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Global risk of deadly heat

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Climate change can increase the risk of conditions that exceed human thermoregulatory capacity[1–6]. Although numerous studies report increased mortality associated with extreme heat events[1–7], quantifying the global risk of heat-related mortality remains challenging due to a lack of comparable data on heat-related deaths[2–5]. Here we conducted a global analysis of documented lethal heat events to identify the climatic conditions associated with human death and then quantified the current and projected occurrence of such deadly climatic conditions worldwide. We reviewed papers published between 1980 and 2014, and found 783 cases of excess human mortality associated with heat from 164 cities in 36 countries. Based on the climatic conditions of those lethal heat events, we identified a global threshold beyond which daily mean surface air temperature and relative humidity become deadly. Around 30% of the world's population is currently exposed to climatic conditions exceeding this deadly threshold for at least 20 days a year. By 2100, this percentage is projected to increase to ~48% under a scenario with drastic reductions of greenhouse gas emissions and ~74% under a scenario of growing emissions. An increasing threat to human life from excess heat now seems almost inevitable, but will be greatly aggravated if greenhouse gases are not considerably reduced.

Sporadic heat events, lasting days to weeks, are often related to increased human mortality[1,2], raising serious concerns for human health given ongoing climate change[1–3,8–16]. Unfortunately, a number of challenges have hampered global assessments of the risk of heat-related death. First, heat illness (that is, severe exceedance of the optimum body core temperature) is often underdiagnosed because exposure to extreme heat often results in the dysfunction of multiple organs, which can lead to misdiagnosis[2,3,5,17]. Second, mortality data from heat exposure are sparse and have not been analysed in a consistent manner. Here we conducted a global survey of peer-reviewed studies on heat-related mortality to identify the location and timing of past events that caused heat-related deaths. We used climatic data during those events to identify the conditions most likely to result in human death and then quantified the current and projected occurrence of such deadly climatic conditions. Hereafter, we use 'lethal' when referring to climatic conditions during documented cases of excess mortality and 'deadly' when referring to climatic conditions that are projected to cause death. We make this distinction to acknowledge that climatic conditions which have killed people in the past are obviously capable of causing death, but whether or not they result in human mortality in the future could be affected by adaptation. We do not quantify human deaths *per se* because the extent of human mortality will be considerably modified by social adaptation (for example, use of air conditioning, early warning systems, and so on[18–20]). Although social adaptation could reduce the exposure to deadly heat[18–20], it will not affect the occurrence of such conditions. Given the speed of climatic changes and numerous physiological constraints, it is unlikely that human physiology will evolve the necessary higher heat tolerance[21,22], highlighting that outdoor conditions will remain deadly even if social adaptation is broadly implemented. Our aim is to quantify where and when deadly heat conditions occur, which in turn can provide important information on where social adaptation will likely be needed.

We searched available online databases for peer-reviewed publications on heat-related mortality published between 1980 and 2014 (see Methods). From over 30,000 relevant references, we identified 911 papers that included data on 1,949 case studies of cities or regions where excess mortality was associated with high temperatures. Case studies were broadly grouped into those focusing on temperature–mortality relationships in a specific city, region, or country (1,166 cases from 273 cities across 49 countries) and those focusing on heat-related mortality during specific episodes (783 cases from 164 cities across 36 countries). Cases were predominantly reported for cities at mid-latitudes, with the highest concentration in North America and Europe (Fig. 1a), and included well-documented heatwaves like those in Chicago in 1995 (~740 deaths[23]), Paris in 2003 (~4,870 deaths[24]), Moscow in 2010 (~10,860 deaths[25]) and many other, less publicized events (list of cases provided at https://maps.esri.com/globalriskofdeadlyheat). While data on the number of deaths was inconsistently reported, all studies provided information on the place and dates when climatic conditions were lethal, which we used to identify the specific climatic conditions resulting in heat-related mortality.

To identify the climatic conditions related to lethal heat events, we assessed daily climatic data (that is, surface air temperature, relative humidity, solar radiation, wind speed, and several other metrics, Supplementary Fig. 1) for the duration of lethal heat episodes reported in the literature and an equal number of non-lethal episodes (that is, periods of equal duration from the same cities but from randomly selected dates); then we used Support

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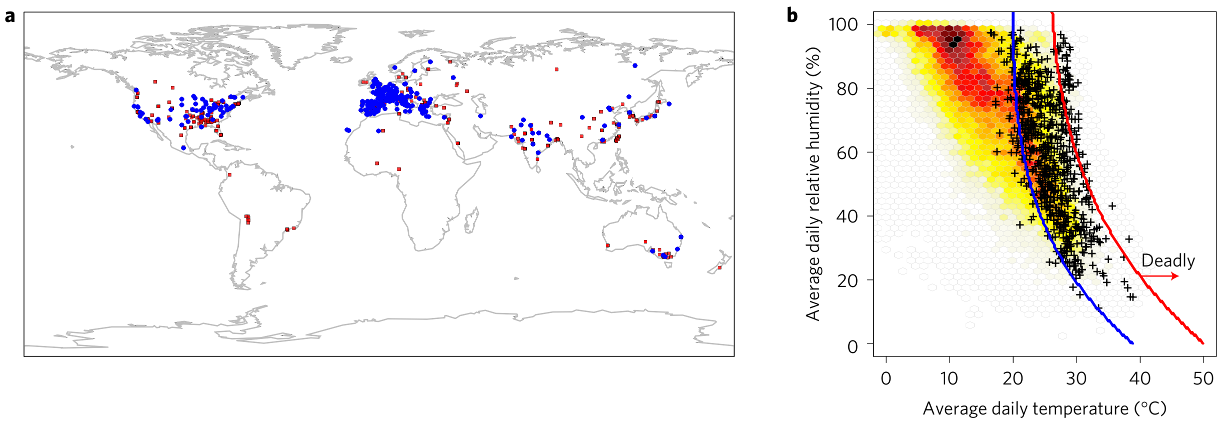

Figure 1 | Geographical distribution of recent lethal heat events and their climatic conditions. a, Places where relationships between heat and mortality have been documented (red squares) and where specific heat episodes have been studied (blue squares). **b**, Mean daily surface air temperature and relative humidity during lethal heat events (black crosses) and during periods of equal duration from the same cities but from randomly selected dates (that is, non-lethal heat events; red to yellow gradient indicates the density of such non-lethal events). Blue line is the SVM threshold that best separates lethal and non-lethal heat events and the red line is the 95% probability SVM threshold; areas to the right of the thresholds are classified as deadly and those to the left as non-deadly. Support vectors for other variables are shown in Supplementary Fig. 2.

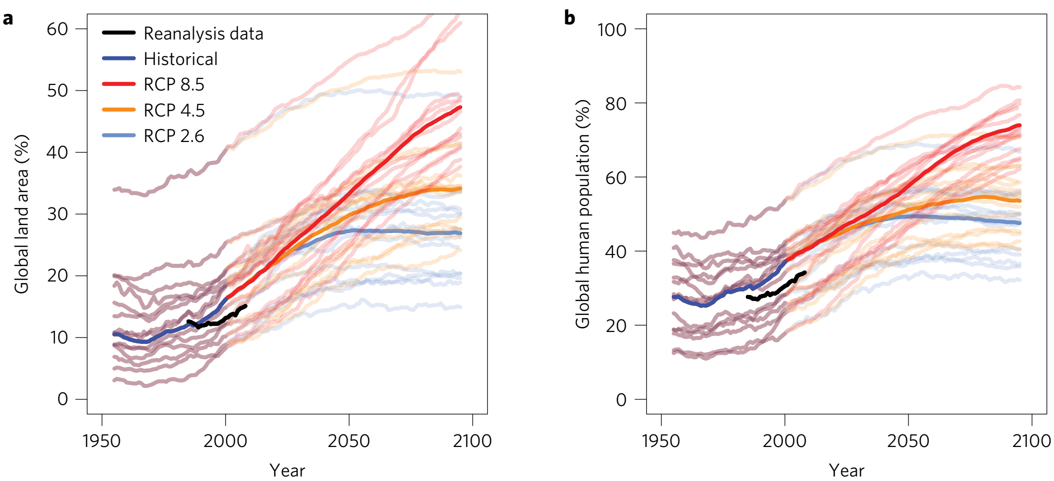

Figure 2 | Current and projected changes in deadly climatic conditions. a,**b**, Area of the planet (**a**) and percentage of human population (**b**) exposed to climatic conditions beyond the 95% SVM deadly threshold (red line in Fig. 1b) for at least 20 days in a year under alternative emission scenarios. Bold lines are the multimodel medians, black lines are the results from reanalysis data and faded lines indicate the projections for each Earth System Model. Time series were smoothed with a 10-year-average moving window. Area of the planet and human population exposed to different lengths of time are shown in Supplementary Fig. 4. Results correcting for climatological mean biases between the reanalysis data and each Earth System Model are shown in Supplementary Figs 8 and 10.

Vector Machines (SVMs) to identify the climatic conditions that best differentiated lethal and non-lethal episodes. SVMs generate a threshold that maximizes the difference in the attributes of two or more groups, allowing for classification of objects in either group based on where their given attributes fall with respect to the threshold. In our case, SVM was used to generate a decision threshold that maximizes the difference in climatic conditions of lethal and non-lethal episodes, with the conditions on one side of the threshold being lethal and those to the other side being non-lethal (for example, Fig. 1b). Among all possible pair combinations of the variables analysed here (Supplementary Figs 1 and 2), the SVM using mean daily surface air temperature and relative humidity most accurately distinguished between past lethal and non-lethal heat episodes (that is, 82%, blue line in Fig. 1b); accuracy was measured as the ratio of the number of correctly classified lethal and non-lethal cases to the total number of cases. Adding other variables to the temperature–humidity SVM resulted in less parsimonious SVMs with minimal increases in accuracy (for example, the SVM model including all 16 variables analysed here was only 3% more accurate, Supplementary Fig. 3). SVM also allows for estimation of a classification probability that increases with the distance of an observation to the decision threshold; the use of a 95% probability for the temperature–humidity SVM (red line in Fig. 1b) resulted in 100% accurate predictions of true positives (that is, only prior lethal heat episodes were on the deadly side of the 95% probability SVM decision boundary). While our analysis used data on local climatic conditions, the resulting pattern between temperature and relative humidity allowed us to accurately classify lethal heat events of different cities worldwide using a single common SVM threshold (Fig. 1b).

The fact that temperature and relative humidity best predict times when climatic conditions become deadly is consistent with human thermal physiology, as they are both directly related to body heat exchange[2–4]. First, the combination of an optimum body core temperature (that is, ~37 °C), the fact that our metabolism generates heat (~100 W at rest) and that an object cannot dissipate

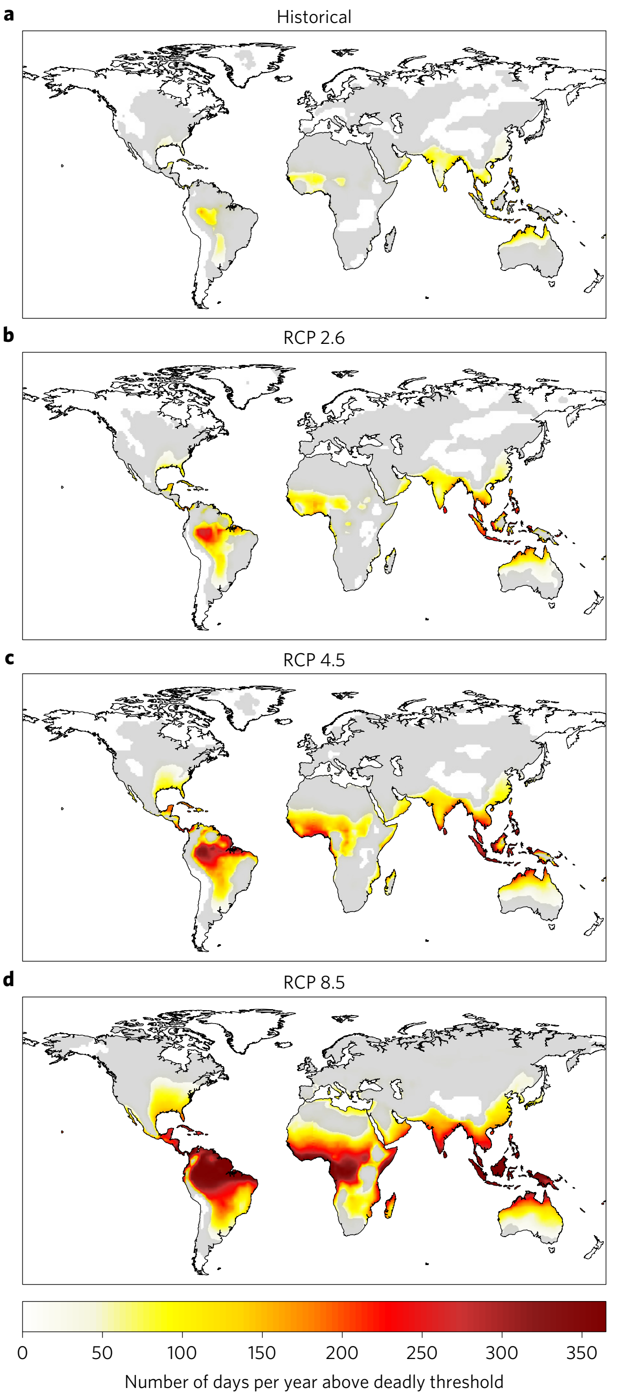

Figure 3 | Geographical distribution of deadly climatic conditions under different emission scenarios. a–d, Number of days per year exceeding the threshold of temperature and humidity beyond which climatic conditions become deadly (Fig. 1b), averaged between 1995 and 2005 (**a**, historical experiment), and between 2090 and 2100 under RCP 2.6 (**b**), RCP 4.5 (**c**) and RCP 8.5 (**d**). Results are based on multimodel medians. Grey areas indicate locations with high uncertainty (that is, the multimodel standard deviation was larger than the projected mean; coefficient of variance >1). The expected lower number of deadly days at higher latitudes (Fig. 4) may help explain the large variability among Earth System Models in the projected number of deadly days at higher latitudes[31] (for example, in the case for New York (illustrated in Fig. 4j) the one model projects nine deadly days by 2100; yet any other model projecting 18 days will double the variability). The uncertainty presented in this figure should be interpreted with that caution in mind.

heat to an environment with equal or higher temperature (that is, the second law of thermodynamics[22]), dictates that any ambient temperature above 37 °C should result in body heat accumulation and a dangerous exceedance of the optimum body core temperature (hyperthermia[5]). Second, sweating, the main process by which the body dissipates heat, becomes ineffective at high relative humidity (that is, air saturated with water vapour prevents evaporation of sweat); therefore, body heat accumulation can occur at temperatures lower than the optimum body core temperature in environments of high relative humidity. These properties help to explain why the boundary at which temperature becomes deadly decreases with increasing relative humidity (Fig. 1b) and why in our results some heat mortality events occurred at relatively low temperatures (Fig. 1b). These consequences of temperature and humidity are why both of these variables are included in traditional thermal indices such as humidex[26] and wet-bulb globe temperature[22,27].

To quantify the global extent of current deadly climatic conditions, we applied the 95% probability SVM decision boundary between mean daily surface air temperature and relative humidity (red line in Fig. 1b, hereafter referred to as deadly threshold) to current global climate data (see Methods). Using data from a climate reanalysis (see Methods), we found that in 2000, ~13.2% of the planet's land area, where ~30.6% of the world's human population resides, was exposed to 20 or more days when temperature and humidity surpassed the threshold beyond which such conditions become deadly (Fig. 2, extended results in Supplementary Fig. 4). Comparatively, using climate simulations for the year 2000 (that is, historical experiment) developed for the Coupled Model Intercomparison Project phase 5 (CMIP5), we found that ~16.2% (±8.3% standard deviation, s.d.) of the planet's land area, where ~37.0% (±9.7% s.d.) of the world's population resides, was exposed to 20 or more days of potentially deadly conditions of temperature and humidity (results are multimodel medians and standard deviations among Earth System Models; Fig. 2). Both the reanalysis and historical CMIP5 data revealed increasing trends in the area and population exposed to deadly climates during the time period for which such datasets can be compared, although the trends in the reanalysis data are slightly weaker than in the Earth System Models (Fig. 2). Overall, there was ~3% mismatch in the area of the planet exposed to deadly climates (~6.4% in global population) between the reanalysis and the multimodel median, and thus, results based on CMIP5 simulations should be interpreted with that error in mind. However, the effects of this mismatch and the uncertainty among Earth System Models were smaller than the predicted changes in deadly days (Supplementary Fig. 10). It is worth noting that most scientific publications on deadly heat events have focused in developed mid-latitude countries (Fig. 1a); yet, deadly heat conditions also occur in developing tropical countries (Fig. 3). This suggests that the risk of deadly heat could be currently underestimated in tropical regions, which has been noted in prior studies[28].

To predict the global extent of future deadly climates, we applied the deadly SVM threshold to mean daily surface air temperature and relative humidity projections from the CMIP5 Earth System Models under low, moderate, and high emissions scenarios (Representative Concentration Pathways, RCPs, 2.6, 4.5, and 8.5, respectively). We found that by 2100, even under the most aggressive mitigation scenario (that is, RCP 2.6), ~26.9% (±8.7% s.d.) of the world's land area will be exposed to temperature and humidity conditions exceeding the deadly threshold by more than 20 days per year, exposing ~47.6% (±9.6% s.d.) of the world's human population to deadly climates (using Shared Socioeconomic Pathways projections of future human population[29] relevant to each of the CMIP5 RCPs, see Methods). Scenarios with higher emissions will affect an even greater percentage of the global land area and human population. By 2100, ~34.1% (±7.6% s.d.) and ~47.1% (±8.9% s.d.) of the

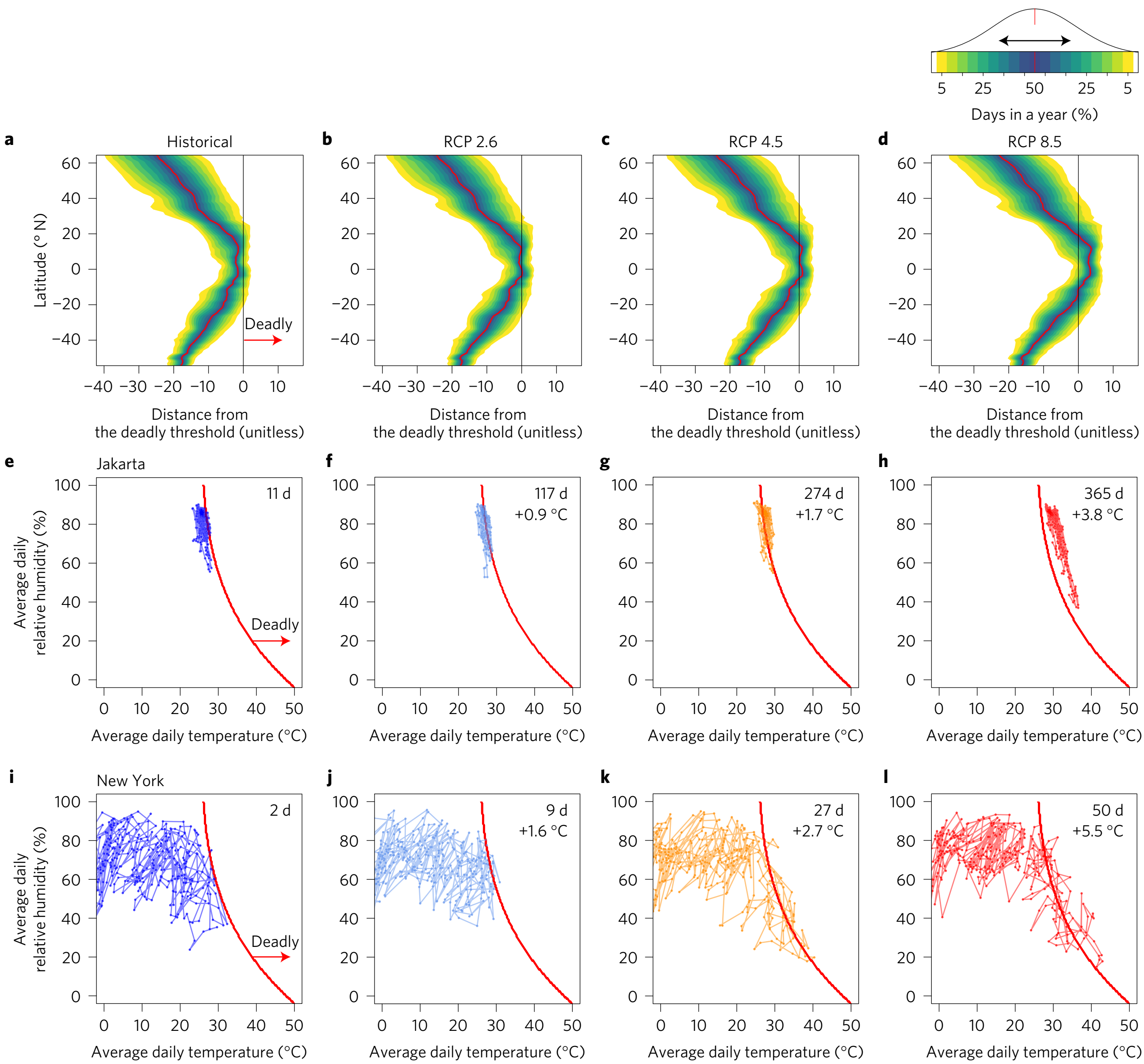

Figure 4 | Latitudinal risk of deadly climates. a–d, Distribution of the percentage of days in a given year (that is, colour gradients), at each latitude, as a function of their distance to the deadly threshold (red line in Fig. 1b). Displayed here are the last year in the historical experiment (that is, 2005; **a**) and the year 2100 under RCP 2.6 (**b**), RCP 4.5 (**c**) and RCP 8.5 (**d**). These plots illustrate that higher latitudes have fewer days near the deadly threshold compared with the tropics. **e–l**, As examples, we show mean temperature and relative humidity for each day in the year 2005 in the historical experiments and the year 2100 for all the RCPs in Jakarta (**e–h**) and New York (**i–l**), with consecutive days connected by lines. The 95% SVM threshold is shown as a red line with numbers on the upper right hand corner indicating the number of days that cross the threshold and the difference in temperature between 2100 and 2005. Examples are based on a single simulation of a randomly chosen model (that is, CSIRO-Mk3-6-0).

global land area will be exposed to temperature and humidity conditions that exceed the deadly threshold for more than 20 days per year under RCP 4.5 and RCP 8.5, respectively; this will expose ~53.7% (±8.7% s.d.) and ~73.9% (±6.6% s.d.) of the world's human population to deadly climates by the end of the century (Fig. 2, extended results in Supplementary Fig. 4).

The projected number of days per year surpassing the deadly threshold increases from mid-latitudes to the equator (Figs 4a–c, 5a and Supplementary Fig. 5a,d,g). By 2100, mid-latitudes (for example, 40° N or S) will be exposed to ~60 deadly days per year compared to almost the entire year in humid tropical areas under RCP 8.5 (Figs 3b–d, 4b–d and 5a). This latitudinal pattern was consistent among all scenarios (Supplementary Fig. 5a,d,g) and is largely determined by the fact that the number of days with temperatures close to the deadly threshold declines with increasing latitude (that is, due to greater seasonality; Supplementary Fig. 6b–d[28]). At mid-latitudes (for example, New York, Fig. 4i–l) temperatures approach the deadly threshold only during the summer, which represents a smaller proportion of the year; compared to tropical locations (for example, Jakarta, Fig. 4e–h), which have consistently warm temperatures near the deadly threshold year-round (Supplementary Fig. 6). Although tropical humid areas will experience less warming than higher latitudes (Fig. 5b, see also ref. 30), they will be exposed to the greatest increase in the number of deadly days over time, because higher relative humidity in tropical areas requires lower temperatures to cross the deadly threshold (Figs 4e–h and 5e); a condition that could be further aggravated by projected increases in relative humidity of tropical areas (Fig. 5a). Subtropical and

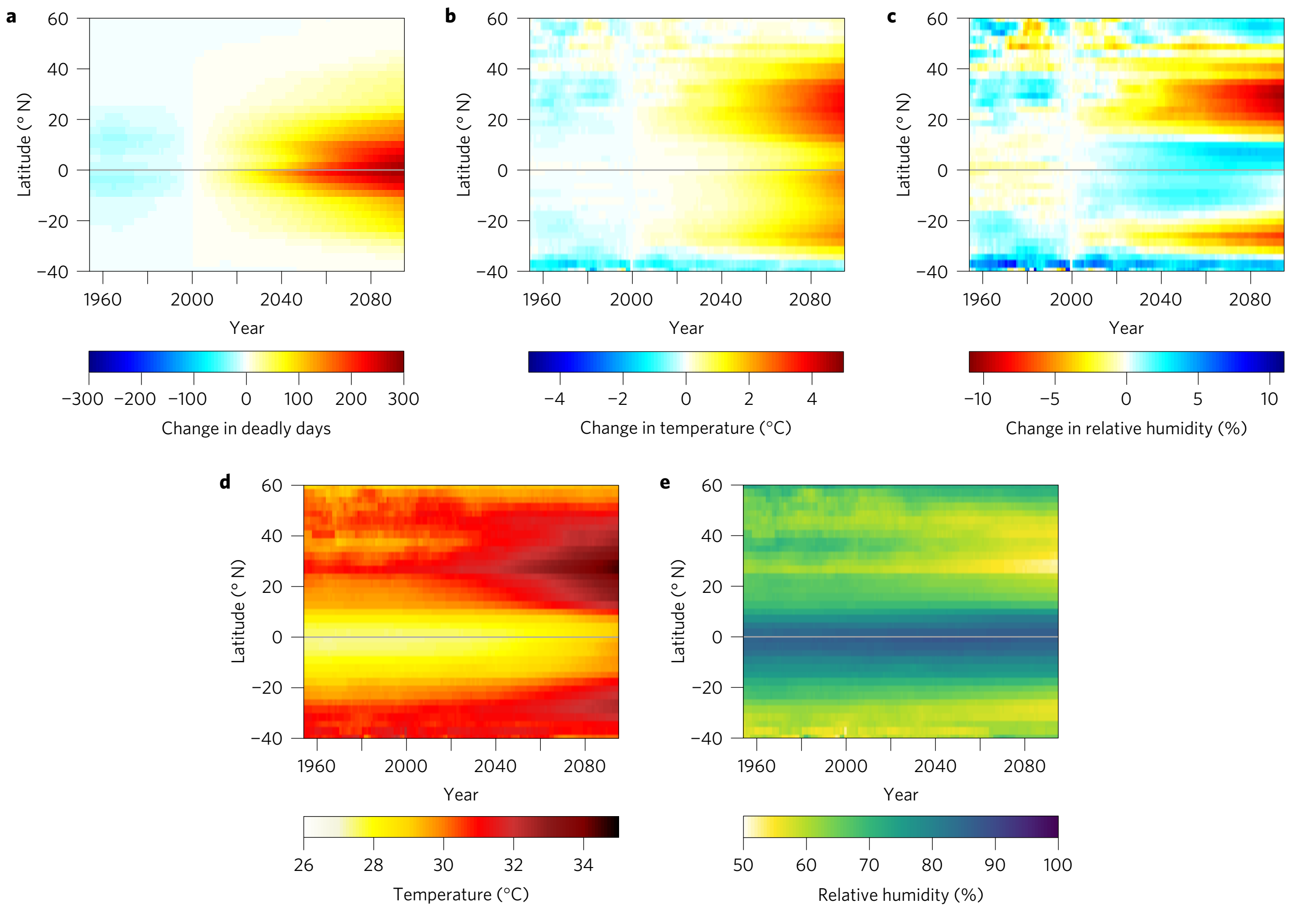

Figure 5 | Simulated spatio-temporal changes in deadly climatic conditions in Earth System Models. a, Average changes over time in the number of days per year exceeding the deadly threshold. **b**,**c**, Changes in temperature (**b**) and changes in relative humidity (**c**) during those deadly days, relative to mean values between 1995 and 2005. **d**,**e**, Mean temperature (**d**) and relative humidity (**e**) during deadly days. Results are grouped by latitude and are based on the multimodel medians for the historical experiment, which runs from 1950 to 2005, and RCP 8.5, which runs from 2006 to 2100. Results for all scenarios are shown in Supplementary Fig. 5.

mid-latitude areas will have fewer days beyond the deadly threshold, but such deadly days will be much hotter in the future (Figs 4e–h and 5b,d). This general variability in the climatic conditions of deadly days (Fig. 5b–d and Supplementary Fig. 7) is probably related to mean global climate patterns associated with the general circulation of the atmosphere: equatorial convection (that is, warm, moist air rising) produces high humidity in low latitudes whereas subtropical atmospheric subsidence (that is, cool, dry air sinking) creates low-precipitation, low-humidity zones, where high sensible heat flux contributes to extreme high temperatures at mid-latitudes (Supplementary Figs 5i and 7).

Our study underscores the current and increasing threat to human life posed by climate conditions that exceed human thermoregulatory capacity. Lethal heatwaves are often mentioned as a key consequence of ongoing climate change, with reports typically citing past major events such as Chicago in 1995, Paris in 2003, or Moscow in 2010[1–6]. Our literature review indicates, however, that lethal heat events already occur frequently and in many more cities worldwide than suggested by these highly cited examples. Our analysis shows that prior lethal heat events occurred beyond a general threshold of combined temperature and humidity, and that today nearly one-third of the world's population is regularly exposed to climatic conditions surpassing this deadly threshold. The area of the planet and fraction of the world's human population exposed to deadly heat will continue to increase under all emission scenarios, although the risk will be much greater under higher emission scenarios. By 2100, almost three-quarters of the world's human population could be exposed to deadly climatic conditions under high future emissions (RCP 8.5) as opposed to one-half under strong mitigation (RCP 2.6). While it is understood that higher latitudes will undergo more warming than tropical regions[30], our results suggest that tropical humid areas will be disproportionately exposed to more days with deadly climatic conditions (Fig. 5a), because these areas have year-round warm temperatures and higher humidity, thus requiring less warming to cross the deadly threshold (Fig. 4 and Supplementary Fig. 6). The consequences of exposure to deadly climatic conditions could be further aggravated by an ageing population (that is, a sector of the population highly vulnerable to heat[2–4]) and increasing urbanization (that is, exacerbating heat-island effects[2–4]). Our paper emphasizes the importance of aggressive mitigation to minimize exposure to deadly climates and highlights areas of the planet where adaptation will be most needed.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

All authors contributed to the design of the paper. C.M., B.D., I.R.C., F.E.P., R.C.G., C.R.B., C.W.W.C., B.S.D., E.T.J., L.V.L., M.P.L., M.M.M., A.G.S., H.T. and C.T. collected data. C.M. and I.R.C. performed analysis. All authors contributed to the writing of the paper.

Additional information

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Competing financial interests

The authors declare no competing financial interests.

Methods

Survey of published cases of heat-related mortality. We searched for peer-reviewed studies published between 1980 and 2014 on heat-related mortality in Google Scholar, PubMed, and the Web of Science using the following keywords: (human OR people) AND (mortality OR death OR lethal) AND (heat OR temperature). We searched for papers primarily in English, but also included papers in Spanish, French, Japanese and Chinese when found. We reviewed the titles and abstracts of the first 30,000 citations in Google Scholar and all citations from other databases and selected any peer-reviewed publications on heat-related human mortality (we also searched for additional sources in the references). These efforts resulted in 911 peer-reviewed papers from which we collected information on the place and dates of lethal heat events. Several papers noted that human mortality may have occurred beyond the dates in which the extreme climatic conditions occurred ('mortality displacement'); in those cases, we extracted the dates for which the extreme climatic conditions were reported in the given studies. Our goal was to identify the dates in which climatic conditions triggered human mortality regardless of whether mortality was displaced or not.

Climatic conditions related to prior cases of heat-related mortality. For the cases in the literature review that reported the place and time of lethal heat events, we assessed information for 16 climatic metrics based on mean daily surface air temperature, relative humidity, solar radiation, and wind speed (Supplementary Fig. 1). For each of the lethal heat events, we also assessed the same climatic variables for a paired 'non-lethal' event of the same duration and from the same city but from a randomly chosen date. Climatic conditions were characterized using daily data from an atmospheric reanalysis of past climate (NCEP-DOE Reanalysis 2). We used the NCEP-DOE Reanalysis database because it is among the most studied and is well characterized relative to newer databases. We used Support Vector Machine (SVM) modelling to separate the climatic conditions associated with prior lethal heat events from those associated with non-lethal events. Using SVM, we generated a decision vector/threshold that maximized the distance between lethal and non-lethal episodes, with the conditions on one side of the threshold being lethal and those to the other side being non-lethal (for example, Fig. 1b). We developed such SVM models for all combinations of the variables collected and then compared the accuracy of models to choose the most parsimonious and best performing one.

Projected occurrence of deadly climatic conditions. To quantify the number of days in a year that surpass the threshold beyond which conditions become deadly under alternative emission scenarios, we applied the 95% SVM probability threshold between mean daily surface air temperature and relative humidity of prior lethal heat events to daily climate projections of the same variables. We used the 95% SVM probability threshold because it resulted in a much more accurate classification of prior lethal heat events, and because it restricts projected lethal heat events to much more extreme conditions, hence yielding more conservative results. We used daily climate projections of mean surface air temperature and relative humidity from 20 Earth System Models under four alternative emissions scenarios developed for the recent Coupled Model Intercomparison Project Phase 5 (Supplementary Table 1). We used the 'historical' experiment, which includes the period from 1950 to 2005 and the Representative Concentration Pathways 2.6, 4.5 and 8.5 (RCP 2.6, 4.5 and 8.5, respectively), which include the period from 2006 to 2100. The historical experiment was designed to model recent climate (reflecting changes due to both anthropogenic and natural causes) and allows the validation of model outputs against available climate observations (Supplementary Figs 8 and 9). RCP pathways represent contrasting mitigation efforts between rapid greenhouse gas reductions (RCP 2.6) and a business-as-usual scenario (RCP 8.5). All analyses were run at the original resolution of each climate database and the results were interpolated to a common 1.5° grid cell size using a bilinear function.

Projections of global land coverage and risk to human populations from deadly climatic conditions. To calculate the amount of land area and fraction of the human population that are likely to be exposed to deadly climates each year, we summed the land area and human population for all cells experiencing varying numbers of days in a year beyond the deadly threshold (Fig. 2 and Supplementary Fig. 4). We used the Gridded Population of the World from the Socioeconomic Data and Applications Center (http://sedac.ciesin.columbia.edu/data/set/gpw-v3-population-count-future-estimates/data-download#) to estimate human exposure up to the year 2005 and human population projections consistent with the different emission scenarios used in the CMIP5 to estimate exposure between 2006 and 2100. For the population projections, we specifically used the spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways (SSP) developed by Jones *et al.*[29], pairing RCP 2.6 with SSP1, RCP 4.5 with SSP3, and RCP 8.5 with SSP5.

Limitations. There are several potential limitations to our study. First, the lethality of deadly climatic conditions can be mediated by various demographic (for example, age structure), socio-economic (for example, air conditioning, early warning systems) and urban planning (for example, vegetation, high albedo surface) factors that were not considered in our study. Consideration of these factors would improve the understanding of global human vulnerability to heat exposure and may reduce the number of human deaths, but they are unlikely to affect the occurrence of deadly climatic conditions, which is what we estimated. Second, our survey of cases of heat-related mortality was restricted to the period between 1980 and 2014, and any bias or temporal heterogeneity in the monitoring of lethal heatwaves and epidemiological studies in this period may influence the cases we studied and the resulting SVM model. Third, while general agreement among models was found in the predictions of deadly climatic conditions in tropical areas, greater variability among models was seen in such projections at higher latitudes (grey areas in Fig. 3). Because deadly conditions are more rare at higher latitudes (Fig. 4), a larger number of model ensembles might allow for more definitive statements about the risk of deadly climates in such regions, as has been suggested for similar cases of rare events[31]. Finally, it is possible that some lethal heat events were not documented in peer-reviewed publications and, if the dates of those undocumented events happened to be selected as part of the non-lethal events in our analysis, this could affect the resulting SVM model. However, this error is likely minimal because there is a low probability of randomly selecting such rare and brief events from a 30-year period in the given cities.

Data availability. The data that support the findings of this study are available from the corresponding author upon request.