 20th century had shown higher warming over the central part of India as compared to other regions, and the observed warming is more conspicuous during summer. Their results have indicated that greenhouse gas emissions and land use distribution were responsible for the increase surface temperature over India in the present climate, with the warming rates as 0.14 ± 0.53 K and 0.06 ±0.02 K per century respectively. The study indicated that anthropogenic aerosols contribute to cooling, more due to indirect than of direct forcing. Further, the results have shown that the sudden increase in the temperature after 1960 were attributable to increase of greenhouse gases whereas the impact of land-use was more since 1980. Further the increase in trends in surface temperature due to greenhouse gases is noted to be higher over north and west parts of India. The results from CMIP5 multi-model simulations with RCP 8.5 of the current climate coincide with the observed variations in surface temperature; and analysis of CMIP5 future projections with RCP 8.5 scenario indicate rapid increase in warming, with corresponding rise of temperature of approximately 5 K by the end of 21st century. The climate projections from CMIP5 simulations also indicated increase of heat wave events through the 21st century. Interestingly, the results with RCP 2.6 emission scenario showed an increasing warming trend till 2050 and a decrease thereafter. This study is comprehensive, as it evaluated the CMIP5 simulations and confirming the concurrence of RCP8.5 scenario results with the current 20th century climate observations as they are important to understand and interpret the future climate projections.

Mishra et al. (2017) analysed the characteristics of heat waves over India during 1951-2015 using IMD gridded daily data of maximum temperatures and also projected future changes in the heat wave characteristics using CESM-CMIP5 projections up to 2100 considering the RCP 2.0 and 8.5 scenarios. The authors have used variable maximum temperature threshold, which are defined based on the 90th percentile centred on a 31-day window, in contrast to IMD definition where the thresholds are fixed and predefined. The authors have reported that most of the heat waves have occurred during May, and also a substantial increase in the frequency of heat waves during the period 1951-2015. Their results indicated that the most severe heat waves have occurred in 1998, 1995 and 2012 sequenced in terms of intensity. Their analysis also had indicated that the heat wave during 2015, which was characterized by high temperatures and high humidity, had caused higher human mortality. Their analysis using ensemble means have indicated that the frequency and duration of severe heat waves over India for the low emission scenarios of RCP 1.5 and RCP 2.0 will be substantially less than of RCP 8.5 during the mid and end of 21 century. The authors have also reported that the frequency of heat waves would have an eight-fold increase in the low warming scenario by 2021-2050 with respect to 1986-2015 and the same would rise by 30 times at 2100. Under the RCP 8.5 scenario the frequency of severe heat waves is expected to increase by 40 times at 2100.

Panda et al. (2017) made a comprehensive study of the spatial variability and trends of heat waves over the Indian subcontinent using IMD daily gridded maximum and minimum temperature data at 1 degree resolution. The authors have computed daytime and night time heat waves considering a centred 15-day time window representative of each day 90th percentile to determine thresholds of both the maximum and minimum temperatures and "excessive heat factor index" based on 3-

consecutive day temperatures. Heat wave characteristics were determined for the three time periods of 1951-2013, 1981-2013 and 1998-2013 representative of current global warming, rapid warming post 1980 and flat pause in global warming periods respectively. The authors' estimated the heat wave number, heat wave duration (days), heat wave frequency (days), heat wave amplitude (^{0}C, hottest day of the hottest event) and heat wave magnitude (^{0}C, average intensity of all heat wave events) considering daily maximum, minimum and mean temperatures for the entire year. Their results have indicated that during the period 1959-2013, the average number of heat wave days were highest of 8-10 over North and Central India; the daytime heat wave number, heat wave days and the heat wave duration had an increasing trend at the rates of 0.49 events, 2.9 days/decade and 0.53 days/decade respectively and with no significant trend in the night time heat wave days or duration. The authors have also reported significant rise in the anomalies of maximum, minimum and mean temperatures at a rate of 0.12, 0.04 and 0.08 ^{0}C/decade whereas heat wave amplitude had shown an increasing trend of 0.18 ^{0}C/decade during 1959-2013 with respect to the baseline period of 1961-1990. The authors have analysed heat waves during the period 1998-2013, which is considered as a pause in the global warming and reported that the trends were not significant. During the period of 1981-2013, the average heat wave number was 3.5-4.5 over most parts of India, whereas the trends in the frequency and duration of heat waves were not significant although increasing trend of two events per decade were noted over North India but due to slightly reduced trend of 0.15 ^{0}C over Central and South India. Interestingly, the study had reported increase of hottest nights during 1981-2013 with warming at 0.51 ^{0}C/decade that was mainly attributed to warming over North India. The authors had specifically analysed the heat waves in relation to droughts and reported that the severe heat wave conditions during 2003 and 2010 were due to the antecedent severe drought conditions in 2002 and 2009 respectively; and that the severe heat waves during 2013 and 2015 were noted to be due to reduced soil moisture and anomalous high temperatures during the preceding years of 2012 and 2014. This study, as the authors claim, is the first to emphasize the role of drought in the preceding year on the succeeding year heat waves.

Mazdiyasni et al. (2017) have studied the trends in the surface temperatures; frequency, severity and duration of heat waves during the summer season over India for the period 1960-2009 using IMD daily gridded temperature data. For the analysis, heat waves were identified considering the criteria that the temperatures above the 85th percentile of the hottest month existing for three or more consecutive days. Specifically, four different metrics (i.e.) the accumulated heat wave intensity, annual heat wave count, mean heat wave duration and heat wave days were considered. The results have shown that the summer mean temperatures have markedly increased all over India during 1960-2009; whereas the accumulated intensity, number of heat waves, heat wave duration and heat wave days have increased over the Northern, Western and Southern parts of India. Further, their results indicated that the heat wave events had increased by 50%, and correspondingly the heat wave days and duration have increased by 25% during 1985-2009 than of 1960-1984, implying that the heat waves had substantially increased during the later 25-year period (1985-2009) than of 1960-1984. The study had also indicated an increase of heat related mortality during the study period i.e., 1960-2009.

Dodla et al. (2017) studied the heat wave that occurred over Andhra Pradesh (AP), India during May, 2005, which was the cause of ~2500 human deaths. The meteorological data from four sources: IMD daily gridded temperature data, IMD AWS (Automatic Weather Station) surface meteorological data, ECMWF ERA (European Centre for Medium-Range Weather Forecasts - European Reanalysis) and NCEP GFS (National Centers for Environmental Prediction Global Forecast System) global analysis were used for analysis and evaluation of model simulation. The authors have considered the IMD criterion for the identification of the heat waves. An analysis of maximum temperatures had shown the occurrence of severe heat wave conditions over Andhra Pradesh during 23 - 26 May, 2005 during which period, temperature anomalies of 6-7 ^{0}C prevailed for 4 consecutive days. During this period, high temperatures of 42-45 ^{0}C were noted on 20th, increased to 46-48 ^{0}C on 22nd and >44 ^{0}C during 23-26 May over AP and Telangana. The authors analysis of synoptic conditions had indicated anomalous westerly flow over North Africa and Middle East starting around 16 May that accentuated the northwest flow advecting heat from Northwest India to Central and Southeast India triggering the heat wave conditions over Andhra Pradesh and Telangana. The authors had observed heat convergence that led to heat accumulation of heat over Andhra Pradesh, and hypothesized that the sea breeze along the coastal regions contributed to the converging of heat air advection from Northwest over coastal regions of Andhra Pradesh. The authors had attempted to predict the heat wave conditions using WRF (Weather Research and Forecasting) model and reported that model prediction was good with a lead time of 72 hours. The authors have established the origin of heat waves over Southeast India to be due to anomalous westerly flow from North Africa to Northwest India and anomalous Northwest flow that advect warm air from Northwest to Southeast parts and heat flux convergence along the coastline supported by sea breeze circulation.

Joseph et al. (2018) have attempted to develop a new criterion to identify the occurrence of heat wave episodes from observational data and assess extended range predictability of the heat waves on time scale of two weeks using a multi-model ensemble prediction system. The ensemble prediction method uses 44 members generated from 4 variants of NCEP-CFSV2 (Climate Forecast System Version2) model. The authors have identified the occurrence of heat waves using a criteria slightly modified to that of IMD wherein 90th, 95th and 99th percentiles of the maximum temperature were considered to designate heat waves and severe heat waves. The CFSV2 model derived temperature have been subjected to bias correction considering the observation for the period 1960-2010 and the bias corrected temperatures were validated. The authors' analysis of heat waves during 1981-2015 has shown that Northwest, Central and Southeast parts of India, which are the three regions of higher heat wave, had an average of six heat wave days per year. In terms of prediction, the authors have indicated that the ensemble prediction skill of hot days has 70% probability up to 20 days. The authors have used anomaly correlation coefficient of maximum and minimum temperatures up to 4 pentads (20 days) and indicated that the probability of prediction is 70, 30 and 50 % for hot, heat wave and severe heat wave categories and that the prediction skill is higher over Northwest and Southeast parts of India where heat wave occurrences are higher. This study is important as the predictability of the heat waves up to 20 days using multi-model ensemble system is conclusively established, which would help implement heat wave alleviation measures.

Ross et al. (2018) analysed the IMD gridded daily maximum, minimum and mean temperature data over India during the period 1951-2013 to identify trends during the pre-monsoon, southwest monsoon and post-monsoon seasons. The authors had reported that a gradual increase in the magnitude of temperatures on a decadal time-scale from 1950-2010 during the pre-monsoon period of April and May, with the temperatures to be of ~ 40 ^{0}C during 1950 that escalated to 42 ^{0}C by 2010.Their results indicated two regions of highest temperature, over northwest and south India and a cooling pattern over northeast India extending towards central parts. The authors have identified the warming over northwest and southern parts of India to be associated with the global warming in the current industrialization period whereas the cooling over northeast India are conclusively shown to be due to the increase of aerosols as notified by the aerosol optical depth data. These results are significant as they brought forth contrasting warming and cooling regions within the Indian subcontinent during the summer months with supporting validation from model experiments.

Oldenborgh et al. (2018) studied the heat waves of 2015 that advect warm air and 2016 over India considering the record high temperatures over Northwest India. The authors considered the occurrence of highest daily maximum temperatures of the year as the criterion of the heat wave on the premise that this definition would better represent as a continuous measure and the severity of the heat wave as required for their extreme value statistics, which contrasts with the definition of IMD. In their analysis, the authors have assessed the influence of three factors, namely the decadal variability, aerosol trends and atmospheric humidity variations on the occurrence of heat waves. The authors' analysis of ERA-Interim daily maximum temperature data for 2016 had shown record highest temperatures between 45-50 ^{0}C and the wet-bulb temperatures higher than 30 ^{0}C on 19th May 2016 over Rajasthan in Northwest India that indicate severe heat stress resulting from the combined effect of temperature and humidity. Further, analysis of the heat wave over Southeast India in 2015 had shown the wet bulb temperatures to be higher but not as much of the 2016 heat wave over Northwest India. The authors' analyses have indicated a clear increasing trend in the annual mean temperatures but not a significant trend in the daily maximum temperatures. The authors have reported that El Nino 3.4 index is an important mode that contributes to 25% of the temperature variance. Apart, the pacific decadal oscillation is noted to influence the higher temperatures along the Indian coastal regions, which implies the indirect effect of El Nino. The results of this study also have conclusively shown that increase in aerosols from air pollution over India had contributed to reduction in maximum temperatures because of decrease in insolation at the surface. This finding connects to the observed cooling trend over East-central India, which is distinctively different from the increasing trends over Northwest, West-central and Southeast parts of India (Ross et al., 2018). The authors have also reported that depleted soil moisture in the preceding rainy season have contributed to higher temperatures over Northwest India during 2016. Contrastingly, increased irrigation causes higher humidity in the atmosphere, which would exacerbate the heat wave stress. This study is important as it identified the causes of heatwaves in relation to El Nino index, and the cooling over east-central parts to be due to aerosol loading.

Mandal et al. (2019) have attempted to establish a possible criterion for the detection of heat waves, using IMD daily gridded maximum temperature data over Indian sub-continent, which could be applicable for characterization of heat waves using numerical models. The authors have used the criterion to determine the occurrence of a heat wave when one of the four specified conditions were satisfied, which are: when the maximum temperature exceeds the climatological 95th percentile computed using data of March-June for the period of 1981-2010, or it exceeds 36 ^{0}C, or its departure from normal is above 3.5 ^{0}C, or its absolute value is higher than 44 ^{0}C. The threshold of 36 ^{0}C was chosen considering the spatial distribution of climatological 95th percentile generated using the data for 1981-2010. The authors first analysed the spatial distribution of maximum temperatures and identified the heat wave prone regions to be over Northwest and Southeast, where higher than 4 heat waves during March-April and May had been recorded. Further, area averaged values of maximum temperatures over Northwest and Southeast regions were considered to detect the heat wave spells over the respective regions. The authors have used hindcast predictions for the period from 2003-2017 using CFSv2 based MME (Multi-Model Ensemble) prediction system developed at Indian Institute of Tropical Meteorology and operationally run at the India Meteorological Department. The authors have reported that anomaly correlation coefficient have indicated remarkable prediction skill with 70% probability up to two weeks lead time. Their results have indicated that the ensemble prediction overestimates the heat waves over Southeast as compared to Northwest regions. Further, the results have shown consistent predictability of heat wave events that extend from Northwest to Southeast.

Satyanarayana and Bhaskar Rao (2020) studied the characterization of heat waves over India during 1951-2015 using IMD daily gridded surface maximum temperature data. An analysis of the spatial distribution of mean surface maximum temperature data and the number of days with temperatures exceeding 42^{0}C had shown (Figure 3) three distinct regions of maximum: over West Rajasthan, Northwest Madhya Pradesh and Southwest Uttar Pradesh, and East Maharashtra (Vidarbha). This study exhibited the regions extending from northwest to north central and to southcentral parts of India are the hottest as compared to rest of the Indian subcontinent during the period from March to May. Synoptic analysis had shown that the wind flow pattern over South Asia reveal the westerly/ southwesterly wind flow from Middle East brings-in hot air into the Indian subcontinent through northwest desert parts, which records the highest temperatures during pre-monsoon (summer) season, and that the northwest winds advect heat from the Northwest to the Central parts of India (Figure 4). Further, heat wave occurrences were identified using the IMD criterion for the Indian subcontinent barring the highland regions for the 65-year period of 1951-2015. This analysis had revealed three distinct heat wave vulnerable regions, one covering parts of North Rajasthan, Punjab and Haryana, one covering parts of Bihar and Jharkhand and another covering Andhra Pradesh (AP) and Telangana (Figure 5). Interestingly, these 3 heat wave vulnerability regions are markedly different from the three identified maximum temperature zones. Principal component analysis of the maximum temperatures for the study period had yielded three modes, with highest variance over North India, followed by Southeast India and Northeast India that corresponded with the three identified heatwave zones. Though seems paradoxical, this study is the first to demarcate the regions of maximum temperature and heat waves based on established statistical methods. Further analysis to understand the causation of heat waves, had shown that anomalous southwesterly, westerly/northwesterly and north-westerly wind flow from the high temperature regions of West Rajasthan, Northwest Madhya Pradesh, Southwest Uttar Pradesh, and East Maharashtra contribute to the onset of heat waves over North, Northeast and Southeast parts of India respectively. The authors have provided an account of the heat wave days during 1951-2015 with respect to the three identified heat wave vulnerable regions, which disclosed that the number (days) of heat waves were 34 (182 days) over Northeast; 31 (165 days) over North; and are 21 (111 days) over Southeast parts of India (Table 1). The authors reported an important notification that the occurrence of heat waves over South India have been noticed since 1970 only, which is attributed to the current global warming trends and complements the result by Ross et al. (2018). The authors had also analysed surface temperature data from four different CMIP5 model simulations and reported that all the simulations yielded three regions of maximum temperature that coincide with the authors identified zones of maximum temperature. This study thus validates the CMIP5 simulations for the Indian subcontinent, as temperature is the prime climate variable that results from several physical processes of radiation, surface processes and boundary layer. This recent study brought out an important result, hitherto not reported, that the heat wave vulnerability zones are distinctly different from the zones of maximum temperatures and that hot air advection from a particular cause heat waves over a particular region due to downwind hot air advection.

Naveena et al. (2020) studied IMD daily gridded temperature data for 1951-2019 and other related data sets to characterize a "hot blob" region over Vidarbha (East Maharashtra) during the pre-monsoon (summer) season. Their results have indicated that highest temperatures with highest frequency of hot days occur over Vidarbha and Telangana, which is contrary to the general notion of Rajasthan over Northwest parts to be the hottest region due to its desert soil conditions. This result was confirmed by Principal Component Analysis which had shown two distinct modes over Northwest and Southeast India. Analysis of synoptic conditions have shown that the existence of a "COL" region embedded between two high pressure circulations situated over the Arabian Sea and Bay of Bengal was attributed to the divergence (sinking motion) and accumulation of heat over Vidarbha and neighbourhood. An analysis of CMIP5 model climate data for the corresponding period confirmed the "hot blob" over the Vidarbha coincident with the results from analysis of IMD gridded temperature data. This research is important for its identification of a region of highest

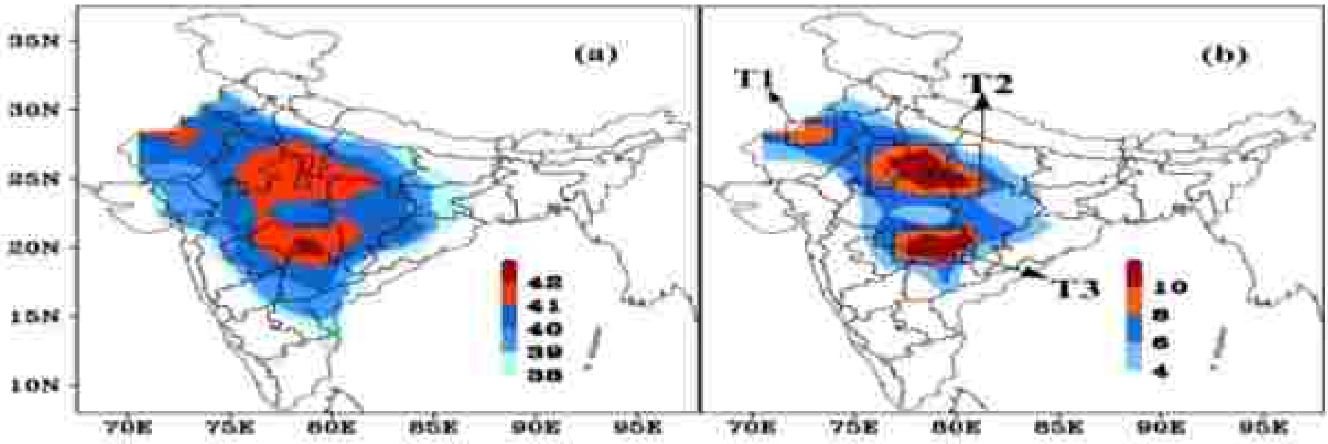

Figure 3: Spatial distributions of (a) mean maximum temperatures (^{0}C) and (b) average number of days with maximum temperatures exceeding 42°C for May. Maximum temperature zones are marked as boxes and labelled in (b).

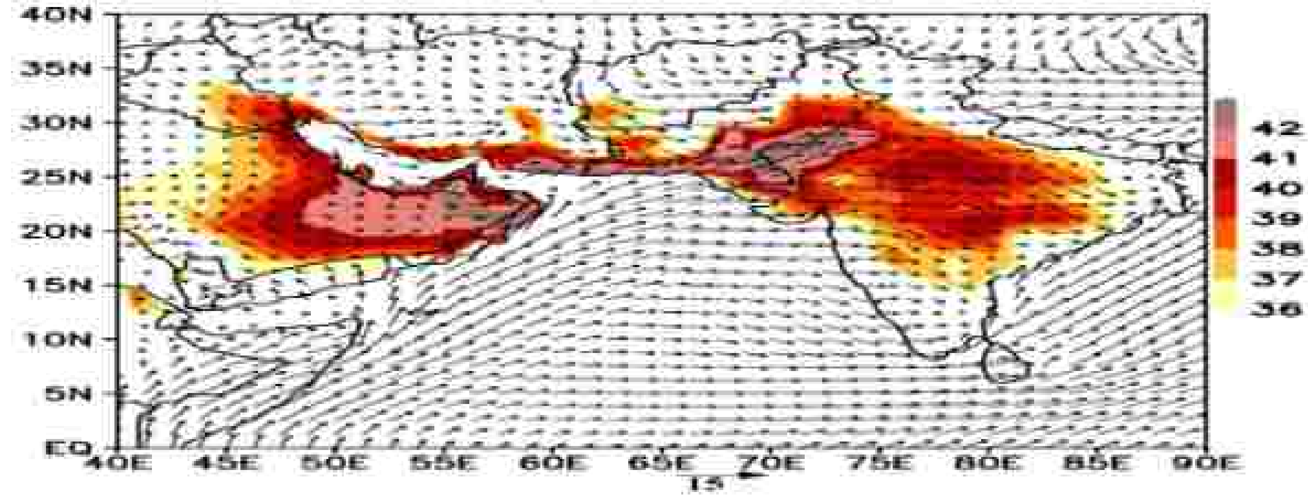

Figure 4: Mean 10-m level wind flow (vectors) and 2-m level air temperatures (^{0}C, shaded) corresponding to 0900 UTC for May. (Wind vector length denote wind speed at 1cm equal to 15m/sec).

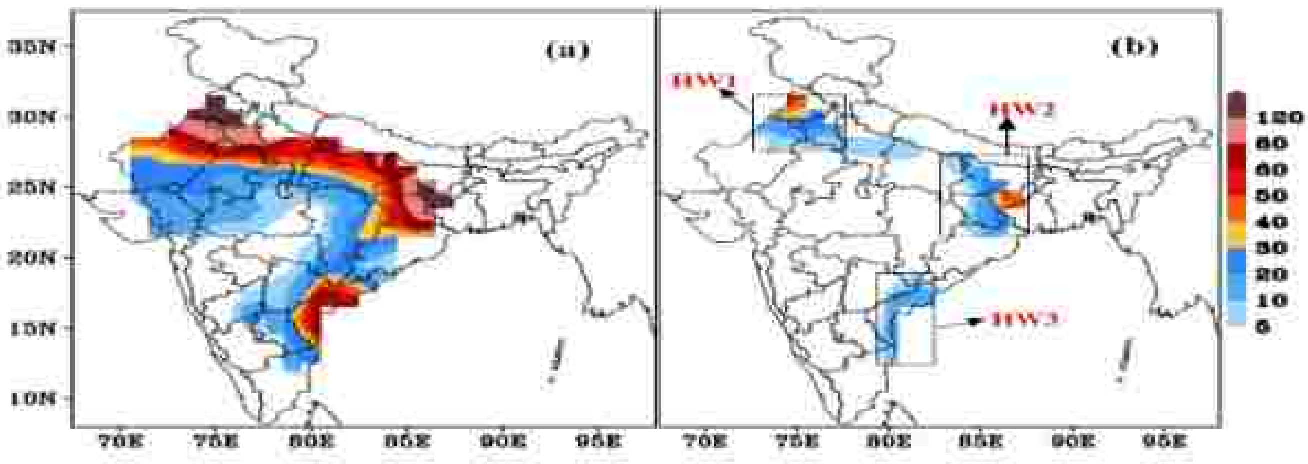

Figure 5: Spatial distributions of the number of days with mean temperatures ≥ 40°C (>37°C) for plains (coastal zones)and anomalies (a) above 4°C and (b) above 5°C days during May as accumulated for the period from 1951 to 2015. Heat wave zones are marked as boxes and labelled in (b).

Table 1. Number of heat waves and heat wave days during May over North, Northeast and Southeast zones of maximum temperature for each year during 1951-2015. Heat waves are identified based on IMD nomenclature. Heat wave days are shown in parenthesis.

Year	North	Northeast	Southeast	Year	North	Northeast	Southeast
1951	0	2(9)	0	1986	0	0	
1952	0	0	0	1987	0	1(4)	0
1955	0	0	0	1988	2(11)	2(18)	0
1956	1(11)	1(3)	0	1989	0	1(4)	0
1957	0	1(6)	0	1991	0	0	0
1958	0	1(11)	0	1992	0	0	0
1959	0	2(12)	0	1993	1(8)	1(4)	0
1960	0	2(11)	0	1994	2(7)	0	1(6)
1961	0	1(3)	0	1995	1(3)	2(14)	0
1962	0	1(3)	0	1996	0	0	1(8)
1964	0	0	0	1997	0	0	0
1965	0	0	0	1998	1(7)	1(5)	1(6)
1966	2 (9)	0	0	1999	1(5)	0	0
1967	0	0	0	2000	0	0	1(3)
1968	0	1(7)	0	2001	2(7)	0	1(4)
1969	0	0	0	2002	1(6)	0	1(5)
1970	1(11)	2(10)	1(5)	2003	0	1(3)	2(12)
1972	0	2(14)	0	2004	2(7)	0	0
1973	2(9)	1(4)	2(7)	2006	1(4)	0	0
1974	0	1(3)	0	2007	0	0	1(3)
1975	1(4)	2(8)	1(4)	2008	1(4)	0	1(4)
1976	0	0	1(6)	2009	1(6)	0	0
1978	2(13)	1(4)	1(6)	2010	1(6)	1(5)	0
1979	0	0	0	2011	1(5)	0	0
1980	2(6)	1(5)	1(9)	2012	0	1(3)	0
1981	0	0	0	2013	1(8)	0	1(5)
1984	1(8)	1(8)	1(4)	2014	0	0	0
1985	0	0	1(6)	2015	0	0	1(8)
Total no. of heat waves (no. of heat wave days)					**31(165)**	**34(182)**	**21(111)**

maximum temperatures (hot blob) over Southcentral parts of India, which may be triggering of heat waves over Southeast regions.

Naveena et al. (2021a), from the analysis of maximum temperatures during the period 1951-2019, reported that the maximum temperatures are the highest during May that mostly prevail over Central India whereas temperatures below 30 ^{0}C are noted over Jammu and Kashmir of North India; West coast hilly region, and over Assam, Meghalaya and Nagaland of Northeast India. Their analysis of trends revealed that temperatures have the highest increasing trend of 1.28 ^{0}C over Jammu and Kashmir and South peninsula (which are relatively cooler during the summer season); and decreasing trends over East-central India, agreeing with Ross et al. (2018). The higher increasing trend over South peninsula makes it heat wave prone in the next decades as temperature would exceed 38 ^{0}C. Naveena et al. (2021b) studied the variations in maximum temperatures over India in relation to El Nino using IMD daily gridded temperature data for the period 1951-2015. Their results indicated that the intensity and frequency of heat waves is more during the 1-year succeeding the El Nino than during El Nino and the 1-year preceding El Nino over North and Southeast parts whereas there is no trend observed over Northeast. The authors, from, the analysis of synoptic conditions, reported that anomalous westerlies are observed to prevail over Northwest India during El Nino +1 year leading to heat waves and that the decreased soil moisture was also a factor to exacerbate the heat wave conditions. This study provided a possible linkage of heat waves over India to climate mode teleconnections, especially the El Nino phenomenon.

5. Disaster Management in India

Government of India, recognising the soaring human deaths due to heat waves in recent decades and other societal impacts, coordinated three agencies namely the National Disaster Management Authority (NDMA), India Meteorological Department (IMD) and National Resources Defense Council (NRDC), to prepare a "Heat Action Plan" specific for a city that would help mitigate heat wave consequences. These agencies have come out with a "Heat Action Plan" that comprises of early-warning systems from IMD, structured as color-coded temperature alerts, initiating community outreach programs, and establishing capacity-building networks among government and health professionals (Padmanabhan, 2021). As the plan would be tailor-made for a specific location, the local municipal authority will be responsible to implement the heat action plan on the ground akin to tropical cyclone advisories. This plan will clearly specify the role and responsibility of various departments to act upon the heat wave alerts and to implement the action plan. The heat action plan was first designed and implemented for the city of Ahmedabad, Gujarat in 2013 as a testbed and finding it successful, plan for Nagpur city in Maharashtra is underway.

6. Summary

This paper presents a review of the scientific progress in the understanding and prediction of heat waves over India. Humanity and all species of life thrive on energy received from Sun as radiation, which manifests as heat that is measured as temperature. For this reason, tropical regions where highest temperatures are recorded, which receive greater insolation, are more vulnerable to heat waves whereas the polar regions are more vulnerable to extreme cold. Confining our focus on heat waves alone, extreme hot weather (temperatures) are known to impact human life in several ways notably to cause health problems sometimes leading to death. Normally nature protects life through adaptation, which is the reason why human susceptibility differs from place to place and which is also the reason for differences in the identification of heat wave vulnerability as noted in the introduction. This review confines to the heat waves over India alone and so the gradual development of scientific understanding of heat waves is presented chronologically and also as groups related to investigations based on location based temperature observations; studies using global and Indian-region gridded analysis; and those related to climate mode teleconnection mechanisms.

Studies on heat waves have been initiated since 1960s as temperature data from observatories have become available for a considerable period. First attempts were made for specific regions such as Andhra Pradesh, Karnataka, Gujarat etc. as case studies and later for North and South India and entire India as the observations increased spatially and temporally. While most of the studies reported maximum temperatures to be over North India and during May, one study analysed the severe heat of July, 1966 that existed for ~10 days and extended at least over 60% of India, which was shown to result from an unusual prolonged break monsoon conditions. As such, the earlier studies could bring forth the salient features over India with respect to the regions of occurrence and duration of the heat waves and it is possible that the analysis could not be exhaustive due to the sparsity of data.

Ever since global reanalysis data, from different sources such as NCEP-RA, ERA, JRA that include temperature and other atmospheric variables at four cardinal time points daily for periods from 1950 onwards, and IMD daily gridded temperature data since 1951 have become available, investigations on the characterisation of heat waves over India had increased. As the review elaborated in one of the previous sections, heat wave studies conclusively identified the heat wave vulnerability in terms of the area, frequency and intensity. All of the studies have confirmed the heat wave prone regions, based on the anomalies of maximum temperature (mostly as per the IMD criterion and few using percentile method) to be over North, Northwest and South-central parts of India and also that the heat wave frequency and intensity show increasing tendency. One study brought out a decisive result that there exist three regions of maximum temperature and three heat wave vulnerability, which are distinctly different and that the advection of heat by anomalous winds directed from the regions of maximum temperature triggers heat waves over the downwind regions. This result is an important revelation, which modifies the general notion of maximum temperature regions are also the heat wave vulnerable regions, that would be imperative in the formulation and planning disaster mitigation. Two studies have shown conclusive evidence of cooling over East-central parts, which were attributed to aerosol loading that effects to reduced insolation. One study has shown the role of global scale climate mode teleconnections on the heat waves over India, with the inference that atmospheric teleconnections emanating due to anomalous blocking high pressure region over North Atlantic Ocean and anomalous Pacific Ocean cooling are responsible for triggering heat waves over North India and Southeast coast India regions respectively. Other studies have shown heat waves to be impacted by El Nino and La Nina conditions over Pacific Ocean in the preceding year indirectly through causing drought and dry soil conditions over Indian subcontinent. Another important finding is the existence of a zone of maximum temperature over Vidarbha (East Madhya Pradesh) that would cause heat wave conditions over East Coast India under favourable wind flow conditions. This review presents the current status of the understanding and prediction of heat waves over India. Needless to say, the availability of daily gridded temperature data for the Indian subcontinent from 1951 onwards from the India Meteorological Department had led to many important research findings during the last 2 decades. This review also brings forth the necessity of further research on the quantification of the heat wave duration and intensity in the current climate along with their transformation in future climate at least till 2100. A probability based quantification will help the administrators, planners and the social communities to have realistic perception of the vulnerability and disaster management. Thus, a brief narration of the "Heat Action Plan" initiated by the Government of India is provided as part of this review.

References

Basha, G., Kishore, P., Ratnam, M.V., Jayaraman, A., Kouchak, A. A., Ouarda, T.B., Velicogna, I., 2017, "Historical and Projected Surface Temperature over India during the 20th and 21st century", Sci. Rep. 7, 2987.

Bedekar, V.C., Dekate M.V., and Banerjee, A.K., 1974, Heat and cold waves in India", Forecasting Manual-Part-IV-6, India Meteorological Department.

Bhadram, C. V. V., B. V. S. Amatya, G. B. Pant, and K. Krishna Kumar, 2005, "Heat waves over Andhra Pradesh: A case study of summer 2003", MAUSAM, 56, 2, 385-394.

Dodla, V. B., Satyanarayana, G. C., Desamsetti, S., 2017,"Analysis and prediction of a catastrophic

Indian coastal HW of 2015", Natural Hazards, 87, 395–414, https://doi.org/10.1007/s11069-017-2769-7.

Hsiang, Solomon; Burke, Marshall; Miguel, Edward., 2015, "Climate and Conflict". Annual Review of Economics. 7 (1): 577–617. doi:10.1146/annurev-economics-080614-115430. S2CID 17657019.

Jain, S. K, Agarwal PK, Singh V.P., 2007, "Physical Environment of India", In. Hydrology and Water Resources of India. Water Science and Technology Library, vol 57. Springer, Dordrecht. https://doi.org/10.1007/1-4020-5180-8_1.

Joseph, S. R., Mandal, A. K. Sahai, R. Phani, A. Dey and R. Chattopadhyay., 2018, "Diagnostics and Real-Time Extended Range Prediction of Heat Waves over India", Indian Institute of Tropical Meteorology (India), Research Report No. RR-141, https://www.tropmet.res.in/~lip/Publication/RR-pdf/RR-141.pdf.

Koteswaram P and De A C., 1959, "Study of pre-monsoon thunderstorms over GWB by radar", Indian J. Meteorol. Geophys. 10 275–282.

Kothawale, D. R., Revadekar, J. V. & Rupa Kumar, K., 2010, "Recent trends in pre-monsoon daily temperature extremes over India", J. Earth Syst. Sci.119, 51-65. doi:10.1007/s12040-010-0008-7.

Mandal R, Joseph S, Sahai AK, Phani R, Dey A, Chattopadhyay R, Pattanaik D. R., 2019, "Real time extended range prediction of heat waves over India", Sci Rep. 21;9(1):9008. doi: 10.1038/s41598-019-45430-6.

Mazdiyasni, O., AghaKouchak, A., Davis, S. J., Madadgar, S., Mehran, A., Ragno, E., Sadegh, M., Sengupta, A., Ghosh, S., Dhanya, C. T., &Niknejad, M.,2017, "Increasing probability of mortality during Indian heat waves", Science Advances, 3(6), e1700066. https://www.science.org/doi/10.1126/sciadv.1700066.

McGregor, G. R., Bessemoulin P, Ebi K. L., Menne, B., 2015," Heatwaves and health: guidance on warning-system development", World Meteorological Organization, http://www.who.int/globalchange/publications/WMO_WHO_Heat_Health_Guidance_2015.pdf.

Mishra, Vimal, Sourav Mukherjee, Rohini Kumar, D. A., 2017, "Stone Vimal, Heat wave exposure in India in current, 1.5^{0}C, and 2.0^{0}C worlds", Environ. Res. Lett., 12, 124012. https://doi.org/10.1088/1748-9326/aa9388.

Naveena N, Satyanarayana G. Ch, Dharma Raju, A, Sivasankara Rao, K., and Umakanth, N., 2021a,"Spatial and statistical characteristics of heat waves impacting India", AIMS Environ. Sci. 8(2) 117–134, https://doi.org/10.3934/environsci.2021009.

Naveena, N, Satyanarayana G. C, Rao D.V.B, et al., 2020," An accentuated "hot blob" over Vidarbha, India", during the pre-monsoon season. Nat Hazards. 105: 1359–1373.

Naveena, N., Satyanarayana, G.C., Rao, K.K. et al.,2021b,"Heat wave characteristics over India during ENSO events",J Earth Syst Sci130, 166. https://doi.org/10.1007/s12040-021-01674-3.

Normand C. W. B., 1921,"Wet-bulb temperature and thermodynamics of air; India" Meteorological Memoirs, 23, Part I.

Oldenborgh, Geert Jan van, Sjoukje Philip, Sarah Kew, Michiel van Weele, Peter Uhe, Friederike Otto, Roop Singh, Indrani Pai, Heidi Cullen, and Krishna AchutaRao., 2018,"Extreme heat in India and anthropogenic climate change". Nat. Hazards Earth Syst. Sci., 18, 365–381. https://doi.org/10.5194/nhess-18-365-2018.

Padmanaban, D., 2021, Specifically tailored action plans combat heat waves in India, Eos, 102, https://doi.org/10.1029/2021EO161871.

Pai, D. S., Smitha, A. & Ramanathan, A. N., 2013, " Long term climatology and trends of heat waves over India during the recent 50 years (1961–2010)". Mausam, 64(4), 585–604.

Panda, D. K, AghaKouchak, A., and Ambast, S, K., 2017, "Increasing heat waves and warm spells in India, observed from a multiaspect framework", J. Geophys. Res. Atmos., 122,3837–3858, doi:10.1002/2016JD026292.

Poornachandra Rao, C. and Prabhakar, M. S. S., 1999,"A study of the severe heat wave of May 1980 in coastal Andhra Pradesh", Mausam, 50, 3, 304-305.

Raghavan, K., 1966. "A climatological study of severe heat waves in India", Indian J. of Meteorol. Geophys, 17, 581-588.

Ramachandra, V. S., Nagaraj, S. T., and Rajegowda M. B., 1988," A climatological study of heat and cold waves in Karnataka State", Mausam, 39, 1, 71-74.

Ramamurthy, K., 1972,"Case study of a heat wave during July 1966", Indian Journal of Meteorology and Geophysics, 23,2,165-172.

Ratnam, J. V., Behera, S. K., Ratna, S. B., Rajeevan, M. & Yamagata, T., 2016,"Anatomy of Indian heatwaves", Sci. Rep. 6, 24395, https://doi.org/10.1038/srep24395.

Ross, R.S., Krishnamurti, T. N., Sandeep Pattnaik and Pai, D. S., 2018,"Decadal surface temperature trends in India based on a new high resolution data set", Scientific Reports, 2018, 8:7452, DOI:10.1038/s41598-018-25347-2.

Russo, S., Jana Sillmann and Erich M Fischer., 2015, "Top ten European heatwaves since 1950 and their occurrence in the coming decades", Environmental Research Letters, Volume 10, Number 12, https://doi.org/10.1088/1748-9326/10/12/124003.

Satyanarayana G. C., Bhaskar Rao, D. V., 2020,"Phenology of heat waves over India". Atmos Res. https://doi.org/10.1016/j.atmosres.2020.105078.

Srivastava, A. K., Rajeevan, M. & Kshirsagar, S. R., 2009,"Development of a high resolution daily gridded temperature data set (1969-2005) for the Indian region",Atmos. Sci. Let. 10, 249-254, doi:10.1002/asl.232.

Subbaramayya, I. and D. A., Surya Rao., 1976,"Heat and cold wave days in different states of India", Indian Journal of Meteorology Hydrology and Geophysics, 27, 4, 436-440.

Umakanth, N., Satyanarayana, G.C., Naveena, N., Bhaska Rao, D. V., Srinivas, D., 2021"Statistical and dynamical based thunderstorm prediction over southeast India", J Earth Syst Sci 130, 71, https://doi.org/10.1007/s12040-021-01561-x.

Zhao Qi, Yuming Guo, Tingting Ye et al., 2021,"Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study", The Lancet Planetary Health, Volume 5, Issue 7,Pages e415-e425.https://doi.org/10.1016/S2542-5196(21)00081-4.