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ORIGINAL ARTICLE

Intensification of future severe heat waves in India and their effect on heat stress and mortality

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Abstract Heat waves are expected to intensify around the globe in the future, with potential increase in heat stress and heat-induced mortality in the absence of adaptation measures. India has a high current exposure to heat waves, and with limited adaptive capacity, impacts of increased heat waves might be quite severe. This paper presents the first projections of future heat waves in India based on multiple climate models and scenarios for CMIP5 data. We find that heat waves are projected to be more intense, have longer durations and occur at a higher frequency and earlier in the year. Southern India, currently not influenced by heat waves, is expected to be severely affected by the end of the twenty-first century. Projections indicate that a sizable part of India will experience heat stress conditions in the future. In northern India, the average number of days with extreme heat stress condition during pre-monsoon hot season will reach 30. The intensification of heat waves might lead to severe heat stress and increased mortality.

Keywords Heat wave · Mortality · CMIP5 · Heat stress · Adaptation · Climate extremes

Introduction

Heat waves occupy an important class of climate-related hazards, with numerous studies exploring the connection between health outcomes and thermal stress (Gosling et al. 2008; Robine et al. 2008). Most projections of future climate point to increasing intensity, duration and frequency of heat waves (Diffenbaugh and Ashfaq 2010; IPCC 2007). This intensification has been projected for many regions of North America (Ganguly et al. 2009; Meehl and Tebaldi 2004) and Europe (Fischer and Schär 2010). The increase of stress associated with heat waves may lead to increased heat-induced mortality in the absence of appropriate public policy action (Fischer and Knutti 2012; Gosling et al. 2008; Sherwood and Huber 2010). Understanding the characteristics of heat waves is thus necessary to design suitable adaptation measures.

In India, a warming trend in the range of 0.8 to 1 °C per century has been observed (Kothawale et al. 2010, 2012), with an increasing number of hot days, defined as days with daily maximum temperature exceeding the 90th percentile of the time series from 1969 to 2005 (Dash and Mamgain

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2011). Northern India shows high occurrence of heat waves (De et al. 2005), averaging between five and six per year (Srivastava et al. 2009). Fine resolution projections (at 0.44°) over south Asia, obtained using PRECIS (Providing REgional Climates for Impacts Studies), indicate an increase in temperature extremes toward the end of the twenty-first century for A2 and B2 scenarios using CMIP3 projection (Revadekar et al. 2011).

Previous studies on extreme temperature in India (Dash and Mamgain 2011; Revadekar et al. 2011) are based on extreme indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI); the latter refers to moderate extremes, typically occurring several times a year (Tank et al. 2009). Rare extremes, such as severe heat waves, may have a widespread socioeconomic impact. In India, heat waves often lead to loss of human and animal life, while enhancing morbidity and discomfort. Official records of the India Meteorological Department (IMD) indicate that there have been approximately 223 heat wave incidents between 1978 and 1999, causing more than 5,300 deaths (Chaudhury et al. 2000). Premature mortality in India is experienced more in rural populations, particularly among elderly and outdoor workers (Chaudhury et al. 2000). High casualties during the 1998 heat wave in the state of Orissa are attributed to poor awareness of general public and state administration (Das and Smith 2012). Analysis of heat waves using observed and projected temperatures is unavailable in India. It is thus important to understand how patterns of severe heat wave features might change under a warming climate in India. Key heat wave features include intensity, duration, frequency and time of first occurrence in the pre-monsoon warm season. Effects of severe heat waves on health stress and mortality rates are also open issues to be addressed for a proper development of mitigation strategies.

Here, we present the first comprehensive analysis of pre-monsoon warm season (March to June) daily temperatures in India. Our analysis combines observations and daily temperature projections from a suite of CMIP5 models. The novelty of our analysis lies in the characterization of intensity, duration and frequency of projected severe heat waves in India. We also present an initial assessment of possible health impacts of future severe heat waves; however, this impact analysis is intended to be illustrative in nature, due to the lack of data required to perform a complete vulnerability assessment.

Methods

Data

Daily gridded temperature data at 1° resolution is available for the period between 1969 and 2009. These data, released by the India Meteorological Department (IMD), are obtained using the Sheppard's angular distance weighting algorithm from 395 weather stations across India (Srivastava et al. 2009). Climate change simulations of seven Earth System Models (ESMs) are obtained from the CMIP5 portal (www.pcmdi.llnl.gov). Details of the models are provided in Table S1. Most of the ESMs are coarse-gridded climate models and may not simulate, with confidence, finer-scale processes such as precipitation extremes. Since heat waves are typically a large-scale phenomena, we think that the use of ESMs to study heat waves is appropriate.

In addition, NCEP/NCAR reanalysis daily relative humidity data is used for the heat stress analysis. The potential impact of future heat waves on mortality is estimated using historical data of heat wave-induced mortality rates obtained from the Ministry of Home Affairs (Government of India). This analysis of mortality is performed in the states of Delhi, Rajasthan, Maharashtra and Orissa, for which observed data are available from 1997 to 2009; the 2001 population census data of these states are also utilized.

Statistical analysis

Scaling and bias correction

The ability of general circulation models (GCMs) to capture small-scale and regional-scale observed climatic phenomena is limited, mainly because of insufficient representation of key physical mechanisms and difficulties with parameterization (Meehl et al. 2007). Direct use of modeled values may not be appropriate for climate analysis at a regional scale due to systematic biases present in climate modeled data. The effect of temperature-dependent biases in GCMs and regional climate models has recently been demonstrated in Mediterranean regions (Christensen and Boberg 2012), where the authors suggested the possibility of incorrect estimations of temperature projections if such biases were not eliminated.

Available bias correction approaches, such as standardization (Wilby et al. 2004), cumulative distribution function (CDF) matching, and techniques based on transfer functions (Dosio and Paruolo 2011; Piani et al. 2010), neglect the changes in distribution parameters particularly with respect to higher-order moments; this may result in incorrect estimations of future climate heat waves. The bias correction approach proposed by Li et al. (2010) uses the quantile-based transformation method, incorporating changes in the distribution of future climate. Here, we use this method and apply it to ESM simulations, after re-gridding maximum temperature data into 1° spatial resolution using bilinear interpolation. Mathematically, the bias correction algorithm is expressed as (Li et al. 2010)

$$x_{m-bc} = x_{m-p} + F_{o-b}^{-1}(F_{m-p}(x_{m-p})) - F_{m-b}^{-1}(F_{m-p}(x_{m-p})), \tag{1}$$

where x stands for temperature data, m for model, bc for bias-corrected output, o for observed record, p for projected ESM output, b for base (training) period (1970–1984) data, and F indicates the CDF. The methodology is validated for the period 1985–1999, and bias correction is performed for every 15-year time series data starting from 2010.

We analyze daily maximum pre-monsoon warm season temperatures from the observed data in the period 1970–1999, bias-corrected climate model data in the historical period (1970–1999) and future projections in three 30-year periods (2010–2039, 2040–2069 and 2070–2099).

Severe heat wave definition and features

India has four marked seasons: pre-monsoon hot weather season (March to May, often until mid-June, the onset of the monsoon), summer monsoon (June to September), post-monsoon (October to November) and winter (December to February). Here, we analyze severe heat waves only for the pre-monsoon hot weather season, considering that impacts are likely to be experienced during the time of year.

We focus on severe heat waves since these are the rare extreme events that have potential to affect society. Here, we use the definition of severe heat waves provided by the IMD, based on maximum daily temperature thresholds (Pai et al. 2004). As such, the average pre-monsoon warm season, daily temperature of the period 1970 and 1999 is defined as the normal temperature. If the maximum temperature of a day exceeds 45 °C, irrespective of the normal maximum temperature of a region, that day is defined as a severe heat wave day. In case a day's maximum temperature is less than 45 °C, that day is defined as a severe heat wave day when (1) the day's maximum temperature is at least 7 °C greater than the normal temperature, and (2) the maximum temperature of that day is above 40 °C.

If the daily maximum temperature stays above these thresholds, severe heat waves can last for several days; we refer to those periods as clusters. We assume that severe heat wave clusters are separated when there is at least a single day between them with the maximum temperature lower than the threshold. Severe heat wave intensity is defined as the peak temperature of a cluster; the duration corresponds to the number of days in a cluster, and the frequency is the number of clusters per season. Unkašević and Tošić (2011) have used a similar approach to define the 2007 heat wave in Serbia.

Analysis of heat stress

Prolonged increased temperature during a severe heat wave may produce thermoregulatory stress on human bodies; such a stress might be exacerbated by the presence of high relative humidity. Heat stress associated with the public health system has been studied in parts of India as reported by Dash and Kjellstrom (2011). Temperature-based indicators, such as apparent temperature (also heat index) (Diffenbaugh et al. 2007; Fischer and Schär 2010) and Wet Bulb Globe Temperature (WBGT) (Dash and Kjellstrom 2011; Epstein and Moran 2006; Hyatt et al. 2010), have been used in the literature. Specifically, the WBGT index is adopted as the ISO7243 standard for setting criteria to determine exposure to hot environments (Epstein and Moran 2006). The WBGT index accounts for temperature, wind speed and relative humidity in a more detailed manner than other heat indices (Hyatt et al. 2010). We have estimated WBGT values for the observed and future climate using the assumptions suggested by Hyatt et al. (2010). The simplified WBGT estimation requires air temperature and vapor pressure; this method presents an error lower than 2 % for temperature greater than 25 °C. Ideally, WBGT should be calculated with simultaneous values of temperature and relative humidity (or vapor pressure), obtained from the same source. Since observed data of vapor pressure are unavailable, we used the NCEP/NCAR reanalysis data for the period 1970–1999. Future projections of specific humidity from ESMs are first interpolated to 1° and then converted to vapor pressure using standard methods of conversion (Oleson et al. 2010). The quantile-based bias correction, already used for the temperature record (Eq. 1), has then been applied to specific humidity data. These sets of data are then employed for heat stress analysis.

Heat-induced mortality

Although estimating a relationship between severe heat waves and mortality is complicated due to the absence of knowledge of confounding factors, such as occupation, income level, gender and age group, quantitative estimations of heat-related mortality are available in the literature (Gosling et al. 2008; Peng et al. 2011). Air pollution has also been discovered to be a confounding factor, affecting the estimation of mortality associated with extreme temperatures (Gosling et al. 2008).

Given the dearth of data at the scale of individual districts or at 1° grid scale, we chose to perform an analysis at the scale of a state, assuming that cultural habits and adaptation practices were similar within the state.

Heat wave–mortality relationships were obtained by applying regression between temperature or duration above threshold and heat-related mortality. Gosling et al. (2008) and Koppe et al. (2004) provide a detailed review of literatures on the methodologies adopted in various studies. We apply a linear regression analysis to relate the number of heat wave days per year to the mortality per unit of population in grid points with occurrences of heat waves. We use observed mortality records in four states to establish a linear relationship between heat wave days per year and mortality. These four states are Delhi and Rajasthan (in northern India), Maharashtra (western part of India) and Orissa (eastern India). We use heat wave days to explain future mortality of these states, keeping population fixed as 2001 census. The regression model is

$$M_t = b \times \mathrm{HWD}_t + \varepsilon_t, \qquad (2)$$

where b is the regression coefficient, M is mortality per million of population, t is the year, HWD is number of severe heat wave days in a year, and ε is the residual.

Future projection of mortality is performed utilizing the same regression coefficients transferred into the twenty-first century ESM severe heat wave days. The underlying assumptions are that (1) the regression coefficients remain constant, (2) business-as-usual practice toward heat wave preparedness prevails, and (3) the adaptation capacity of communities does not change over time.

Results and discussion

Performance of bias correction

Figure 1 shows the differences in mean temperatures between bias-corrected model data and observed data. The mean differences are computed and shown for a testing period from 1984 to 1999. The difference of the mean values of bias-corrected temperature data and observed temperature data for most of India is lower than 0.5 °C. Although the difference for individual models, on a regional basis, is slightly higher than 0.5 °C, ensemble averaging of the seven selected models gives a difference closer to 0.5 °C. This indicates that the bias correction works well for maximum temperatures in India.

A further comparison of intensity, duration and frequency of severe heat waves for the period from 1970 to 1999 also shows a close resemblance of values simulated by the models and observed data (Figure S1). Although there remains a slight bias in intensity, the magnitude of this bias is similar to the bias that we obtained with the mean temperatures. Biases in duration (in days) and frequency (in severe heat wave spells per season) do not exceed one, indicating that the bias correction methodology works for severe heat wave features. Climate models

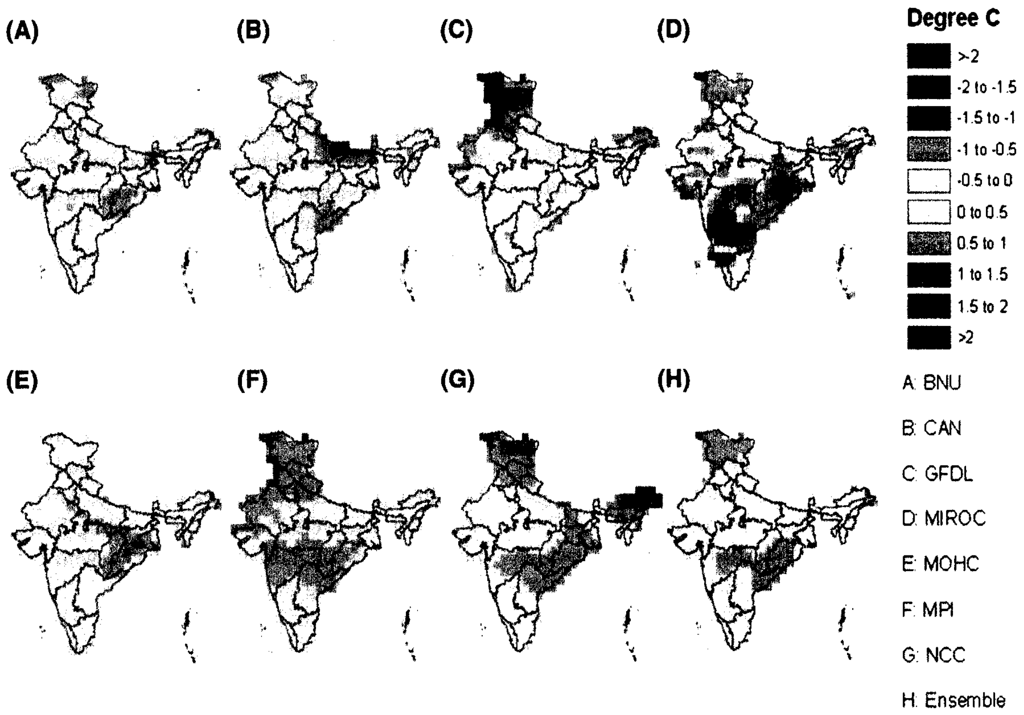

Fig. 1 Comparison of bias-corrected climate model data with observed data, as the difference between mean temperatures calculated from different models and observations during the testing period (1985–1999). Model minus observed data is shown as positive bias

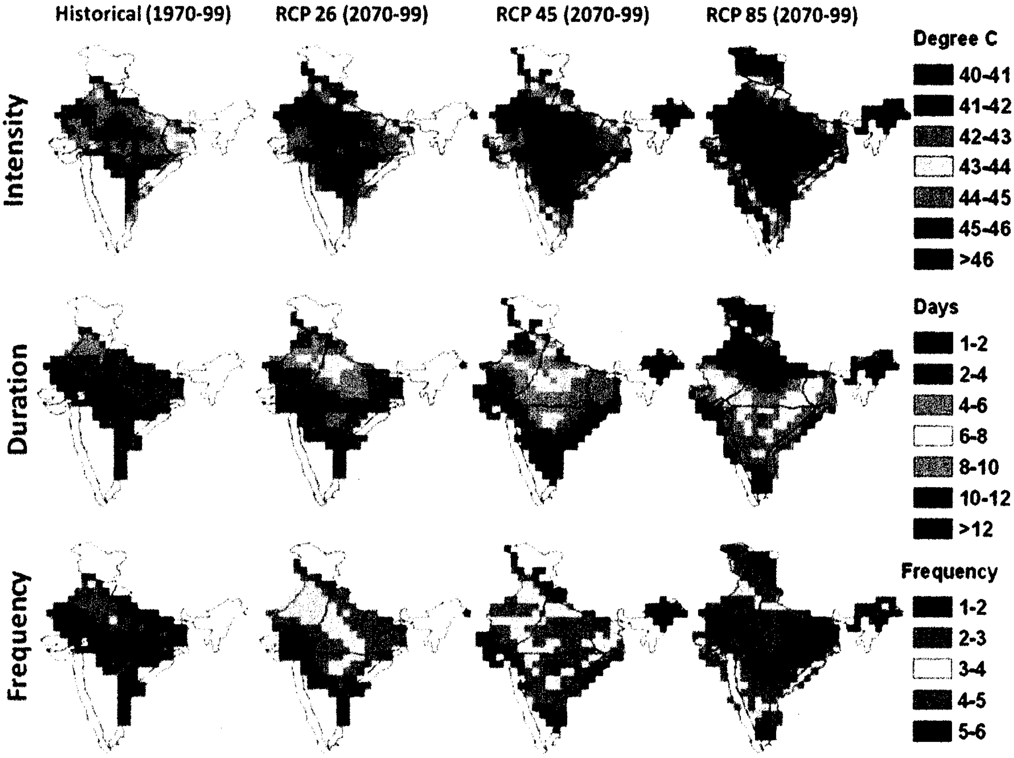

Fig. 2 Intensification of severe heat waves for different emission scenarios as predicted by the ensemble of 7 ESMs

data with cumulative distribution-based bias correction may now be used for future projections of heat wave characteristics in India.

Future projections

The projections of intensity, duration and frequency of severe heat waves are presented for three representative concentration pathways (RCPs): RCP26 (a peak-and-decline pathway consistent with the 2 °C target), RCP45 (considering this scenario as the most probable) and RCP85 (considering this as the worst-case possibility) (Vuuren et al. 2011). Figure 2 shows intensity, duration and frequency calculated using the bias-corrected model data for the periods 1970–1999 and 2070–2099 and for the three RCP scenarios. Under the most probable-case and the worst-case scenarios, the period, 2070 onward, shows increases in intensity, duration and frequency of severe heat waves. In particular, a large part of southern India, East and West coasts, which are presently unaffected by heat waves, are projected to be severely affected after 2070. Increase in severe heat wave features, such as intensity, duration and frequency, is leading to intensification of future severe heat waves in most parts of India. The magnitude of intensification in northern India is noted to be high as compared to other regions of the country. Interestingly, under RCP26 scenario, in which climate models are subjected to peak forcing input around the year 2050s and then decline (Vuuren et al. 2011), intensification of heat wave features is projected only for northern India. Southern India, under RCP26 scenario, does not show intensification, thereby implying that severe heat waves might be avoided in this region if future forcing were constrained to those of RCP26.

First occurrence

The impact of heat waves early in the year could be severe because of the surprise effect on the population not expecting early occurrence of severe heat spells (Hajat et al. 2005); this is especially relevant to regions such as southern India, which do not experience severe heat wave conditions in current observations. The first occurrence of severe heat waves is characterized as the day in the pre-monsoon season when the first severe heat wave hits a particular location. Figure 3 shows the period during which the first severe heat wave occurred, averaged over 30-year time windows, for both observed (1970–1999) and future

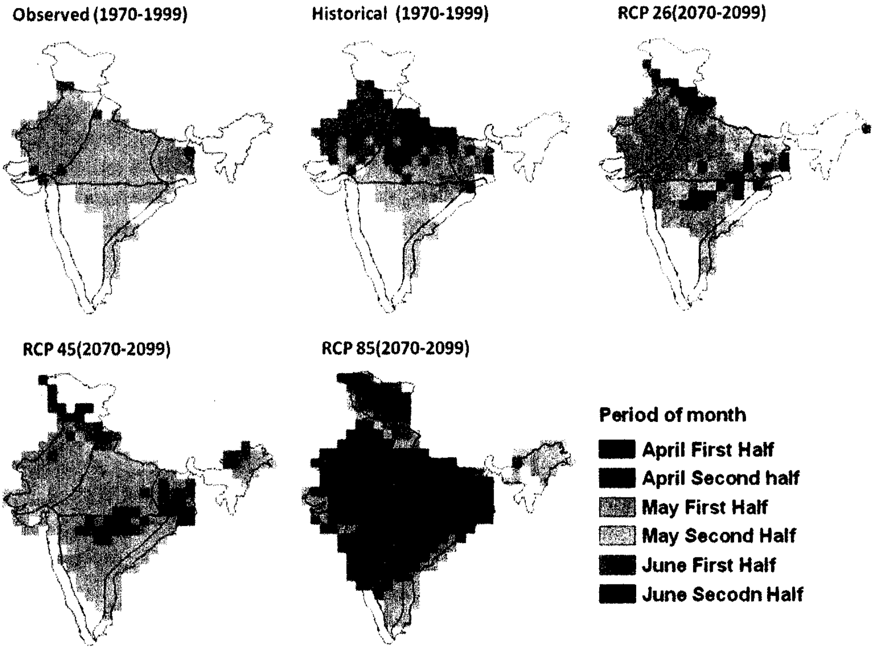

Fig. 3 First occurrence of severe heat waves, expressed as mean value over a 30-year time window of the day in the year when a severe heat wave first hits a particular location. The figure presents the ensemble mean of the early occurrence values for seven climate models

periods (2070–2099). The first severe heat wave occurs mostly between the second half of May and the first half of June for the observed and historical periods, while toward the end of the twenty-first century severe heat waves are expected to occur between April and the first half of May in most parts of India for the three scenarios. These results support concerns regarding intensification and early occurrence of severe heat waves in North and Central India under all the three scenarios. Unlike southern India, intensification of severe heat waves in the remaining parts of India cannot be avoided under any scenario, representing less than 2 °C increases in global temperature.

Impact on humans

To assess the potential impact of intensified and longer-lasting projected severe heat waves, we examined heat stress and heat-induced mortality.

Heat stress

The potential implications of the increase in heat stress in labor productivity were observed in Dunne et al. (2013). These are particularly relevant for India, where a large proportion of the workforce is engaged in outdoor activities, such as agriculture and construction. Heat stress at grid points is estimated using WBGT indices. Hyatt et al. (2010) measured monthly average WBGT values for India; accordingly, WBGT values ranging from 26 to 33 are considered as moderate to high risk condition, while WBGT values larger than 33 are associated with extreme stress conditions that could be more fatal to humans. According to Hyatt et al. (2010), extreme heat stress conditions were not detected by observing data in the period 1975–2000; however, if mean temperature were inflated by 3 °C, a large part of India could experience extreme heat stress conditions. To prove this assertion, we used temperature and relative humidity data from climate models to estimate future heat stress conditions. We estimate the number of extreme stress days in the measured period (1970–1999) and the worst case scenario (RCP85) for three future time periods (2010–2039, 2040–2069 and 2070–2099). As shown in Fig. 4, both measured data and the data in 2010–2039 do not show a significant number of days with extreme stress conditions; however, toward the mid and end of the century, high increase in the number of extreme stress days over a larger region of India is projected. Specifically, northern India is projected to be largely affected by extreme heat stress in the future; these projections, combined with the lack of infrastructure, high population density and large workforce in agriculture, may lead to possible heat-health risk to the population of this region.

Mortality projections

We assessed the relationship between mortality and severe heat waves for the states of Delhi, Rajasthan, Maharashtra and Orissa, the locations of which are shown in Fig. 5. Mortality data obtained from the observed records show a

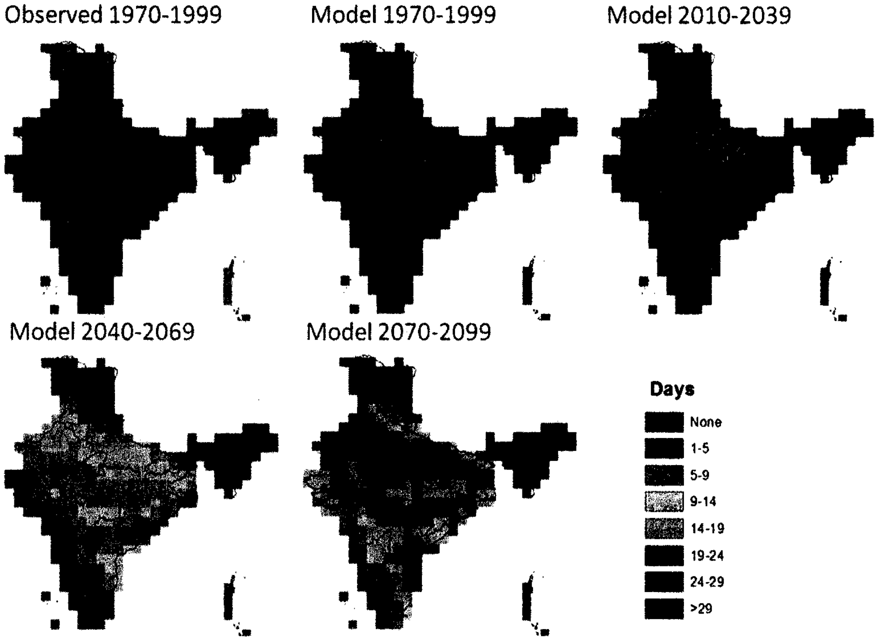

Fig. 4 Wet Bulb Globe Temperature (WBGT) index for outdoor occupation conditions in India. Panels show the average number of days in a year when individual grid points are under high-stress conditions according to the modeled data in the periods 1970–1999 (observed and historical), 2010–2039, 2040–2069 and 2070–2099, respectively. The figure shows mean of days for the ensemble of 7 climate models using the scenario RCP85. Severe heat stress days are defined as days when WBGT value exceeds 33

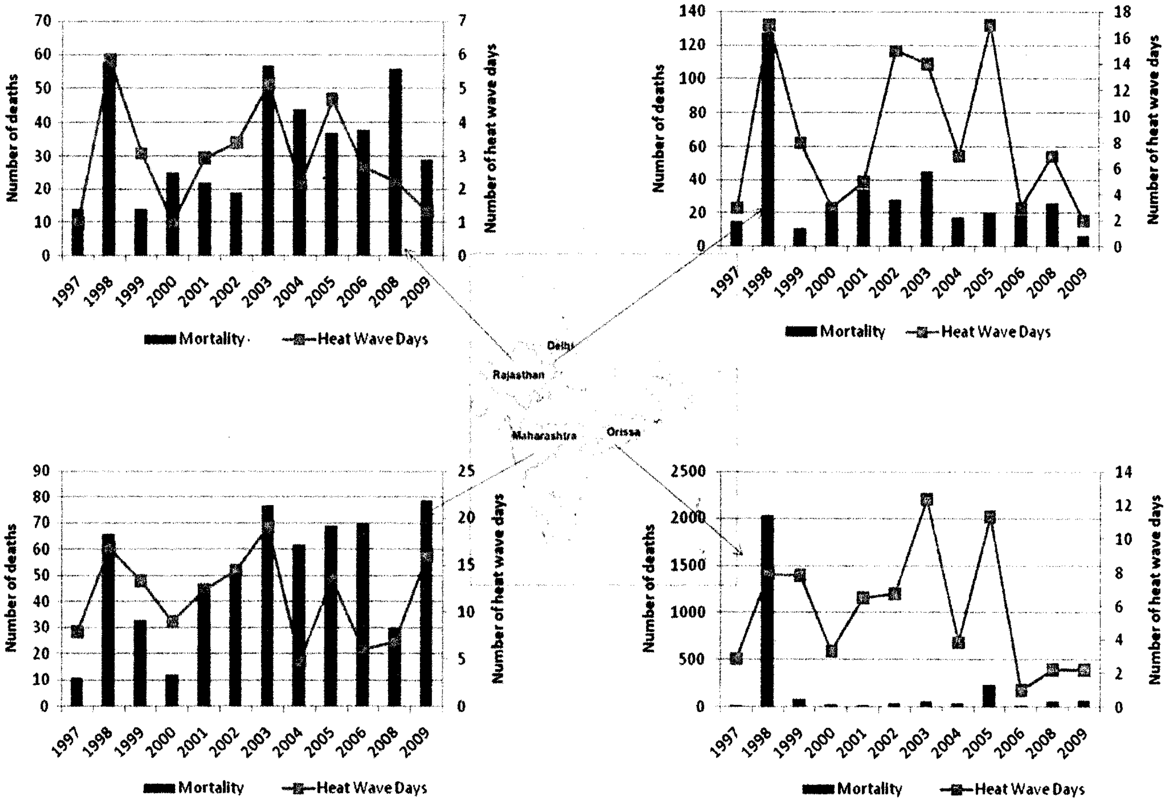

Fig. 5 Twelve years of annual mortality rates and annual severe heat wave days in four states of India

correlation with severe heat wave days; notwithstanding, the relationship fails to explain few sudden jumps in the mortality. We also obtained a fair regression between the annual number of severe heat wave days and mortality (Table 1), with the exception of Orissa because of very large mortality estimates in the year 1998.

Table 1 Statistical parameters of heat wave mortality relationship

Regression test	Delhi	Orissa	Rajasthan	Maharashtra
Slope (b)	3.1422	38.55	5.5939	2.3254
R	0.3195	0.0618	0.2902	0.202
p value of F test	0.0554	0.4359	0.0708	0.1427
Standard error	1.45	47.4928	2.7667	1.4617

Slope (annual mortality rates per annual number of severe heat wave days) gives regression coefficient b in Eq. (2); standard error shows uncertainty in parameter estimates using student t test; and p value shows the confidence using F test

The heat wave of the year 1998 was very brutal for most part of India, being associated with higher number of deaths, particularly in the states of Delhi and Orissa. The state of Orissa is a special case, where disaster relief management (DRM) plans at district levels have commenced after the super cyclone in 1999. Awareness generation was one of the important strategies of the plan where a major grassroots campaign was carried out to make people aware and inform them with risk reduction measure when disaster strikes (Das and Smith 2012). This could possibly be one of the reasons for the reduction in mortality during the severe heat waves in the years 2003 and 2005.

The regression coefficients obtained from measured mortality rates and the number of heat wave days in a year for four states were used to estimate future heat wave-induced mortality risk using the modeled climate data. Figure 6 presents historical and future mortality risk of the

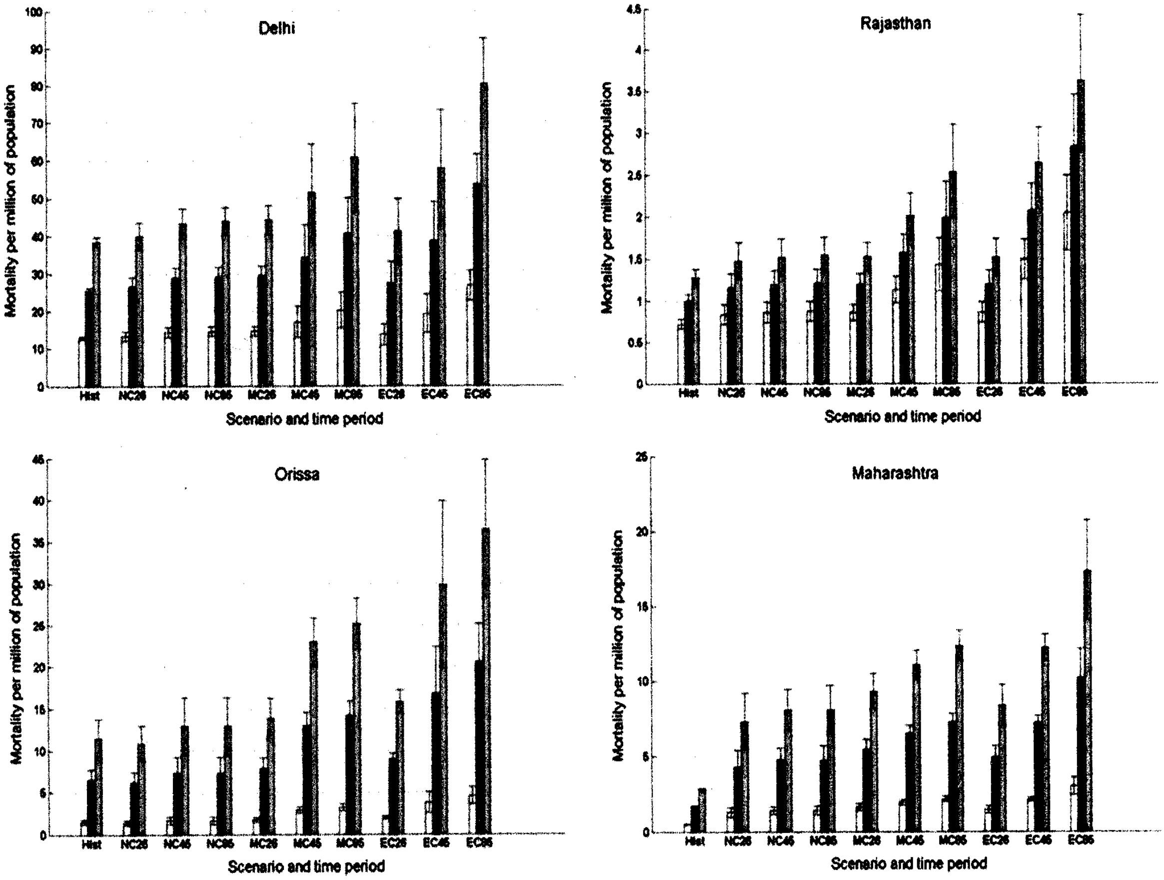

Fig. 6 Projection of mortality estimates obtained using the ensemble mean of seven climate models, in four Indian states. The *bar* shows the ensemble mean of mortality estimation from climate models. *Yellow* and *magenta bars* show the upper and lower bounds (obtained by 5 and 95 % confidence interval value of regression coefficients) of the mortality estimates obtained from the fitted regression model, shown by the *cyan bar*. The *black error bar* shows the spread of mortality estimation from temperature projections of seven climate models. NC (near century), MC (mid-century) and EC (end of century) indicate the periods 2010–2039, 2040–2069 and 2070–2099, respectively (color figure online)

four states based on the annual average mortality estimates; the figure represents the mean (that is, mean of an ensemble of seven models) of the estimates by applying the regression model. Lower and upper bounds based on 5 % and 95 % confidence interval of the mortality estimates (for regression models) for the four states are shown by bars, and the spread due to climate models is shown by the black error bars.

The results show that among the four states, heat wave-induced mortality in Delhi is projected to be higher, followed by Orissa, Maharashtra and Rajasthan. In the period 2010–2039, mortality projections under all three scenarios and by all the models are similar. The projection of mortality for Maharashtra is more than double that of the historical period. Furthermore, we observe that mortality projections under RCP26 are not very high, except for Maharashtra. This suggests that heat wave impacts could be limited if global warming is restricted to 2 °C.

One of the major assumptions in linear regression is that the residuals are normally distributed. Q–Q plots between residuals and standard normal quantiles show the validity of this assumption in all the states (Figure S2). The statistical significance of the goodness of fit is reported in Table 1. Results for Orissa and Maharashtra indicate poor statistical significance, and hence, the mortality projections have to be considered with caution.

Limitations of severe heat wave impacts analysis

Here, we use seven CMIP5 models, the increase of which may improve reliability to the projections. It is better to combine multiple model outputs rather than selecting or rejecting any specific model (Tebaldi and Knutti 2007). The physical parameterization changes across models, which may engender uncertainty in projections. Bayesian averaging is an approach that may combine models based on performance and convergence (Tebaldi et al. 2004). This was not performed in the present study and may be considered as a potential area for future research.

The heat stress analysis has been conducted at the daily temporal resolution and considers the daily mean value of specific humidity, instead of the humidity occurring concurrently as maximum temperatures. Nevertheless, the WGBT so calculated still provides insights into the role of temperature and humidity and other parameters such as wind speed and radiation on heat stress. The use of WBGT index and associated mortality analysis is not directly associated with the labor productivity. Such direct establishment requires detailed socioeconomic information, which is unavailable for India.

In India, mortality due to severe heat waves occurs mainly during the pre-monsoon hot season, and hence, the regression analysis was limited to the period from March to June. Data on timing of mortality are unavailable in India, and hence, analysis based on the correlation between the timing of severe heat waves and mortality figures is not performed here. This constitutes a limitation of the present analysis.

The lack of availability of other variables such as demographic details (age group, occupation, income level, resources available, the proportion of infants and the proportion of people suffering with the disease) places limitations on performance of the regression model. A significant source of uncertainty in projections of future mortality is also due to changes in exposure patterns (population distribution and occupation) and adaptation measures to heat, which are hard to determine.

Conclusion

In this study, we analyzed the future patterns of severe heat wave characteristics and the possible impact of heat waves on human health and mortality. Some of the key results of the work are highlighted as follows:

1. Severe heat waves will intensify in the future in India. Large regions of southern India, East and West coasts, which are presently unaffected by severe heat waves, are projected to be severely affected after 2070.
2. Severe heat waves are expected to appear early in the future. Our results suggest that under the worst case scenario (RCP 85), the first occurrence of severe heat waves is projected to be in early April.
3. A sizable part of India is projected to be exposed to extreme heat stress conditions.
4. Intensification of heat wave and heat stress condition may lead to increased mortality in India.

Our results suggest the necessity of adaptation policies to address the adverse effects of heat wave hazards, expected to occur earlier in the year and affect larger areas of India, including southern India. Although there are limitations in the present approach, our results are the first step in alerting policy makers to plan responses to more intense and persistent heat waves. This is applicable, more particularly, to the context of heat waves that have not yet been considered as a serious risk to human health, as well as heat wave hazards not being in the priorities of the disaster management plan of the Government of India (National Disaster Management Authority 2007). Our assessment calls strongly a better warning system, in addition to alerting the public and policy makers to translate our findings into an executable adaptation policy. We also emphasize the need for an extensive and elaborate study in order to understand the risk of such catastrophic events by meaningful interactions among scientists, society and policy makers.

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