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# Increasing Probability of Mass-Mortality During Indian Heatwaves

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An increase of 0.5 °C in summer mean temperatures increases the probability of mass heat-related mortality in India by 146%.

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Rising global temperatures are causing increases in the frequency and severity of extreme climatic events such as floods, droughts, and heatwaves. Here, we analyze changes in summer temperatures, the frequency, severity and duration of heatwaves, 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 heatwaves. 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 heatwaves 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 efforts of governments and international organizations to build-up the resilience of these vulnerable regions to more and more severe heatwaves.

Global mean temperatures are expected to increase by as much as 5.5 °C by the end of this century<sup>1</sup>, which in turn is expected to increase the intensity of heatwaves around the world<sup>2-4</sup>, with the largest relative effects on summer temperatures in developing regions such as Africa, South America, the Middle East and south Asia<sup>5</sup>. The impacts of such heatwaves 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<sup>6,7</sup>. Heat stress during periods of high temperatures may also exacerbate health problems such as cardiovascular and respiratory disease and cause life-threatening crises<sup>8,9</sup>. Certain segments of the population such as the young, elderly, and poor may therefore be especially susceptible to these health impacts due to existing health conditions as well as lack of basic resources such as clean drinking water, shelter, access to air conditioning and healthcare<sup>10</sup>. Populations without central air conditioning tend to have higher heat-related mortality rates<sup>11</sup>.

In light of geographical patterns of warming and vulnerable populations, here we present an analysis of a half-century (1960-2009) of temperature, heatwaves, and related mortality in India. Previous studies report that between 1971 and 2007, there was an increase of over 0.5 °C in mean temperatures across India<sup>12</sup>, and the projected annual spatial warming in India will be between 2.2 – 5.5 °C by the end of the 21<sup>st</sup> Century, with higher projections over north, central, and west India<sup>13,14</sup>. Based on 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 impacts of heatwaves<sup>15</sup>. This vulnerability has been made clear by events in recent years: heatwaves in 2010 killed over 1300 people in the city of Ahmedabad alone, prompting the start of efforts to develop coordinated Heat Action Plans<sup>16</sup>. However, these efforts remain limited and localized, and in 2013 and 2015 the country experienced another bout of intense heatwaves that killed over 1500 and 2500 people across the country, respectively. Since then, there have been several more deadly heatwaves, including the most intense Indian heatwave in recorded history in May of 2016 when maximum temperatures in Jaisalmer reached 52.4°C.

Heatwaves are usually described as successive hot days<sup>4,17</sup>, and are often defined on a percentile basis<sup>6</sup>. Here, we consider heatwaves to be three or more consecutive days of temperatures above the 85<sup>th</sup> percentile of the hottest month for each specific location. Figure S1 shows the heatwave threshold values across India (85<sup>th</sup> percentile of hottest month's mean temperature °C). For each warm season in India (April-September) from 1960 to 2009, we assess four different heatwave properties: (1) accumulated heatwave intensity, (2) annual heatwave count, (3) mean heatwave duration, and (4) heatwave days. The annual heatwave count and mean duration are simply the number of heatwave events that occur each year and their average duration in days, respectively. Heatwave days is the product of heatwave count and heatwave duration, and represents the number of days under heatwave condition. We evaluate accumulated heatwave intensity as the cumulative cooling degree-day (CDD), or the sum of the daily mean temperature during a heatwave subtracted by 22 °C, over the entire heatwave event [i.e. (daily temperature °C – 22 °C) x duration in days]. We perform our heatwave analyses based on summer mean temperatures (i.e. the average of mean daily temperatures during the 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 Information section. These analyses are performed using 1° x 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 mean temperatures, heatwave 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 the Methods section.

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 trend test. The accumulated intensity, count, duration, and heatwave days of Indian heatwaves have also increased over the analyzed time period over most of the country, and especially in northern, southern, and western parts of India (Figure 1b-e).

The red shading that dominates most of the maps in Figure 1 indicates that the observed increases are widespread and strong: southern and western India experienced 50% more heatwave events during the period 1985-2009 than during the previous 25-year period (calculated by dividing the difference in the number of events from 1985-2009 relative to 1960-1984 by the total number of events). Similarly, heatwave days and the mean duration of heatwaves have increased by approximately 25% in the majority of India. Supplementary Figure S2 shows the same analysis for

heatwaves calculated by using summer maximum temperatures. Supplementary Figure S3 shows mean values for each heatwave characteristic from 1960 – 1984 and 1985 – 2009, separately. Supplementary Figure S4 shows the areas where there was a statistically significant trend confirmed by the Mann-Kendall Trend Test.

Figure 2a shows the relationships among standardized values of summer mean temperatures, heatwave days, and annual heat-related mortality occurring over the period 1967-2007 (the period for which reliable mortality data were available; see Supplementary Information 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 with the number of heatwave 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 heatwave mortality, we further explored its relationship with population and income-levels in India. Figure 3 shows that the relationship between population-weighted heatwave days and mortality rates is only slightly better than that between mortality and summer mean temperatures (Pearson's linear correlation 67%,  $r^2=0.44$ ; Fig. 3b). However, the correlation between income-weighted heatwave days and mortality rates is better (Pearson's linear correlation 77%,  $r^2=0.58$ ; Fig. 3c).

Based on these correlations, we infer that the relationship between income and human health is stronger than that of 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 (e.g., northern India) and also many rural, low populated regions also have low income per capita (i.e. central and eastern India), which we show in Figure S5.

Figure 2a highlights several years—1972, 1988, 1998, and 2003—in which there were more than ten heatwave 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 heatwave days, but a low number of deaths. A possible explanation is that the areas where these latter heatwaves occurred tended to be less populous and/or wealthier regions (see Supplementary Figure S5). Such observations reinforce previous work that has highlighted poverty as a significant factor in climate-induced mortality, such as heatwave deaths<sup>18</sup>.

Figure 4 presents the results of a conditional probability density analysis (see Methods) of annual mortality given certain thresholds for summer mean temperatures and heatwave days. The shaded region represents the probability of mass heat-related mortality (i.e. heat-related deaths of more than 100 people), given different summer temperature values. For example, the Figure 4a shows that there is 13% probability that years with summer mean temperatures equal to 27 °C will have mass heat-related mortality. However, with an increase in summer mean temperatures of just 0.5 °C (to 27.5 °C), the probability of such 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, Figure 3b shows that the probability of heat-related mass mortality events increases from 46% to 82% (78% increase) where the average number of heatwave days across India shift from 6 days to 8 days, respectively. The substantial increase in mortality rates due to either a 0.5 °C increase in summer mean temperature or 2 more heatwave 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 2.2 – 5.5 degrees Celsius<sup>13,14</sup>.

By almost all measures, heatwaves have increased dramatically across India over the past half-century and with them 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 heatwaves 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° x 1° spatial resolution was obtained from the India Meteorological Department<sup>19</sup>. Mortality data was also obtained from the India Meteorological Department and based on mortality data from annual reports which compiled information from newspaper and other sources about mortality during specific extreme heat events<sup>20</sup>.

### Statistical Methods

This paper uses the Kolmogorov-Smirnov test to test changes in distribution functions of heatwaves in different periods. We use the two-sample Kolmogorov-Smirnov (KS) test to analyze the differences between the cumulative distribution functions (CDFs) for the number of heatwaves. This study compares the different types of heatwaves 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-change and post-change samples, defined as:

$$\hat{F}_S(x) = \frac{1}{\tau} \sum_{i=1}^{\tau} I(X_i \leq x);$$

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

where  $\hat{F}_S(x)$  and  $\hat{F}_T(x)$  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:

$$D_{\tau,n} = \sup_x |\hat{F}_S(x) - \hat{F}_T(x)|,$$

Larger divergence values ( $D_{\tau,n}$  and  $W_{\tau,n}$ ) represent greater changes in the cumulative distributions<sup>21,22</sup>.

The Mann-Kendall (MK) trend test analyzes whether there is a statistically significant trend (95% confidence interval) in the number of heatwaves 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<sup>23</sup>.

In this paper, we use R-squared measure to determine how close the mortality and heatwave characteristics' data are to the respective fitted regression lines. The R-squared statistic measures the proportion of variance in the dependent variable that is predictable from the independent variable. Lower R-squared values depict the dependent variable (mortality) cannot be predicted from the independent variable (heatwave days), and higher values portray the dependent variable can be predicted with little to no error from the independent variable<sup>24</sup>.

### Calculation of Conditional Probabilities

To derive the conditional probabilities presented in Figure 4, this paper utilizes the multivariate copula functions<sup>25-28</sup> to find the joint probability distribution of mortality and summer mean temperatures across India. We fit the Frank copula and t-copula families to the summer mean temperatures and mortality, and heatwave days and mortality data, respectively, because they have the highest statistically significant (95% confidence interval) maximum likelihood out of all the copula families. Maximum Likelihood values and p-values for five major copula families with respect to summer mean temperatures and heatwave days relative to mortality are in the Supplementary Table S1. A copula function is defined as the multivariate distribution function<sup>29,30</sup>:

$$F_{X_1 \dots X_n}(x_1, \dots, x_i, \dots, x_n) = C[F_{X_1}(x_1), \dots, F_{X_i}(x_i), \dots, F_{X_n}(x_n)] = C(U_1, \dots, U_i, \dots, U_n) \quad (1)$$

where  $C$  is the cumulative distribution function (CDF) of the copula and  $F_{X_i}(x_i)$  is the non-exceedance probability of  $x_i$  (marginal distribution). Here we use the bivariate form to estimate the joint probability distribution of mortality rates and summer mean temperatures as well as mortality rates and heatwave days in India:

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

To determine the conditional probabilities of mortality rates exceeding a threshold ( $Y > y$ ) at different summer mean temperatures ( $X = x_1, x_2, \dots$ ), i.e.  $F_{Y|X}(Y > y | X)$ , we develop the conditional probability density function<sup>31</sup>:

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

where  $c$  is the probability density function (PDF) 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:  $f_{Y|X}(y | x)$ . This allows calculating conditional PDF  $f_{Y|X}(y | x)$  for different values of  $x$  (e.g., summer mean temperatures=27 °C or heatwave days=6 in Figure 4).

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**Authors Contributions:** AA and OM conceived the study. OM carried out the data analysis, and conducted the experiment. SM contributed to the development of the code. ER reviewed the mathematical framework. OM, AA and SJD prepared the first draft. OM, AA, SJD, AM, MS, AS, SG, CTD, MN contributed to the discussion and interpretation of the results. All authors reviewed and commented on the paper.

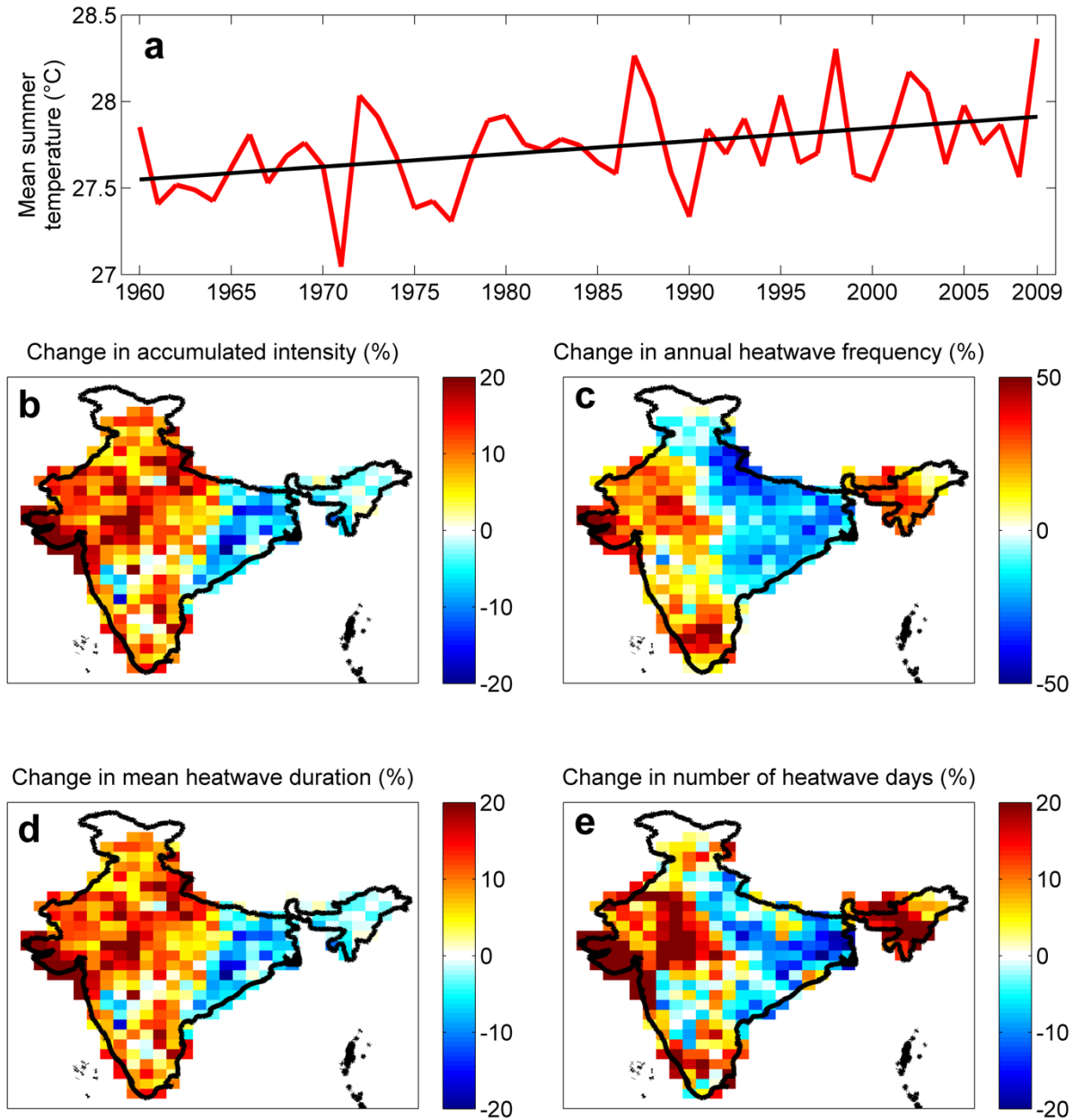
**Competing interests:** The authors declare no competing interests.

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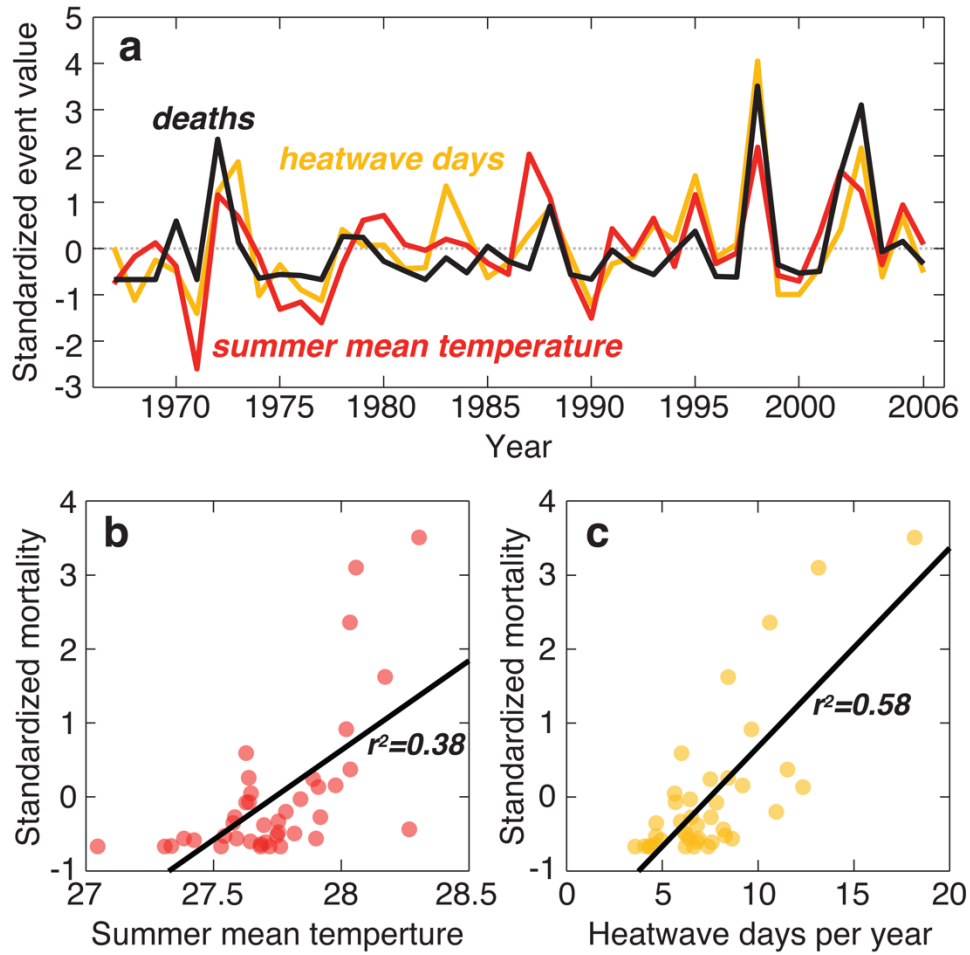
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### Figures

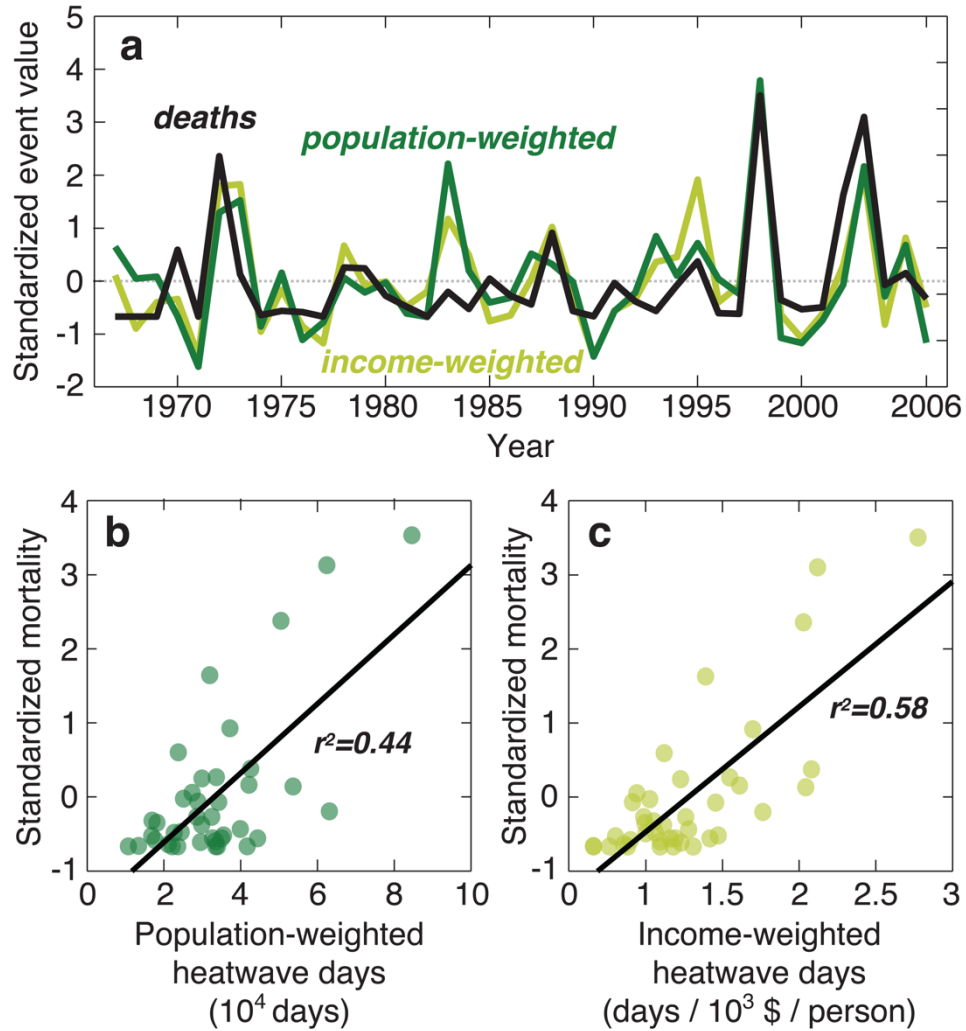


**Figure 1| Temperature and heatwave increases in India 1960-2009.** Summer mean temperatures in India have increased 1960-2009 as indicated by the Mann-Kendall Trend Test (a). The (b) accumulated heatwave intensity, (c) number of heatwave events, (d) heatwave duration, and (e) heatwave days during the latter period (1985-2009) has also increased over most areas of India relative to the preceding period of 1960-1984.

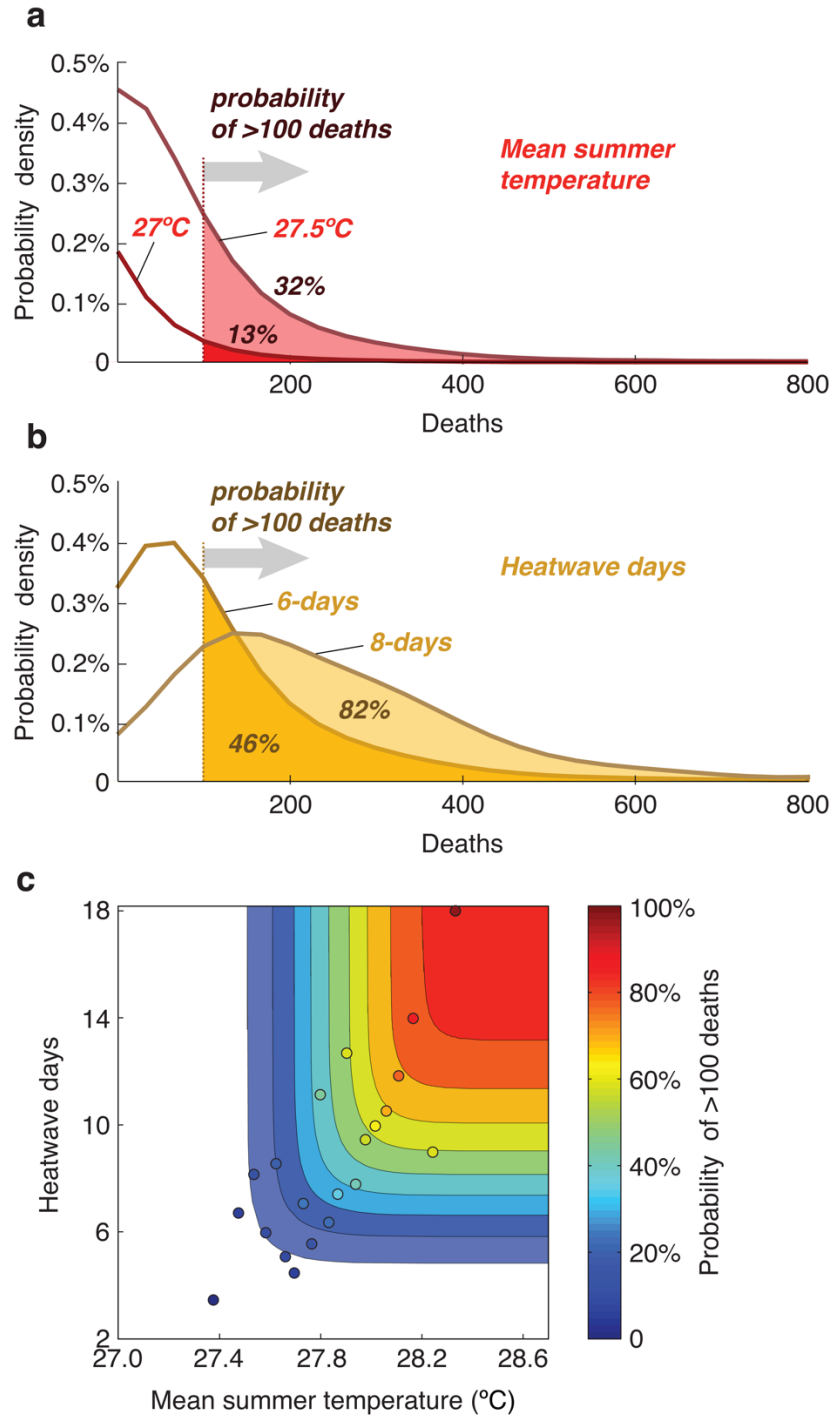




**Figure 2 | Standardized number of heatwave days, summer mean temperatures, and heat-related mortality.** Standardized trends show the correspondence among the three variables. In years where heatwaves days (yellow) and summer mean temperature (red) are above-average, heat-related deaths also spike upwards.



**Figure 3 | Standardized population-weighted heatwave days, income-weighted heatwave days, and heat-related mortality.** Standardized trends show the correspondence among the three variables. In most years where income-weighted heatwaves (red) and population-weighted heatwaves (yellow) are above-average, heat-related deaths also increase dramatically.



**Figure 4 | Probabilities of heatwave-caused mass-mortality events.** Parametric conditional probability density functions for yearly mortality given certain thresholds for summer mean temperatures (a) and heatwave days (b). With 0.5 °C warmer mean temperatures or 2 more heatwave days per year, the probability of >100 heat-related deaths increase dramatically. The relationship between the two variables and probability of mass mortality events is shown in panel c.

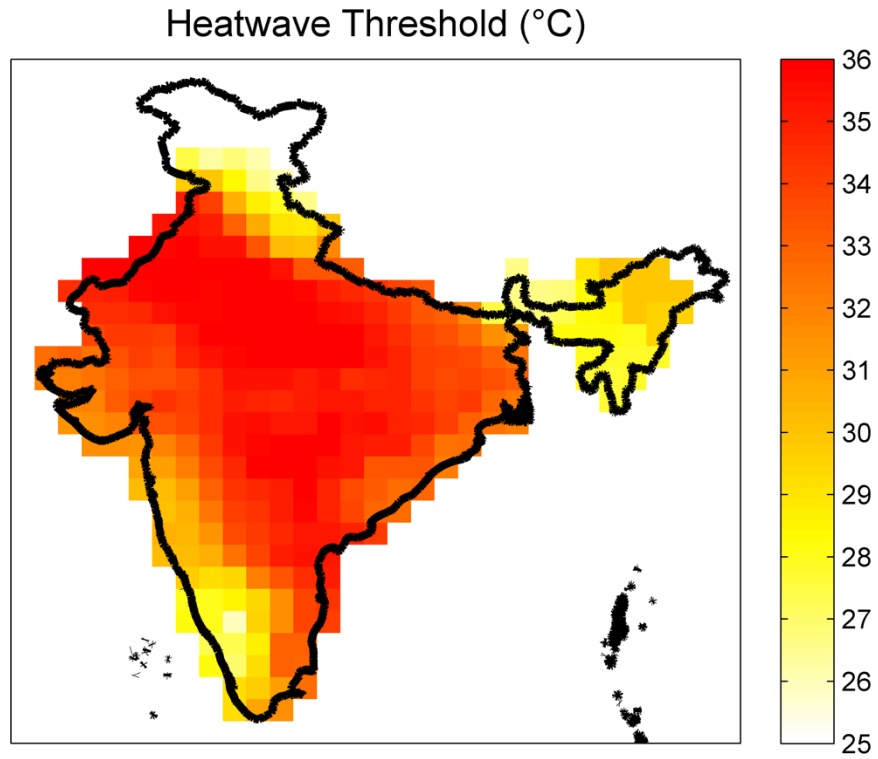


Figure S1 shows the heatwave thresholds across India. We calculate these thresholds by obtaining the 85<sup>th</sup> percentile of the daily mean temperatures of the hottest month in each grixbox. We show that the threshold of heatwaves are extremely high (>36 °C) for the majority of India.

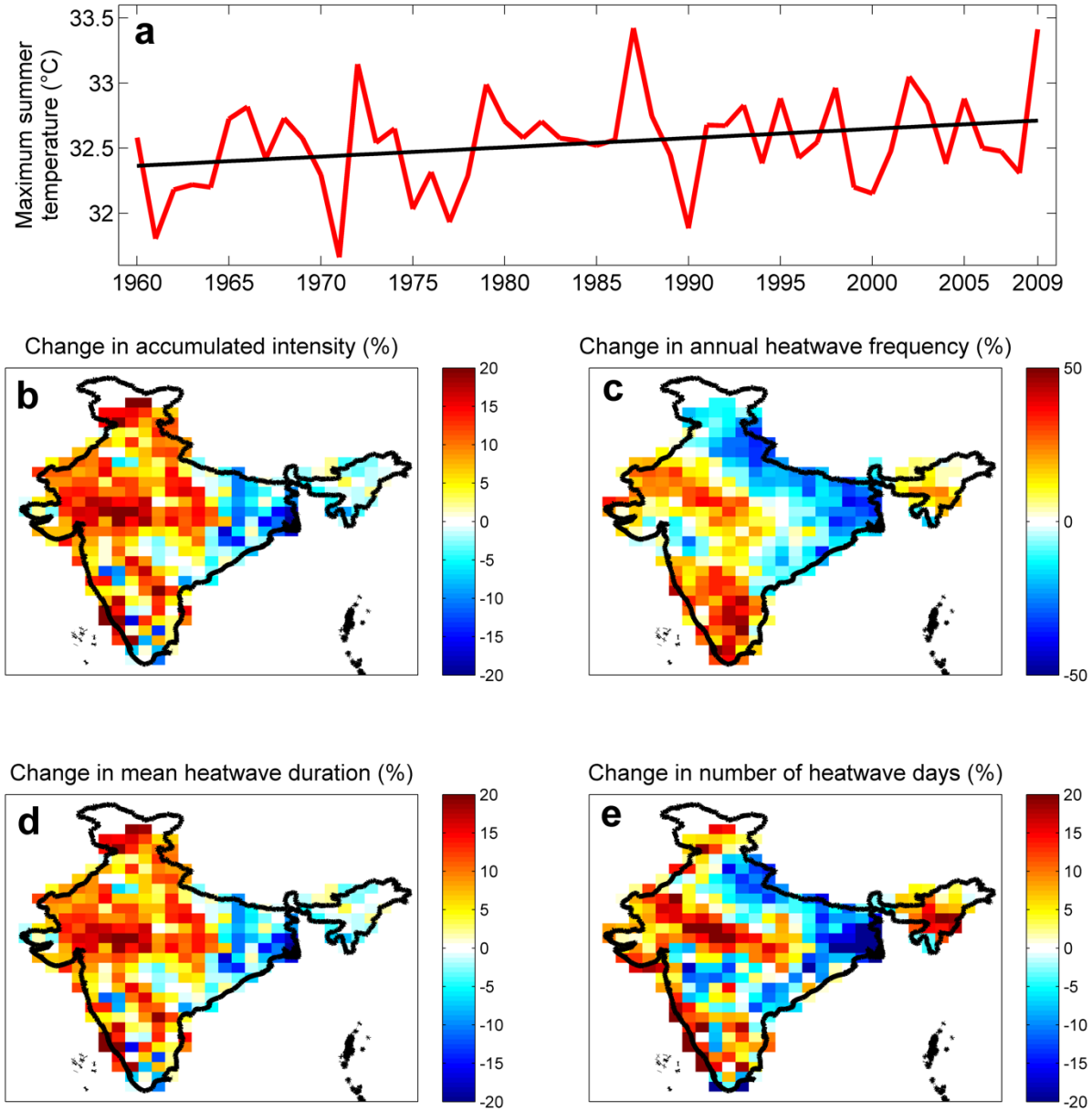


Figure S2a shows that summer mean temperatures have increased substantially from 1960 –to 2009. The time series exhibits a statistically significant ( $p=0.05$ ) upward trend confirmed using the Mann-Kendall trend test.

In turn, the accumulated intensity, count, duration, and heatwave days of Indian heatwaves have also increased over the analyzed time period over most of the country, and especially in northern, southern, and western parts of India (Figure S2b).

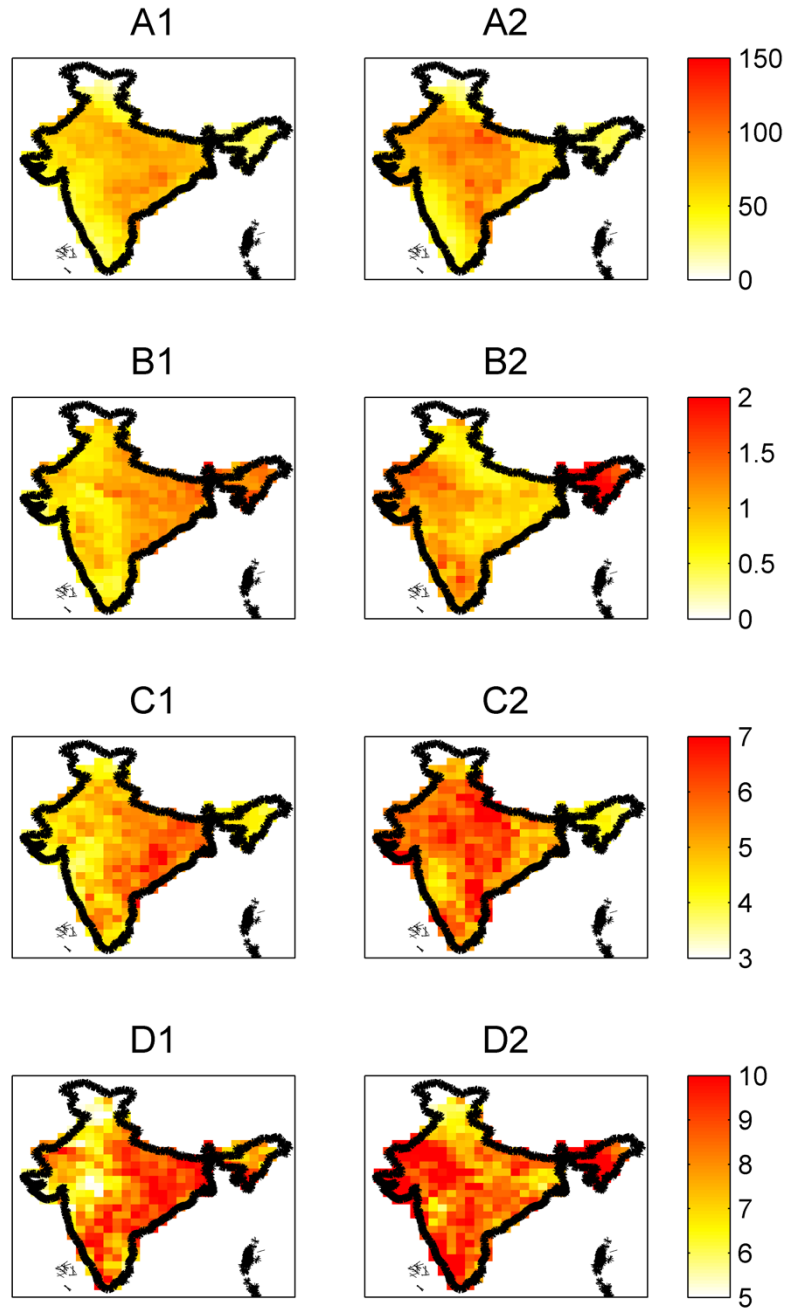


Figure S3 shows the mean heatwave characteristic value for two 25-year periods (1960 – 1984 and 1985 – 2009). Column 1 represents mean heatwave values for 1960 – 1984 and column 2 represents mean values for 1985 – 2009. Row ‘A’ represents accumulated intensity ( $^{\circ}\text{C}$ ), row ‘B’ represents count (Number of Events), row ‘C’ represents duration (days), and row ‘D’ represents heatwave days (days). For example, B1 represents the mean heatwave count during 1960 – 1984, and C2 represents the mean heatwave duration during 1985 – 2009.

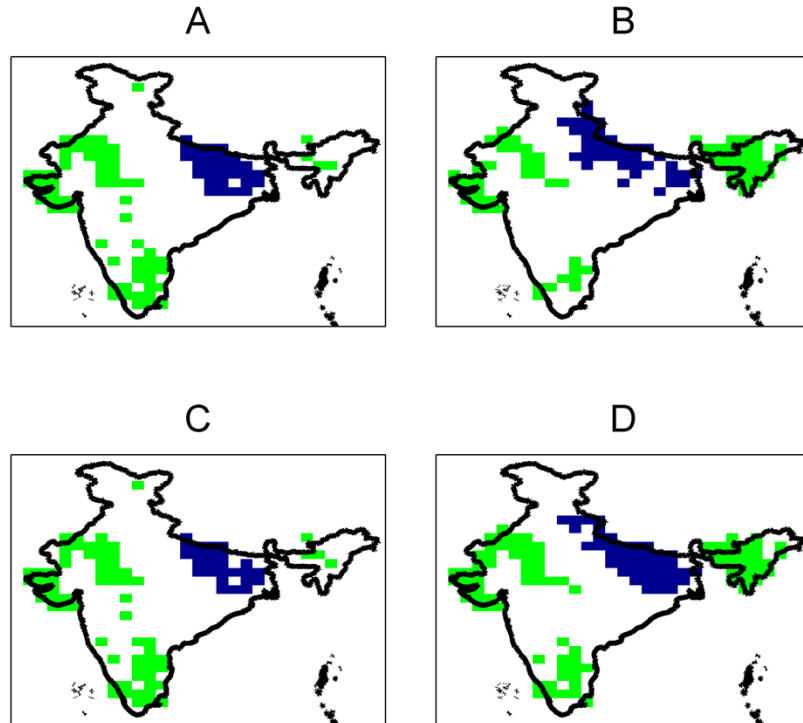


Figure S4 shows the trend in the accumulated intensity, count, duration, and heatwave days of Indian heatwaves' distribution functions from 1960 – 2009 based on the Mann-Kendall trend test. Subplot 'A' represents accumulated intensity, subplot 'B' represents count, subplot 'C' represents duration, and subplot 'D' represents heatwave days. The green pixels show locations where there is a statistically significant (significance level 0.05) positive trend, and the blue pixels show locations where there is a statistically significant negative trend. South and western India show that there is a significant increase in heatwave duration, frequency, and severity.

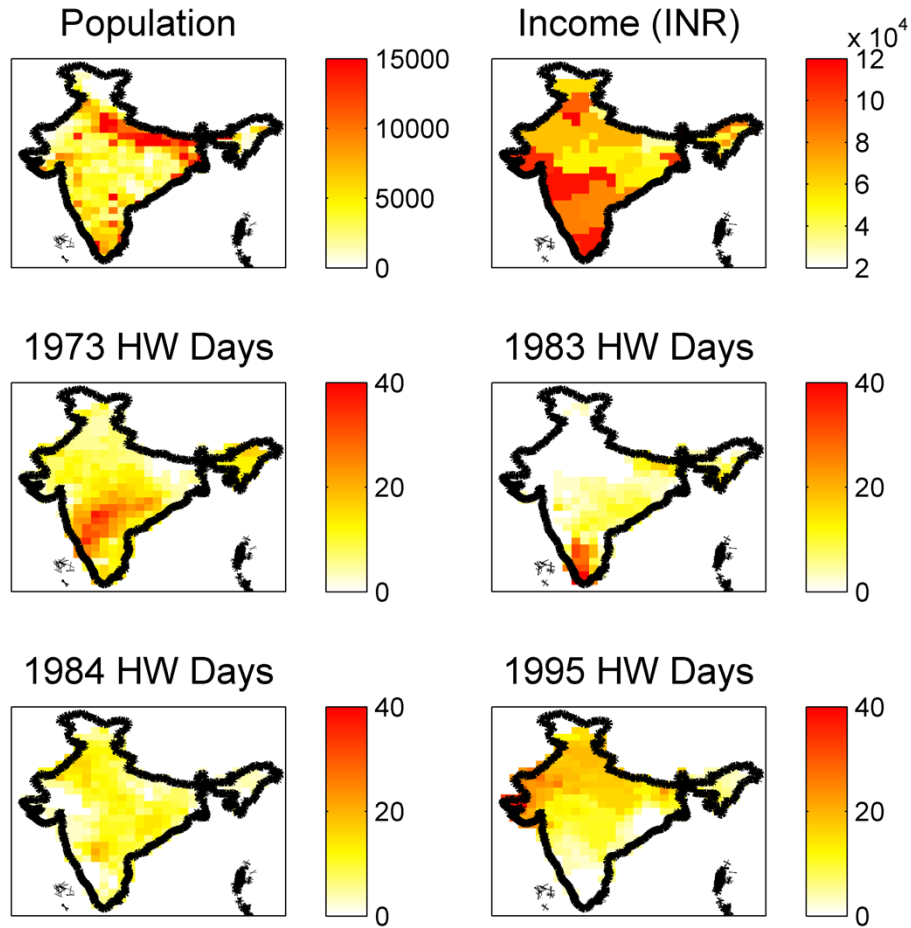


Figure S5 shows the population and income spatial distribution in India, and the number of heatwave days that occurred in 1973, 1983, 1984, and 1995. This figure shows that although many heatwaves occurred during those years, they occurred in less populous and/or wealthier regions, and therefore caused a low heat-related mortality rate.



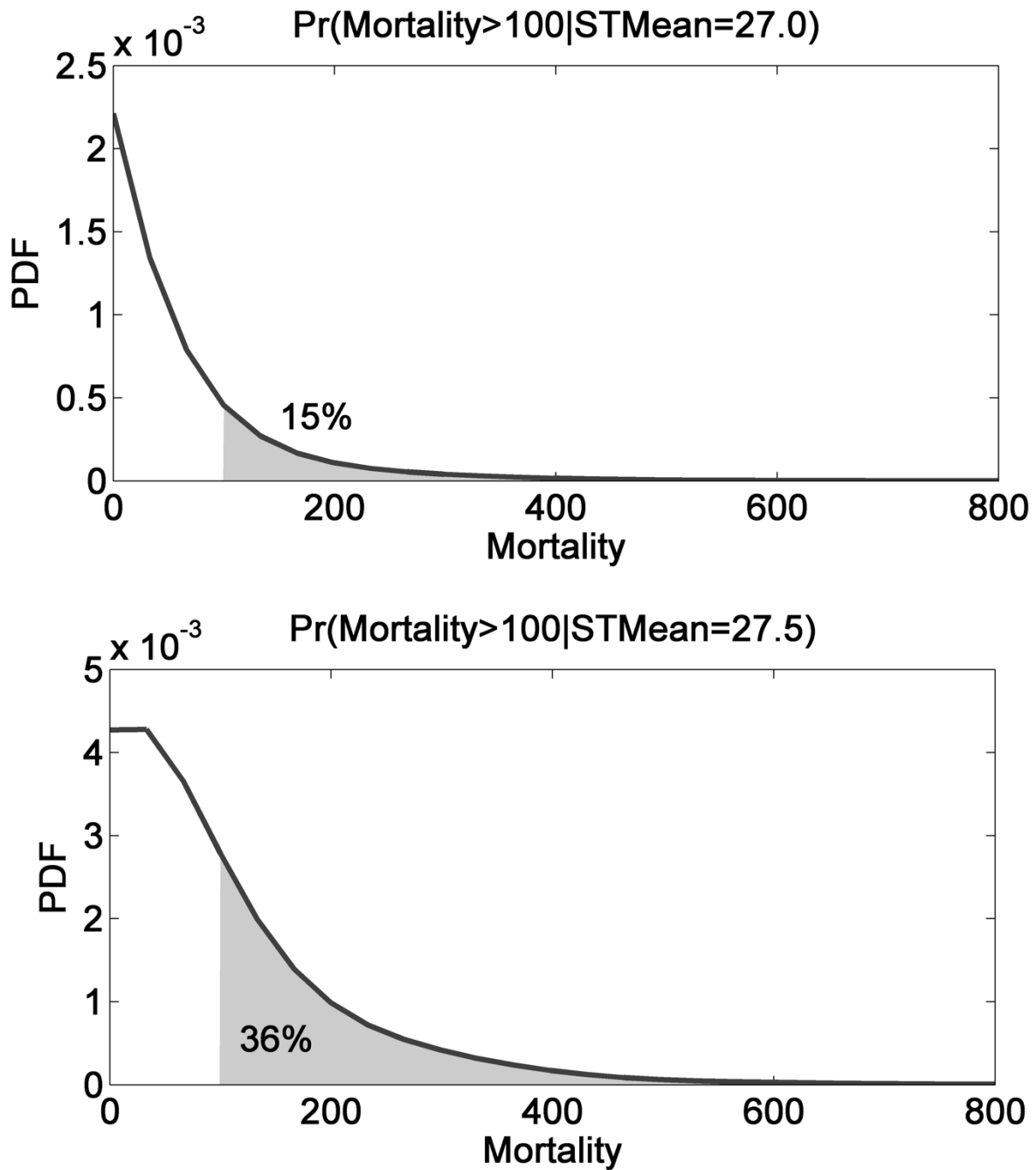


Figure S6 shows the results of a conditional probability density analysis of mortality given certain thresholds for summer maximum temperatures. This figure shows that there is 15% probability that years with summer maximum temperatures equal to 27° C will have mass heat-related mortality. However, with an increase of only 0.5 °C in summer maximum temperatures, the probability of mass heat-related mortality jumps by a factor of 2.4.

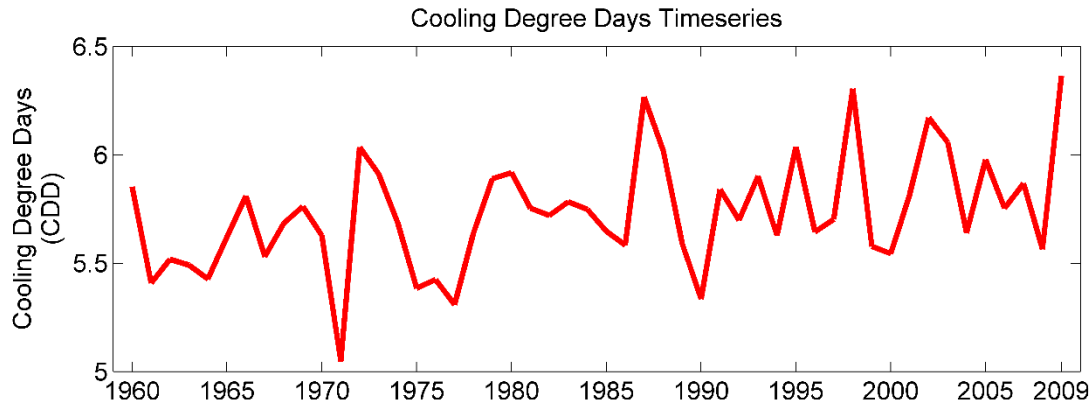


Figure S7 shows that cooling degree days have increased substantially from 1960 –to 2009. The time series exhibits a statistically significant ( $p=0.05$ ) upward trend confirmed using the Mann-Kendall trend test.

Table S1: Maximum Likelihood and p-values for mean summer mean temperature (MST Mean)/mortality and heatwave days (HW Days)/mortality for different copula families. Columns 2 and 4 show Maximum Likelihood values and columns 3 and 5 show their corresponding p-values. The copula family with the highest maximum likelihood value with a p-value below 0.05 was chosen to be used for Figure 4.

Copula Family	MST Mean MLV	MST Mean p-val	HW Days MLV	HW Days p-val
Gumbel	11.6	0.080	14.2	0.149
Clayton	6.5	0.001	10.0	0.004
Frank	7.9	0.004	10.6	0.016
Normal	9.8	0.018	13.5	0.090
t	10.0	0.027	13.5	0.102

Table S2: Values of mortality, heatwave days, and summer mean temperatures. We obtained the datasets from the India Meteorological Department. The mortality data is from 1967 – 2006, while the heatwave days and summer mean temperature data is from 1960 – 2009.

Year	Mortality	HW Days	Summer Mean Temperatures
1960		9.050739	27.8521519
1961		5.754764	27.4080983
1962		5.930383	27.51762347
1963		4.150327	27.49037859
1964		6.845197	27.42619596
1965		6.960335	27.62023659
1966		7.707924	27.80948661
1967	0	7.401298	27.52937173
1968	0	4.352241	27.68388849
1969	0	6.658364	27.76147249
1970	500	6.013894	27.62789409
1971	0	3.595238	27.04596265
1972	1200	10.61896	28.03449524

<b>1973</b>	317	12.34712	27.9105063
<b>1974</b>	11	4.621805	27.68548921
<b>1975</b>	43	6.398347	27.3842219
<b>1976</b>	34	4.960204	27.42377627
<b>1977</b>	0	4.33396	27.30842847
<b>1978</b>	368	8.435231	27.63775698
<b>1979</b>	361	7.516383	27.88949626
<b>1980</b>	156	7.535881	27.91779152
<b>1981</b>	75	6.17398	27.75313802
<b>1982</b>	0	6.224471	27.71969241
<b>1983</b>	185	10.95383	27.78297578
<b>1984</b>	58	8.298676	27.74795401
<b>1985</b>	284	5.653175	27.64714428
<b>1986</b>	156	6.512237	27.58309827
<b>1987</b>	91	8.188689	28.26588249
<b>1988</b>	627	9.663396	28.01920181
<b>1989</b>	42	6.89859	27.59048017
<b>1990</b>	2	4.103175	27.33463379
<b>1991</b>	252	6.455109	27.84021383
<b>1992</b>	114	6.826083	27.69787413
<b>1993</b>	42	8.6519	27.90152599
<b>1994</b>	234	7.829858	27.62782151
<b>1995</b>	413	11.53829	28.03556385
<b>1996</b>	26	6.818267	27.64455423
<b>1997</b>	21	7.587665	27.70257507
<b>1998</b>	1655	18.17089	28.30480507
<b>1999</b>	126	4.680534	27.57711712
<b>2000</b>	55	4.672401	27.54351233
<b>2001</b>	70	6.206297	27.81637593
<b>2002</b>	909	8.443608	28.17109168
<b>2003</b>	1494	13.15832	28.05730882
<b>2004</b>	237	5.69694	27.63898922
<b>2005</b>	326	9.186835	27.97736915
<b>2006</b>	135	5.959325	27.75310397
<b>2007</b>		7.791435	27.86753166
<b>2008</b>		4.220098	27.56406295
<b>2009</b>		9.273163	28.36352389

In Figure 3, the annual number of heatwaves and annual mortality rates are standardized for better visualization using the following formula:

$$Standardized = \frac{x - \bar{x}}{\sigma}$$

where  $\bar{x}$  is the dataset mean and  $\sigma$  is the dataset standard deviation.