ENVIRONMENTAL SCIENCE

Increasing probability of mortality during Indian heat waves

Omid Mazdiyasni,[1] Amir AghaKouchak,[1]* Steven J. Davis,[2] Shahrbanou Madadgar,[1] Ali Mehran,[1,3] Elisa Ragno,[1] Mojtaba Sadegh,[1,4] Ashmita Sengupta,[5] Subimal Ghosh,[6] C. T. Dhanya,[7] Mohsen Niknejad[1]

Rising global temperatures are causing increases in the frequency and severity of extreme climatic events, such as floods, droughts, and heat waves. We analyze changes in summer temperatures, the frequency, severity, and duration of heat waves, and heat-related mortality in India between 1960 and 2009 using data from the India Meteorological Department. Mean temperatures across India have risen by more than 0.5°C over this period, with statistically significant increases in heat waves. Using a novel probabilistic model, we further show that the increase in summer mean temperatures in India over this period corresponds to a 146% increase in the probability of heat-related mortality events of more than 100 people. In turn, our results suggest that future climate warming will lead to substantial increases in heat-related mortality, particularly in developing low-latitude countries, such as India, where heat waves will become more frequent and populations are especially vulnerable to these extreme temperatures. Our findings indicate that even moderate increases in mean temperatures may cause great increases in heat-related mortality and support the efforts of governments and international organizations to build up the resilience of these vulnerable regions to more severe heat waves.

INTRODUCTION

Global mean temperatures are expected to increase by as much as 5.5°C by the end of this century (*1*), which is, in turn, expected to increase the intensity of heat waves around the world (*2*–*4*), with the largest relative effect on summer temperatures in developing regions, such as Africa, South America, Middle East, and South Asia (*5*). The impact of these heat waves on human and natural systems include decreased air quality, diminished crop yields, increased energy consumption, increased evapotranspiration, intensification of droughts, and—perhaps most concerning of all—direct effects on human health (*6*, *7*). Heat stress during periods of high temperatures may also exacerbate health problems, such as cardiovascular and respiratory diseases, and cause life-threatening crises (*8*, *9*). Certain segments of the population, such as the young, elderly, and poor, may therefore be especially susceptible to this health impact due to existing health conditions and lack of basic resources, such as clean drinking water, shelter, access to air conditioning, and health care (*10*). Populations without central air conditioning tend to have higher heat-related mortality rates (*11*).

In light of geographical patterns of warming and vulnerable populations, we present here an analysis of a half-century (1960–2009) of temperature, heat waves, and related mortality in India. Previous studies report that between 1971 and 2007, there was an increase of more than 0.5°C in mean temperatures across India (*12*), and the projected annual spatial warming in India will be between 2.2° and 5.5°C by the end of the 21st century, with higher projections over northern, central, and western India (*13*, *14*). On the basis of data from the World Bank, of the 1.24 billion people living in India in 2011 (18% of global population), an estimated 23.6% earned <$1.25 per day and ~25% did not have any access to electricity, making them especially vulnerable to the impact of heat waves (*15*). This vulnerability has been made clear by events in recent years: Heat waves in 2010 killed more than 1300 people in the city of Ahmedabad alone, prompting the start of efforts to develop coordinated Heat Action Plans (*16*). However, these efforts remain limited and localized, and, in 2013 and 2015, the country experienced another bout of intense heat waves that killed more than 1500 and 2500 people across the country, respectively. Since then, there have been several more deadly heat waves, including the most intense Indian heat wave in recorded history in May of 2016 when maximum temperatures in Jaisalmer reached 52.4°C.

Heat waves are usually described as successive hot days (*4*, *17*) and are often defined on a percentile basis (*6*). Here, we consider heat waves to be three or more consecutive days of temperatures above the 85th percentile of the hottest month for each specific location. Figure S1 shows the heat wave threshold values across India (85th percentile of hottest month's mean temperature in °C). For each warm season in India (April to September) from 1960 to 2009, we assess four different heat wave properties: (i) accumulated heat wave intensity, (ii) annual heat wave count, (iii) mean heat wave duration, and (iv) heat wave days. The annual heat wave count and mean duration are simply the number of heat wave events that occur each year and their average duration in days, respectively. Heat wave days are the product of heat wave count and duration and represent the number of days under heat wave conditions. We evaluate accumulated heat wave intensity as the cumulative cooling degree day (CDD), or the sum of the daily mean temperature during a heat wave subtracted by 22°C, over the entire heat wave event [that is, (daily temperature in°C − 22°C) × duration in days]. We perform our heat wave analyses based on summer mean temperatures (that is, the average of mean daily temperatures during summer) because we believe this to be a better indicator of accumulated heat stress. However, we also provide analyses based on summer maximum temperatures in the Supplementary Materials. These analyses are performed using $1° \times 1°$ daily temperature records from the India Meteorological Department. Finally, we use the results from these retrospective analyses to develop a conditional probabilistic model of the relationships among summer

[1]Department of Civil and Environmental Engineering, University of California, Irvine, Irvine, CA 92697, USA. [2]Department of Earth System Science, University of California, Irvine, Irvine, CA 92697, USA. [3]Department of Geography, University of California, Los Angeles, Los Angeles, CA 90095, USA. [4]Department of Civil Engineering, Boise State University, Boise, ID 83725, USA. [5]Southern California Coastal Water Research Project, 3535 Harbor Boulevard, Costa Mesa, CA 92626, USA. [6]Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, Maharashtra 400076, India. [7]Department of Civil Engineering, Indian Institute of Technology Delhi, New Delhi, Delhi 110016, India.
*Corresponding author. Email: amir.a@uci.edu

mean temperatures, heat wave days, and heat-related mortality that we apply to estimate the probability distribution of heat-related mortality related to mean climate warming in the future. Further details of our analytic approach are provided in Methods.

RESULTS AND DISCUSSION

Figure 1A shows that summer mean temperatures have increased substantially from 1960 to 2009. The time series exhibits a statistically significant (95% confidence interval) upward trend confirmed using the Mann-Kendall (MK) trend test. The accumulated intensity, count, duration, and days of Indian heat waves have also increased over the analyzed time period over most of the country and especially in the northern, southern, and western parts of India (Fig. 1, B to E).

The red shading that dominates most of the maps in Fig. 1 indicates that the observed increases are widespread and strong: Southern and western India experienced 50% more heat wave events during the period 1985–2009 than during the previous 25-year period (calculated by dividing the difference in the number of events from 1985 to 2009 relative to 1960 to 1984 by the total number of events). Similarly, heat wave days and the mean duration of heat waves have increased by approximately 25% in the majority of India. Figure S2 shows the same analysis for heat waves calculated using summer maximum temperatures. Figure S3 shows the mean values for each heat wave characteristic from 1960 to 1984 and 1985 to 2009 separately. Figure S4 shows the areas where there was a statistically significant trend confirmed by the MK trend test.

Figure 2A shows the relationships among standardized values of summer mean temperatures, heat wave days, and annual heat-related mortality occurring over the period 1967–2007 (the period for which reliable mortality data were available; see the Supplementary Materials for details). Although high summer mean temperatures often correspond to spikes in deaths, the correlation of temperatures to deaths is weaker (Pearson's linear correlation = 63%, $r^2 = 0.38$; Fig. 2B) than the correlation to the number of heat wave days each year (Pearson's linear correlation = 77%, $r^2 = 0.58$; Fig. 2C), especially in the years when there were high mortality rates.

In an effort to understand the underlying mechanisms of heat wave mortality, we further explored its relationship with population and income levels in India. Figure 3 shows that the relationship between population-weighted heat wave days and mortality rates is only slightly better than that between mortality and summer mean temperatures (Pearson's

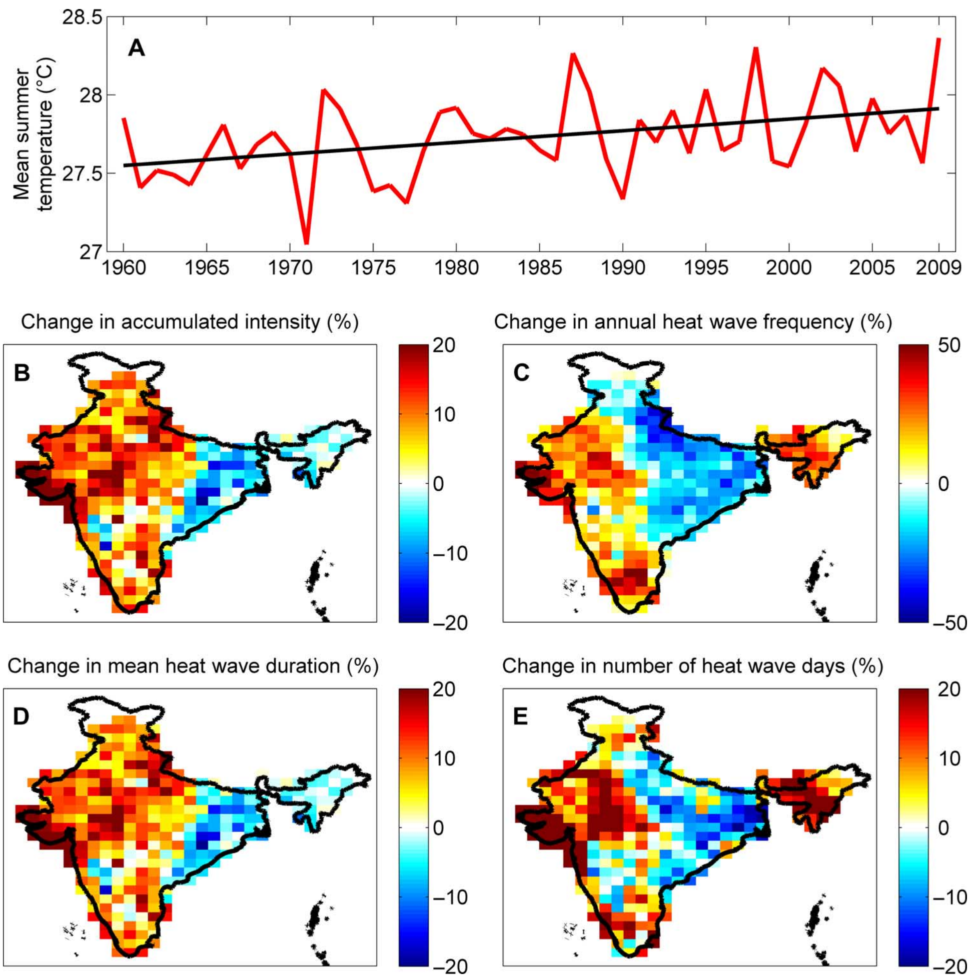

Fig. 1. Temperature and heat wave increases in India (1960–2009). Summer mean temperatures in India have increased from 1960 to 2009, as indicated by the MK trend test (**A**). The (**B**) accumulated heat wave intensity, (**C**) number of heat wave events, (**D**) heat wave duration, and (**E**) heat wave days during the latter period (1985–2009) has also increased over most areas of India relative to the previous period of 1960–1984.

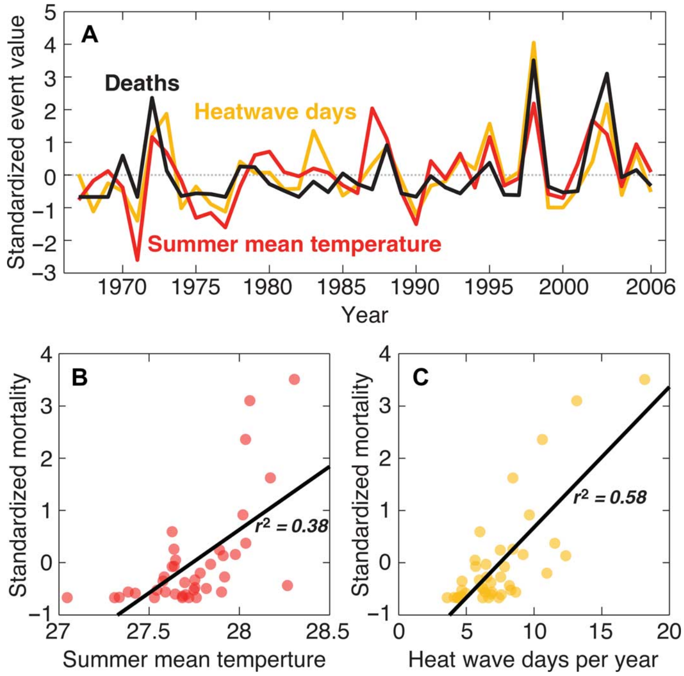

Fig. 2. Standardized number of heat wave days, summer mean temperatures, and heat-related mortality. Standardized trends show the correspondence among the three variables. In years when heat wave days (yellow) and summer mean temperature (red) are above average, heat-related deaths also spike upward.

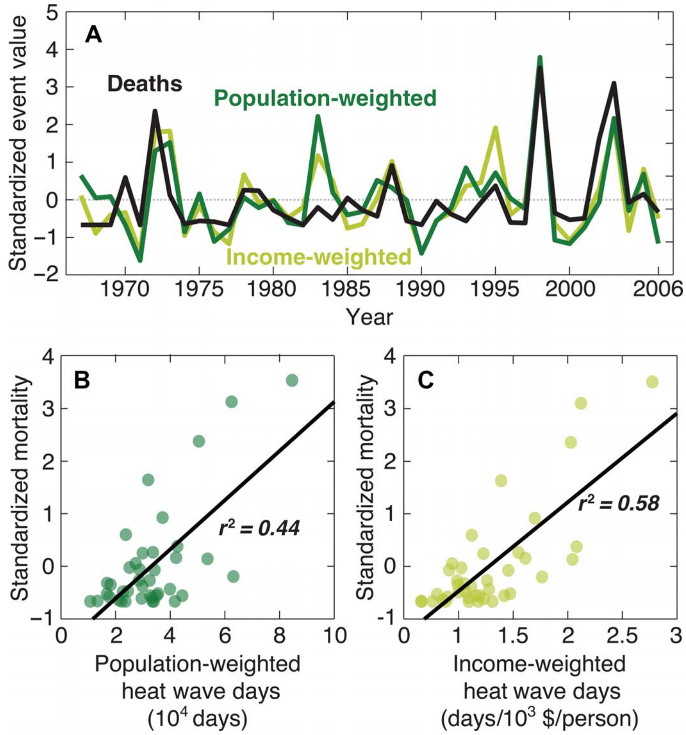

Fig. 3. Standardized population-weighted heat wave days, income-weighted heat wave days, and heat-related mortality. Standardized trends show the correspondence among the three variables. In most years when income-weighted heat waves (light green) and population-weighted heat waves (dark green) are above average, heat-related deaths also increase markedly.

linear correlation = 67%, r^2 = 0.44; Fig. 3B); however, the correlation between income-weighted heat wave days and mortality rates is better (Pearson's linear correlation = 77%, r^2 = 0.58; Fig. 3C).

On the basis of these correlations, we infer that the relationship between income and human health is stronger than that between physical conditions and health, perhaps as the result of access to air conditioning or medical care. It is known that some highly populated regions have low income per capita (for example, northern India), and many rural low-populated regions also have low income per capita (that is, central and eastern India), which we show in fig. S5.

Figure 2A highlights several years—1972, 1988, 1998, and 2003—in which there were more than 10 heat wave days on average across India, with corresponding spikes in heat-related mass mortality of between 650 and 1500 people. However, there are a few years, such as 1973, 1983, 1984, and 1995, in which there were an above-average number of income-weighted heat wave days but a low number of deaths. A possible explanation for this is that the areas where these latter heat waves occurred tended to be less populous and/or wealthier regions (see fig. S5). These observations reinforce previous work that highlighted poverty as a significant factor in climate-induced mortality, such as heat wave deaths (*18*).

Figure 4 shows the results of a conditional probability density analysis (see Methods) of annual mortality, given certain thresholds for summer mean temperatures and heat wave days. The shaded region represents the probability of mass heat-related mortality (that is, heat-related deaths of more than 100 people), given different summer temperature values. For example, Fig. 4A shows that there is 13% probability that years with summer mean temperatures equal to 27°C will result to mass heat-related mortality. However, with an increase in summer mean temperatures of just 0.5°C (to 27.5°C), the probability of these levels of heat-related deaths jumps by a factor of 2.5 to 32%. Figure S6 shows a similar relationship with summer maximum temperatures. Similarly, Fig. 3B shows that the probability of heat-related mass mortality events increases from 46 to 82% (78% increase) when the average number of heat wave days across India shifts from 6 to 8 days, respectively. The substantial increase in mortality rates due to either a 0.5°C increase in summer mean temperature or two more heat wave days suggests that future climate warming could have a relatively drastic human toll in India and similarly in developing tropical and subtropical countries. Meanwhile, some experts expect India's temperature to rise from 2.2° to 5.5°C (*13*, *14*).

By almost all measures, heat waves have increased markedly across India over the past half-century and, with this, the incidence of heat-related mortality. Projected increases in global mean temperatures under a range of climate change scenarios can be expected to extend these trends. Although India is particularly susceptible to heat waves given its geography and current state of human development, there are many countries that are similarly vulnerable to the extreme heat events in the ever-warming world. Our results suggest that even moderate and practically unavoidable increases in mean temperatures, such as 0.5°C, may lead to large increases in heat-related mortality, unless measures are taken to substantially improve the resilience of vulnerable populations.

METHODS

Temperature and mortality data

Daily temperature data based on 395 weather stations and interpolated at 1° × 1°spatial resolution was obtained from the India Meteorological

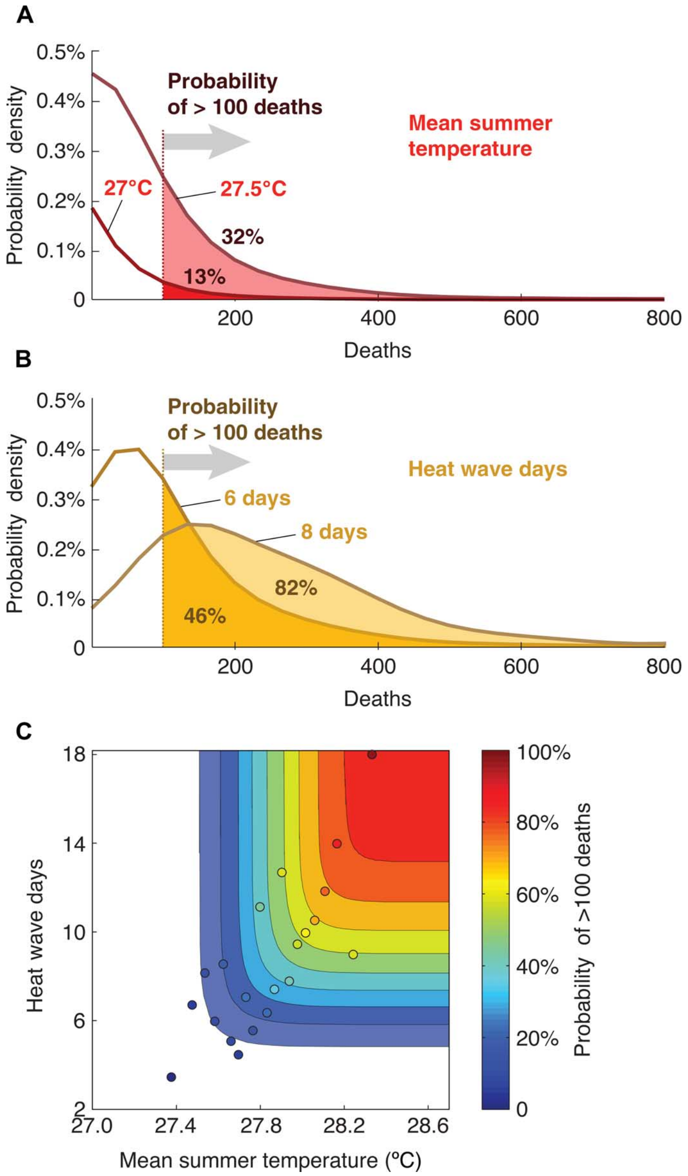

Fig. 4. Probabilities of heat wave–caused mass mortality events. Parametric conditional probability density functions (PDFs) for yearly mortality given certain thresholds for summer mean temperatures (**A**) and heat wave days (**B**). With 0.5°C warmer mean temperatures or two more heat wave days per year, the probability of >100 heat-related deaths increase markedly. The relationship between the two variables and probability of mass mortality events is shown in (**C**).

Department (*19*). Mortality data were also obtained from the India Meteorological Department and from annual reports, which compiled information from newspaper and other sources about mortality during specific extreme heat events (*20*).

Statistical methods

This paper used the Kolmogorov-Smirnov (KS) test to analyze the changes in distribution functions of heat waves in different periods. We used the two-sample KS test to analyze the differences between the cumulative distribution functions (CDFs) for the number of heat waves. This study compared the different types of heat waves that occurred in 1985–2009 relative to those in 1960–1984. The KS test is a nonparametric test that evaluates whether there is a statistically significant change between two distributions by calculating the largest distance between their empirical distributions. The null hypothesis is that the data sets come from the same distribution at a certain confidence interval (95% confidence interval in this study).

The KS test determines changes in empirical distribution functions by comparing pre- and postchange samples, defined as

$$\hat{F}_{\mathrm{S}}(x) = \frac{1}{\tau}\sum_{i=1}^{\tau} I(X_i \leq x)$$

$$\hat{F}_{\mathrm{T}}(x) = \frac{1}{n-\tau}\sum_{i=\tau+1}^{n} I(X_i \leq x)$$

where $\hat{F}_{\mathrm{S}}(x)$ and $\hat{F}_{\mathrm{T}}(x)$ are the empirical CDF of the two subsamples, I is the indicator function, n denotes sample size, and the terms $\frac{1}{\tau}$ and $\frac{1}{n-\tau}$ are adjustment factors for the length of each subsample. The KS test statistic is the maximum difference between two empirical distributions

$$D_{\tau,n} = \sup_x \left|\hat{F}_{\mathrm{S}}(x) - \hat{F}_{\mathrm{T}}(x)\right|$$

Larger divergence values ($D_{\tau,n}$) represent greater changes in the cumulative distributions (*21*, *22*).

The MK trend test analyzes whether there is a statistically significant trend (95% confidence interval) in the number of heat waves per year time series. The MK test is a nonparametric test that uses the empirical ranks of time series and is widely used in hydrology and climatology (*23*).

Here, we used the r^2 measure to determine how close the mortality and heat wave characteristics data are to their respective fitted regression lines. The r^2 statistic measures the proportion of variance in the dependent variable that is predictable from the independent variable. Lower r^2 values depict the fact that the dependent variable (mortality) cannot be predicted from the independent variable (heat wave days), and higher values portray the fact that the dependent variable can be predicted with little to no error from the independent variable (*24*).

Calculation of conditional probabilities

To derive the conditional probabilities presented in Fig. 4, we used the multivariate copula functions (*25*–*28*) to find the joint probability distribution of mortality and summer mean temperatures across India. We fitted the Frank copula and *t* copula families to the summer mean temperatures and mortality, and heat wave days and mortality data, respectively, because they have the highest statistically significant (95% confidence interval) maximum likelihood among all the copula families. Maximum likelihood and *P* values for five major copula families with respect to summer mean temperatures and heat wave days relative to mortality are shown in table S1. A copula function is defined as the multivariate distribution function (*29*, *30*)

$$\begin{aligned} F_{X_1 \ldots X_n}&(x_1, \ldots, x_i, \ldots, x_n) \\ &= C[F_{X_1}(x_1), \ldots, F_{X_i}(x_i), \ldots, F_{X_n}(x_n)] \\ &= C(U_1, \ldots, U_i, \ldots, U_n) \end{aligned} \quad (1)$$

where C is the CDF of the copula and $F_{X_i}(x_i)$ is the nonexceedance probability of x_i (marginal distribution). Here, we used the bivariate form to estimate the joint probability distribution of mortality rates and summer mean temperatures, as well as mortality rates and heat wave days in India

$$F_{XY}(x,\ y) = C[F_X(x),\ F_Y(y)] \tag{2}$$

To determine the conditional probabilities of mortality rates exceeding a threshold ($Y > y$) at different summer mean temperatures ($X = x_1, x_2, \ldots$), that is, $F_{Y|X}(Y > y \mid X)$, we developed the conditional PDF (*31*)

$$f_{Y|X}(y \mid x) = c[F_X(x),\ F_Y(y)] \cdot f_Y(y) \tag{3}$$

where c is the PDF of the copula function and $f_Y(y)$ is the mortality marginal distribution. Once we choose a certain summer mean temperature conditional PDF from Eq. 3, the probability of the mortality rates (Y) exceeding a particular threshold (y) is given by the area under the curve $f_{Y|X}(y \mid x)$. This allowed the calculation of conditional PDF $f_{Y|X}(y \mid x)$ for different values of x (for example, summer mean temperatures = 27°C or heat wave days = 6 in Fig. 4).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/6/e1700066/DC1

fig. S1. Heat wave thresholds across India.

fig. S2. Summer mean temperatures have increased substantially from 1960 to 2009.

fig. S3. Mean heat wave characteristic value for two 25-year periods (1960–1984 and 1985–2009).

fig. S4. Trend in the accumulated intensity, count, duration, and days of Indian heat waves' distribution functions from 1960 to 2009 based on the MK trend test.

fig. S5. Population and income spatial distribution in India and the number of heat wave days that occurred in 1973, 1983, 1984, and 1995.

fig. S6. Results of a conditional probability density analysis of mortality given certain thresholds for summer maximum temperatures.

fig. S7. CDDs have increased substantially from 1960 to 2009.

table S1. Maximum likelihood and *P* values for mean summer mean temperature (MST mean)/mortality and heat wave days (HW days)/mortality for different copula families.

table S2. Values of mortality, heat wave days, and summer mean temperatures.

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