Future Heat Wave Projections and Impacts

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Abstract Heat waves are a special class of climatic hazards that have a disastrous impact on many different systems. In the recent past, there has been a considerable improvement in scientific understanding of heat waves; however, most of this understanding is limited to the climatology of developed countries. There is a limited systematic understanding of heat waves and their impact on developing countries including India. This chapter reviews studies in establishing plausible links between climate variations, climate change and the heat waves, particularly in the context of India. The chapter also tries to understand the mechanisms responsible for the occurrence of heat waves. Further, the chapter shows evidence from studies that use climate models with statistical techniques for more accurate characterization of heat extremes and improving projections. Heat waves in India are expected to be intense, more frequent, and to be of longer duration in future due to global warming. This possibility will make the population more vulnerable to the impact of heat waves. The consequence of future heat waves might be severe; therefore, there is an urgent need to prepare a strategy to deal with its likelihood consequences. This is important in the context because the current policy does not consider heat waves as a serious hazard. The content of this chapter aims to provide the general public, policy makers and planners with the kind of effectual information which would enable them to understand and deal with the heat waves as a natural disaster.

Keywords India · Heat waves · Climate variability · Climate change · Hazards Climate models · Climate extremes · Natural disaster

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1 Introduction

One of the most worrisome aspects of global warming is that as the earth becomes warmer overall, other facets of its climate patterns will also change. Extremes may rise everywhere. This is one of the reasons that climatic extremes have received a special attention by the scientific community. The recent Intergovernmental Panel on Climate Change (IPCC) assessment report also stresses upon the observed evidence of increase in climatic extremes and their impacts (Field et al. 2014).

Extreme temperatures are already having impacts on human health (Patz et al. 2005), agriculture (Lobell et al. 2012), forest and ecosystems (Teuling et al. 2010). The projections of increased intensity, duration and frequency also point to a serious concern for ecosystem and society (Field et al. 2014). However, assessment of the impact of extreme temperature on the socio-economic system is not straightforward because of the influence of other stresses such as social deprivation, disease and conflict (Easterling et al. 2000). The future changes in temperature extremes associated with human-induced warming may put some additional challenges by affecting both society and ecosystem (Stott et al. 2004).

All of these will have severe ecological, socio-economic and physical repercussions. It is essential, therefore, to focus on climate extremes such as heat waves and invest in understanding and preparing for them. This requires an understanding of characteristics of extreme temperature episodes, in the past as well as future, to develop a knowledge base about the future course of action. As things stand, however, even as the scientific understanding of human-induced climatic change grows, significant gaps yawn in the scientific understanding of climate extremes. This is largely due to the fact that warming is a global phenomenon, whereas extremes are local ones.

There are several methods of projection global and regional temperatures. General circulation models (GCMs), popularly referred as global climate models, is one such tool to project global and regional temperatures. On the global scale, these are all quite effective for the purposes that they are used, but not for monitoring or understanding localized climate patterns, especially extremes. Statistical methods and other data mining-based approaches would be more effective in this context. However, such methods are applied in the limited sense partially due to lack of availability of appropriate observed data at required spatial scale. Despite significant progress made in recent years, however, our ability to establish credible links between climate variations, climate change and climate extremes is still not robust enough. A great deal of work needs to be done to generate predictive insights and address the knowledge gaps.

There is no doubt that future pattern of heat waves might result in devastating impacts; the poor and vulnerable will be the most impacted (Mazdiyasni et al. 2017). Undoubtedly, India is more vulnerable to the impacts of heat waves, the rationale for this assertion is that it has a large proportion of the population which is poor and has no access to basic amenities such as water, electricity and primary health facility. In addition, a large proportion of population already live in areas where summer is much warmer. What do we know about the past patterns of heat waves? How do we measure them? How will heat waves be changed in the warming world? These are some of the key questions that are centred on the current scientific debate on the issues of climate variability and climate change. This chapter provides an overview of the current scientific literature on the subject and attempts to seek the answers to these questions. This chapter also reviews India-specific studies that utilized more accurate characterization of climate extremes and improving projections by a comprehensive assessment of uncertainties.

In the chapter, first two to six sections are themed around: understanding extreme temperature and heat waves; relevance of heat waves as a climatic hazard, and heat wave as a climatic hazard in the Indian context and their projection using climatic models. By the end of this chapter, the reader is expected to have a clear understanding of how heat waves are distinctive with respect to the other climatic hazards. There are, of course, gaps and limitations in the literature, which, if filled, would provide a comprehensive understanding of issues that are discussed in the chapter. The chapter ends with concluding remarks that call for an overview of recent developments where future research on heat waves should focus.

2 Understanding Extreme Temperature and Heat Waves

This section gives a background on an understanding of heat waves. It covers the definition of heat waves and a background on the implication of the use of different definitions of heat waves. In doing so, the section gives an overview of the role of synoptic meteorology, land surface and soil moisture, climate variability and teleconnections, and global warming for the occurrence of heat waves.

2.1 Definition of Heat Waves

Heat waves are defined as a period of anomalously high temperature leading to hotter conditions (Robinson 2001); such episodes are common in the summer months in most places across the world. There is no universally accepted definition of heat waves, the definition of heat waves varies with geography. The definition also varies with the parameters used in the impact assessments by the user community.

The existing definitions of heat wave lead to various estimation of heat wave characteristics and impact (Smith et al. 2013). Heat wave characteristics refer to (1) intensity (maximum temperature during heat wave episodes, also referred as magnitude in some literature), (2) duration (length of heat wave episodes in days), (3) frequency (occurrence of heat wave episodes per year or per season), (4) the date of first occurrence of heat waves and (5) geographical exposure. The implication of the use of different definition of heat waves is that the inference of heat wave

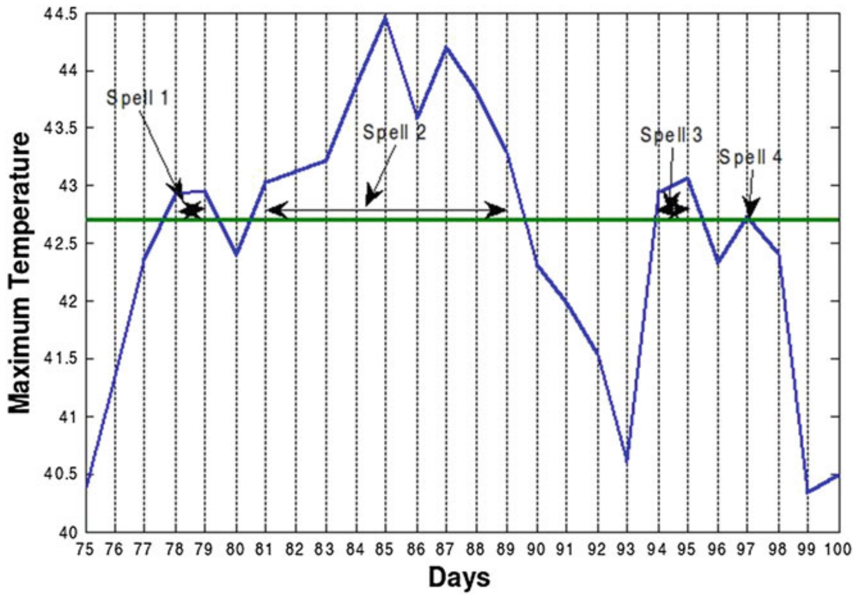

Fig. 1 A schematic illustration of heat wave characteristics. The blue line shows daily maximum temperature profile, and the green line shows the IMD threshold for heat waves in India. Days in the horizontal axis show the days of a year starting from January 1 of that year

characteristics changes with the choice of definition, and therefore, there is a change in impact associated with heat waves.

Figure 1 shows an illustration of heat wave characteristics—intensity, duration and frequency—using a daily maximum temperature data and threshold as suggested by India Meteorological Department (IMD). According to the IMD definition, if a day's temperature is about 6 °C above its long-term average or greater than 45 °C, the days are declared as heat wave day.[1] A heat wave can last for several days if the daily maximum temperature is above the threshold. The consecutive periods of high temperature are referred to clusters or spells. Heat wave clusters or spells are separated if there is at least a single day between them when the maximum temperature is lower than the threshold. Heat wave intensity (or magnitude) is defined as the peak temperature of a cluster or spell, for instance, spell 2 has heat wave intensity of about 44.5 °C. The duration corresponds to the number of days in a cluster or spell, for instance, spell 2 has a duration of 8 days; the frequency is the number of clusters or spells per season, and there are about 4 spells of heat waves in a season as illustrated in Fig. 1.

The choice of definition of the heat wave is an important step for impact studies. Smith et al. (2013) and Perkins and Alexander (2013) provide a comprehensive

[1]See IMD glossary for the definition of heat waves. The glossary can be accessed at imd.gov.in/section/nhac/termglossary.pdf (as on 1 January 2018).

review of various existing definitions of heat waves and their corresponding merits and limitations. According to Perkins and Alexander (2013), there is a wide variation of heat wave definitions within the impact community. Definitions and related indices have been constructed by impact group keeping the sector (such as health, wildlife, agriculture, transport and power) in mind; these are generally too specialized for the individual sector, and therefore, cannot be easily applied to other sectors. This indicates to a point that construction of a common or universal definition of the heat wave is not possible. However, it is important to note that heat waves are abnormal periods of high temperature and their impact on a sector depends upon the susceptibility and resilience of a sector. Therefore, whatever definition or metric we use for a heat wave, it is useful to remember that heat waves are high-temperature conditions leading to warmer atmospheric conditions.

2.2 Physical Drivers for Heat Waves

This section shows evidence on the meteorological background responsible for heat waves. There are four main physical drivers responsible for the occurrence of heat waves.

2.2.1 The Role of Synoptic-Scale Meteorology

The synoptic-scale meteorology is the large-scale atmospheric circulation, which is mainly understood in terms of high- and low-pressure systems. These results in the development of anticyclonic conditions which are responsible for a longer duration high-pressure atmospheric conditions (Matsueda 2011; Dole et al. 2011). Formation of anticyclonic conditions results in the blocking of low-pressure areas that lead to a clear sky in the atmosphere. The clear sky conditions result in more downward solar irradiation and the poor wind circulation, which leads to the warming of the surface and heat waves (Pfahl et al. 2015). Heat waves in Australia are associated with the propagating Rossby waves, which are planetary waves associated with the pressure systems and jet stream. The 2010 heat wave of Russia is explained in terms of the quasi-stationary anticyclonic condition over Western Russia (Barriopedro et al. 2011). While, the occurrence of intense heat waves in Europe in 2003 is associated with the combined influence of large-scale and local-scale drives (Huth et al. 2000). The local-scale drivers are mostly influenced by land surface and soil moisture conditions.

2.2.2 The Role of Land Surface and Soil Moisture

In the context of 2003 heat wave of Europe, a connection of land surface and soil moisture was also explored (Seneviratne et al. 2006). Soil moisture affects the absorption of energy by the earth's surface. The energy that reaches in the land is transformed into latent and sensible heat components. Latent heat is responsible for the evaporation of soil moisture from the land, while sensible heat is responsible for the heating of the land. If antecedent soil moisture is high, latent heat will be the dominant heat flux and will result in increased evapotranspiration from land. High evapotranspiration cools the surface and increases the concentration of water vapour in the air. When the soil is dry, sensible heat is the dominant mode of heat transfer, resulting in heating of the land surface. Soil moisture variability found to be the main driver of temperature variability in Europe in model simulations of both present and future (Seneviratne et al. 2006).

2.2.3 Climate Variability and Large-Scale Teleconnections

Large-scale atmospheric circulation shows a pattern of variability, all of which have effects on the surface climate variation. The global relationship of El Nino Southern Oscillation (ENSO) and the temperature is clear; however, their role for the manifestation of local temperature depends upon its phase such as El Nino or La Nina (Arblaster and Alexander 2012). In Europe, large-scale circulations are associated with heat waves. Della-Marta et al. (2007) suggested that these large-scale circulations were affected by North Atlantic Oscillation (NAO) via Sea Surface Temperature (SST) changes in the Atlantic Ocean. Over Australia, ENSO has been found to influence the seasonal extremes (Nicholls et al. 2005). In case of North America, La Nina patterns were found coincident with heat wave/drought of the year 2011 (Hoerling et al. 2013). Heat waves over India have also been linked to large-scale circulation (Kalsi and Pareek 2001), ENSO (Pai et al. 2013; Murari et al. 2016), and to the variation of SST in Bay of Bengal (Bhadram et al. 2005).

2.2.4 The Role of Global Warming

The previous section recognized the role of natural variability for the occurrence of heat waves. In the context of above discussion, a usual question that needs to be answered is how much more likely global warming is the cause for heat waves? Links between climate change and heat waves are often highlighted in media and other reports, especially aftermath of European heat wave of 2003. Stott et al. (2004), in the first study, applied the formal methodology of detection and attribution and quantified the change in the probability of a heat wave in Europe similar to the one that was experienced in 2003 under the influence of human activity. The study of Stott et al. (2004) covers two sets of model simulation; the first set accounts for the past effect of climate due to both man-made and natural factors (including increasing greenhouse gas concentration), while the second set mimics only natural climatic factors. This study found that the risk of 2003-like extreme European summer heat is attributable to human influences on the climate system.

In another study, using record-breaking statistics by employing Monte Carlo simulation, Rahmstorf and Coumou (2011) suggested that the occurrence of the Russian heat waves had increased by fivefold during the last decade. Further, this suggested that the warming trend in the Russian temperature is responsible for the record-breaking condition of 2010 like heat waves. However, this finding of Rahmstorf and Coumou (2011) in the context of 2010 Russian heat wave was contradicted by Dole et al. (2011), who used an ensemble of multiple climate models to assess the contribution of human activity on Russian heat wave. According to Dole et al. (2011), they detected no trend in Western Russia temperature extremes in the climate model simulations. Dole et al. (2011) suggested that human activity did not contribute to the intensity of 2010 like heat waves in Russia; they indicated that atmospheric mechanism and land-atmosphere feedbacks were the main responsible factor for heat waves in Russia in 2010. There are two contradicting findings for the same heat wave event, making it confusing to understand the causal mechanism. A year later, Otto et al. (2012) suggested that the conclusions of neither of the study are wrong, instead the conclusions should be verified in the context of the question framed. Otto et al. (2012) pointed out that the magnitude of the Russian heat wave is primarily driven by internal dynamics, as outlined by Dole et al. (2011), however, it stressed upon the fact that the probability in the occurrence of this particular event over the region of interest has increased when anthropogenic climate change is accounted for, which is in line with the conclusions of Rahmstorf and Coumou (2011) (Otto et al. 2012). Therefore, global warming plays an important role and might influence the occurrence of a heat wave in the world.

3 Relevance of Heat Waves as Climatic Hazard

Heat waves are an important class of climatic hazard due to its impact on the human health. Changes in the characteristics of heat waves such as intensity, duration and frequency, and geographical exposure have the potential to have some serious impacts. Observations suggest that in some parts of the World such changes are already happening (Meehl and Tebaldi 2004), leading to impact on human health in terms of heat stress and mortality. Heat waves are expected to intensify around the globe in the future, with a potential increase in heat stress and heat-induced mortality. Table 1 shows a comparison of impacts due to various meteorological and climatological hazards from 1985 to 2015. An observation from Table 1 is that the exposure of heat wave does not result in the monetary damages except the case of the 2010 Russian heat wave where Barriopedro et al. (2011) suggested Russian grain harvest suffered a loss of about 30% due to extreme temperature conditions. However, loss of life data from Table 1 suggests that heat waves are a serious climatic hazard. The statistics show that about 1000 lives lost due to exposure to individual heat waves, which is higher in comparison to the lives lost due to other climatological hazards. This suggests that heat waves are the deadliest climate and weather hazards that has caused higher human causalities on per event basis.

Table 1 Exposure and impacts of weather and climate disaster, at a global scale, for the period from 1985 to 2015

Weather and climate extremes	Total events	Persons killed	People affected (in million)	Monetary damage (in billion US$)
Floods	3713	2,08,846	3147.8	644.5
Drought	439	27,150	1635.6	117.6
Cold waves	264	14,574	13.5	10.5
Heat waves	142	1,50,955	4.8	20.5
Tropical cyclones	1355	4,08,926	607.5	666.5

Disasters are defined according to international disaster database, which is a compilation of information from various governmental and non-governmental sources. Further details of the database are available at http://www.emdat.be/

A multi-model analysis suggests that most intense extreme future heat waves are concentrated around densely populated agricultural regions of the Ganges and Indus river basins (Im et al. 2017). This suggests climate change is expected to present a serious and unique risk in South Asia, a region inhabited by about one-fifth of the global human population, due to an unprecedented combination of severe natural hazard and acute vulnerability. This is an important observation on ground of the fact that model analysis suggest that Asia is expected to be highly exposed to heat waves, which is considered to more vulnerable to heat stress on ground of (1) high population density, (2) higher proportion of poorer people and (3) increasing risk of illness and death related to extreme heat conditions (Im et al. 2017).

4 Heat Waves in the Context of India

This section describes heat waves in the Indian context. It gives an overview of studies about temperature patterns and the role of climate variability on heat waves in India.

4.1 Surface Temperature Trend Over India

Heat waves in India are commonly in the summer months (i.e. from March to June and sometimes in the July months). The monsoon arrives in India after the summer months that brings cooler wind and moisture and causes relief in temperature. There are many studies on the observed temperature trends over India. Kothawale and Rupa Kumar (2005) observed that all-India mean annual temperature has a trend of increase of about 0.5 °C per century for the period 1901–2003; however, the 30-year trend for the period 1971–2003 is 2.2 °C per century, which suggest Indian mean annual temperature has an alarming rate of warming in the recent period.

4.2 The Role of Atmospheric Circulation and Heat Wave Characteristics in India

There are limited studies that describe the role of atmospheric circulation on heat waves in India. Jenamani (2012) suggested the possible role of a cyclonic storm in Bay of Bengal that caused westerly flow in the upper atmosphere resulting in blocking of maritime wind over land. This led to a dry atmospheric condition that has triggered 1998 heat waves in Orissa. The 1998 heat wave of Orissa is also linked to El Nino conditions (De and Mukhopadhyay 1998). Kalsi and Pareek (2001) identified the role of formation of anticyclonic circulation on the upper atmosphere that results in subdued convective activity and entering of more heat on the land, this explains 1999 North Indian heat wave. Bhadram et al. (2005) studied the 2003 heat wave of Andhra Pradesh and found that the warmer SST anomalies over North Bay of Bengal were responsible for heat wave-like condition in the state. In addition to these factors, the late onset of Indian monsoon is also understood to be an important factor responsible for the heat waves in India (Pai et al. 2013).

Heat waves in Indian normally occur in the pre-monsoon summer periods, typically during the months from March to May (Murari et al. 2015). This suggests the possibility of the influence of factors affecting monsoon on the heat waves in India. A delay in the arrival of monsoon will result in extending summer period and thereby the exposure of heat waves. Murari et al. (2016) studied the relationship of the El Nino and the onset dates of the summer monsoon in India and its influence on heat wave characteristics. El Niño is associated with an eastward shift in the Walker circulation and breakdown of circulation patterns, resulting in a delay in the onset of the Indian Summer Monsoon (ISM). Because most heat waves in India occur during the pre-monsoon season, Murari et al. (2016) showed that heat waves during El Niño years were longer and hotter, and it is argued that this is related to a delay in the onset of the ISM.

Figure 2 shows the result of Murari et al. (2016) that compares the heat wave characteristics of El Niño and normal years. Most of the positive anomaly in June and July temperatures occurred in El Niño years. Strong El Niño years (i.e. ENSO[2] index ≥ 1) consistently showed warmer temperatures in June and July (Fig. 2a). Figure 2b–d compares distributions of the summer season heat wave characteristics for El Niño and normal years. A large percentage of grid points experienced higher duration and days during El Niño years compared to normal years. This indicates that heat waves were more frequent and lasted longer during El Niño years. Likewise,

[2]ENSO index is defined based on Oceanic Nino Index (ONI), which uses sea surface temperature of Nino 3.4 region. The ONI values are estimated for 3-month window and are used to define ENSO index. See Murari et al. (2016) for details.

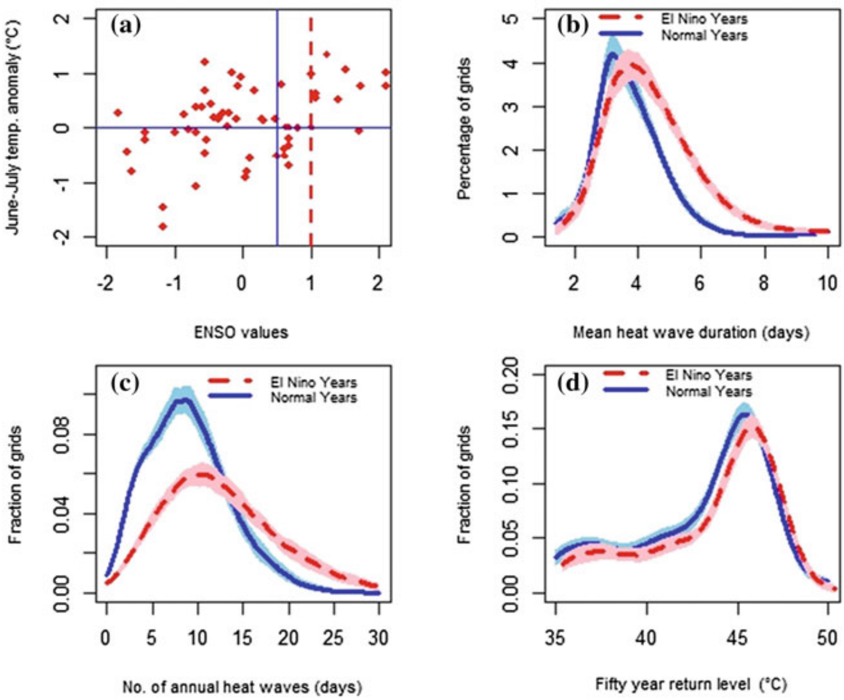

Fig. 2 Comparison of heat wave characteristics between El Niño and normal years. **a** Average June and July temperature anomaly for different values of the El Niño Southern Oscillation (ENSO) index; the vertical continuous and dashed lines show different El Niño conditions. **b–d** Show the fraction of grid points corresponding to different duration, days and T_{max} for El Niño and normal years, respectively. The shaded region shows the 95% confidence intervals for different estimates of duration, days and T_{max} (*Source* Murari et al. (2016))

during El Niño years, a larger number of grid points experienced higher maximum temperature during heat wave episodes (T_{max}), with the curve for El Niño years shifted by about 1 °C with respect to the normal years. These results are consistent with earlier work on extreme temperatures in India (Panda et al. 2014), which suggests that El Niño is related to the number of heat wave days and the maximum temperatures of the pre-monsoon summer heat waves in India. Moreover, the greater number of heat wave days during El Niño years is likely to have resulted in higher mean temperatures.

5 Impacts of Heat Waves in India

There are a number of studies that explored the direct connection between the health and thermal stress (Gosling et al. 2009). The increased stress associated with the heat waves may lead to increased heat-induced mortality in the absence of appropriate

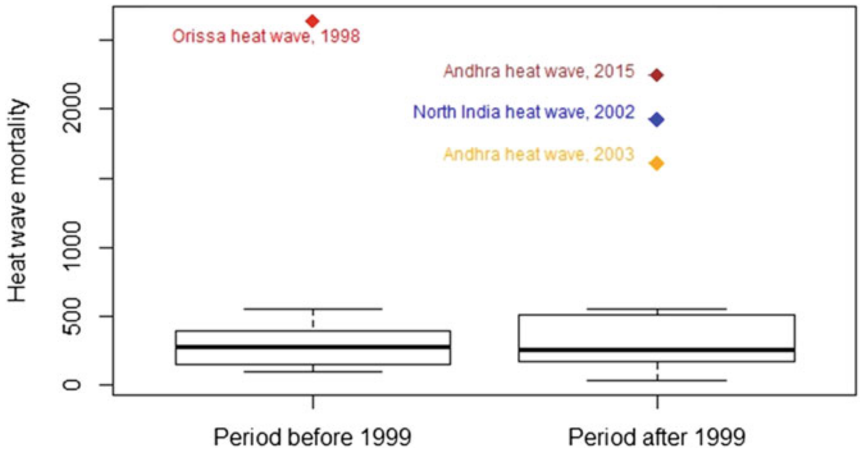

Fig. 3 All-India heat-related mortality for two time periods (*Data source* EM-DAT; www.emdat.be)

adaptation action (Gosling et al. 2009). During heat wave episodes, the exposure to the anomalously high temperature may depress the rate of heat transfer between the human body and the atmosphere. People working outdoors or indoor without basic infrastructures such as electricity and water could be the most vulnerable. In addition to the exposure to high temperature, relative humidity is another important factor that might disturb the thermoregulation of a human body because sweating is the mechanism that controls the body temperature by exchanging with the outside atmosphere. An atmosphere with the high relative humidity results in a decreased rate of sweating and might result in accumulation of heat inside the human body. Extreme conditions, i.e. exposure to high atmospheric temperature and relative humidity, might cause failure of the thermoregulatory system of a human body and might result in skin eruption, heat fatigue, heat cramp, heat exhaustion and heat stroke. Koppe et al. (2004) gave a very good review of the possible implication of exposure to extreme temperature on the human health.

Extreme temperatures in India during summer months often lead to loss of human and animal life and enhanced morbidity and discomfort. Official records of the IMD indicate that there were about 223 heat wave incidences between 1978 and 1999, causing more than 5300 deaths (Choudhary et al. 2000). Figure 3 shows the trend of heat wave mortality in India. The figure divides the mortality data into two periods before and after 1999 and plots the box plots for the mortalities for the two periods. Most of the deadly heat waves in India occurred in the recent period (Fig. 3).

The heat wave of the year 1998 was very much brutal for the most part of India, which is associated with a higher number of deaths, particularly in the states of Delhi and Orissa. Heat waves in India have not, so far, attributed to global warming. Possibly, due to a reason that it is difficult to attribute individual heat waves to climate change, however, their pattern about recent exposure and impact of heat waves gives a first-hand understanding that the effect of global warming on heat waves is already evident in India.

6 Future Projections of Heat Waves in India

The interaction among atmospheric, oceanic and land surface processes that produce prolonged periods of atmospheric conditions of high air temperatures has been explored in the literature (Della-Marta et al. 2007; Dole et al. 2011; Matsueda 2011; Pfahl et al. 2015). While natural variability continues to play a key role in extreme weather, climate change has shifted the odds and changed the natural limits, making heat waves more frequent and intense (Coumou and Rahmstrof 2012). Both record highs and lows are set regularly in a stationary climate. But it is understood that the balance shifts towards a warming climate leading to asymmetry in the temperature distribution (Kodra and Ganguly 2014).

GCMs are good tools available for developing an understanding of how the climate will change under enhanced anthropogenic activity. These models have provided daily data, which are key in the measurement of heat waves. However, a reliable analysis of model outputs depends on the observed data, and therefore for regions where observed records are poorly maintained, such a projection of extremes may lead to insufficient understanding (Field et al. 2014). Regions where good observation records are available, direct uses of GCMs for regional projections are difficult mainly for two reasons. First, GCM data are available at coarse spatial resolution; second, GCM data might be affected by biases because of insufficient knowledge of key physical mechanisms, difficulty with the parameterization and the use of empirical physical laws (Meehl et al. 2007).

In order to employ GCMs for regional- and local-scale studies, downscaling[3] (i.e. generating finer resolution data) and bias correction[4] are essential steps. Application of a suitable bias correction method is an important step for providing regional projections. Murari et al. (2015) used multiple simulations from seven GCMs to understand the future heat wave characteristics in India. Model data are first bias corrected and compared with heat wave characteristics simulated by the IMD gridded data for the observed period. Figure 4 shows the projection of intensity, duration and frequency of heat waves using seven climate model data. The figure indicates the increase in all the three heat wave characteristics for most of India.

[3]Downscaling is an approach of obtaining regional high-resolution climatic variables from GCMs. See https://www.gfdl.noaa.gov/climate-model-downscaling/ for further detail on downscaling.

[4]GCMs are typically at coarse spatial and require a high degree of parameterization (i.e. simplification and approximations) of the physical mechanisms of the earth system at the designed resolution of the GCM. This results in error in simulation of climatic variables from the GCM. The error is generally defined with respect to the observed data. This error is referred to biases in the simulation of GCM, which needs to be corrected before using the GCM simulations for impact assessment. See Murari et al. (2015) for bias correction.

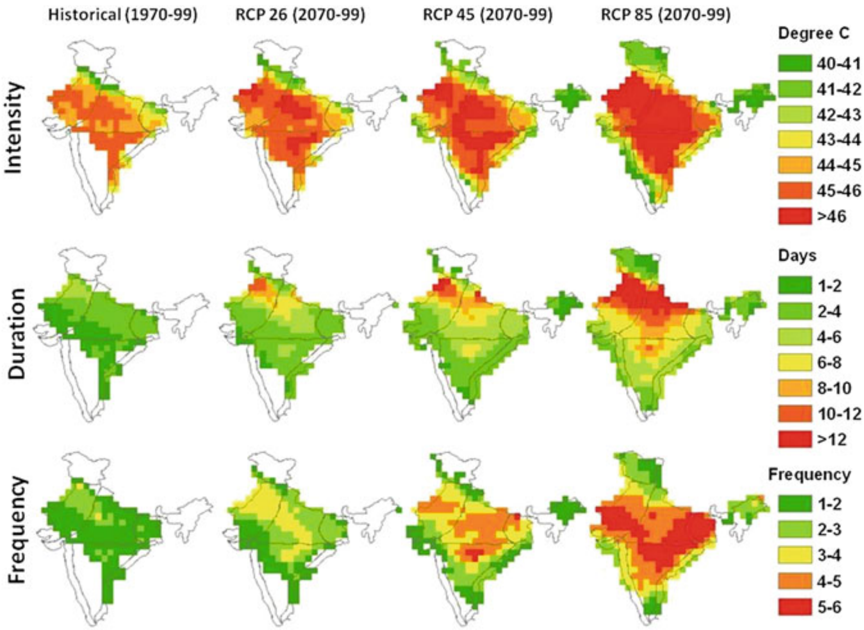

Fig. 4 Intensification of heat wave characteristics in the future

In particular, a large part of Southern India presently not affected by heat waves is projected to be severely affected after 2070. The magnitude of intensification in Northern India is observed to be high compared to other regions of the country. Interestingly, under the RCP 26 scenario, in which most of the climate models are showing the change in global temperature below 2 °C with respect to the average global temperature of the pre-industrial period (van Vuuren et al. 2011), it is observed that intensification in heat wave characteristics is only observed for North India. Southern India, under RCP 26 scenario, does not show intensification; this implicates that the severe heat wave could be avoided for the region if the future forcing is constrained to RCP26.

The first occurrence of heat waves is characterized as the day in the year when a first heat wave hits at a particular location. Figure 5 shows the period during which the first heat wave in summer occurred, where the first occurrence is calculated as the average of the days of the first occurrence in 30-year time window; data are reported for observed data (1970–1999), historical modelled data (1970–1999), and projected data of RCP26, RCP45 and RCP85 (2070–2099). The first heat wave occurs mostly between the second half of May and the first half of June for the observed and historical periods. While towards the end of the twenty-first century, heat waves are expected to occur between April and the first half of May in most parts of India in three scenarios. The impact of early summer heat waves could be severe because of the surprise effect on the population that is not expecting early occurrence of severe

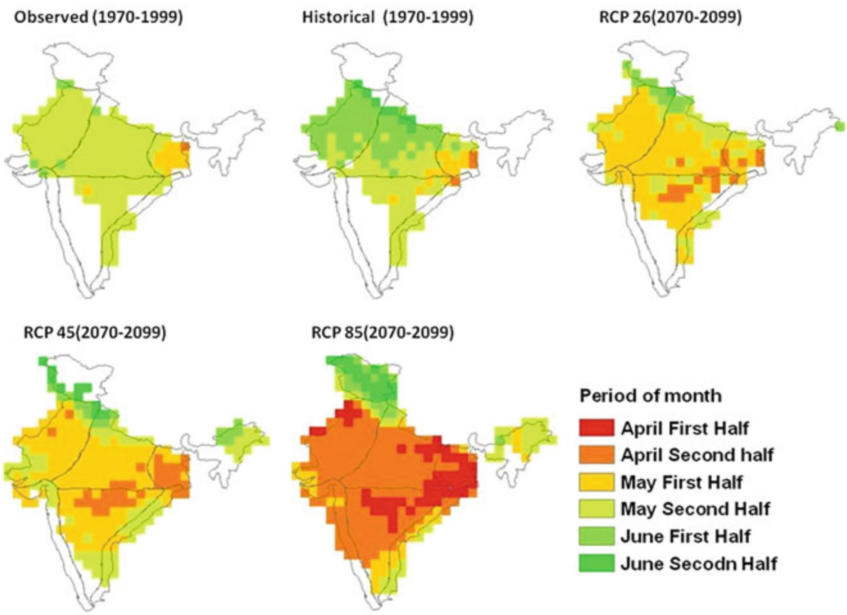

Fig. 5 First occurrence of severe heat waves, expressed as a mean value over a 30-year time window of the day in the year when a severe heat wave first hits a particular location. The figure presents the ensemble mean of the first occurrence values for seven climate models

heat spells (Hajat et al. 2005); this is especially relevant to regions, such as Southern India, that do not experience severe heat wave conditions in the observed data.

These results show that the concerns regarding intensification and early occurrence of a heat wave in North and Central India are serious under all the three scenarios. Unlike Southern India, intensification of heat waves in the remaining parts of India cannot be avoided under any scenario representing less than 2 °C increase in global temperature.

7 Concluding Remarks

A significant amount of work has been done to understand the heat waves and its likely impact due to global warming. This includes understanding heat waves, identifying the physical mechanism responsible for the occurrence of heat waves in various climatological regions, and also the role of global warming on the likelihood of the exposure of heat conditions. This chapter presents an overview of this knowledge. Despite a significant improvement in the scientific understanding of heat waves, there are still limited studies on heat waves, their projections and impact in developing countries, particularly in India. There are studies conducted in a scattered way to understand heat waves in India. This chapter, with a comprehensive review of existing heat wave studies in India, provides a consolidated picture of heat wave studies in India.

Existing studies in India have found various factors that triggered heat waves in different geographical regions. Most of these are related to natural variability in the climatic system. There is no study, so far, that indicates that global warming is responsible for individual heat wave events in India. Such studies are extremely concerning, particularly by impact assessment community, as these provide the basis of likelihood intensification of extreme heat due to global warming. Heat wave community will be significantly benefited by detection and attributional studies. Nevertheless, climate models have been used to understand the future projection of heat extremes in different regions in the world. This chapter presents the findings of Murari et al. (2015), which is perhaps the only study in India that provides a model projection of heat wave characteristics in India.

The results of Murari et al. (2015) suggest that the places which have always experienced heat waves in summer will see heat waves that are greater in intensity as well as duration. This will make the country more vulnerable because a large proportion of the population in India live without sufficient access to water, electricity and primary health facilities. Plants and animals will find it harder to survive through to the end of the summer. A possible consequence of the projected heat waves could be on the health care infrastructure, which might collapse under the strain of overwhelming demand for treatment for ailments as well as emergency services. Moreover, parts of our country that have never been exposed to heat wave conditions will experience conditions that they are unfamiliar with. They will be completely unprepared and unequipped to deal with such situations. Ways of life that have been existed and evolved over countless years will lose the very foundations on which they have been built: the characteristics of the environment which cradled them.

These results point to the necessity for further research on the adverse effects of the heat waves of the future. Policies need to be formulated to cope with their impact on the population. With every passing year, they will occur earlier in the year affect larger areas of India, including Southern India. Worryingly, heat waves are not seriously considered as a disaster, at present.

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