Supplemental material:

Supplemental Methods S1 - Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs)

Greenhouse gas emission and socioeconomic development scenarios are used in climate modeling research to develop plausible potential scenarios of how different aspects of society and the climate may change. Such scenarios can then be used to understand how climate change will impact aspects of human society as well as the cost of mitigation efforts. In an effort to develop scenarios that provide greater detail and explore the effect of potential climate related policies, the Intergovernmental Panel on Climate Change (IPCC) called for the development of such scenarios by the research community. Two complementary modeling efforts were then undertaken by the research community. One was focused on development of the Representative Concentration Pathways (RCPs) which focuses on climate projections and the second on the Shared Socioeconomic Pathways (SSPs) which focuses on projected trends in socioeconomic development of human society.[13] The RCPs and SSPs are then combined in a Scenario Matrix Architecture.[23]

Representative Concentration Pathways (RCPs)

RCPs attempt to capture potential trajectories of atmospheric greenhouse gas concentrations under different possible scenarios of emissions.[44] The RPCs were used for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) for its findings.[45] The RCPs are intended to be representative of the total literature in regard to the available scenarios in the scientific literature for emissions and land use. The RCPs were developed using Integrated Assessment Models (IAMs) which are complex models that integrate socioeconomic features with physical climate factors for the purposes of climate modeling. Based on these IAMs, four RCPs were selected and are defined by their total radiative forcing (i.e., difference between the incoming and outgoing radiation or energy for the planet expressed in Watts per square meter) pathway and level by the year 2100. These four scenarios are as follows:

- RCP2.6 – Representing a stringent mitigation pathway in which global carbon dioxide (CO2) emissions peak by 2020 and go to zero by 2100. Atmospheric CO^2 concentrations peak around mid-century and then start declining. Global average temperatures are projected to increase by 1.6°C (95% CI 0.9°C to 2.3°C) compared to the pre-industrial period.
- RCP4.5 – Representing an intermediate pathway in which emissions peak near mid-century and then decline. Atmospheric CO^2 concentrations increase at current trends to the later part of the century, and then increase at a slower rate. Global average temperatures are projected to increase by 2.4°C (95% CI 1.7°C to 3.2°C) compared to the pre-industrial period.
- RCP6.0 – Representing an intermediate scenario in which CO^2 emissions increase quickly through the later part of the century, followed by dramatic decrease. Atmospheric CO^2 concentrations continue increasing in the rest of the century, but at slower rates near the end of the century. Global average temperatures are projected to increase by 2.8°C (95% CI 2.0°C to 3.7°C) compared to the pre-industrial period.
- RCP8.5 – Representing a large emissions increase scenario in which CO^2 emissions increase rapidly through the early and middle parts of the 21st century. Atmospheric CO^2 concentrations accelerate and continue to increase for another 100 years after 2100. Global average temperatures are projected to increase by 4.3°C (95% CI 3.2°C to 5.4°C) compared to the pre-industrial period.

Shared Socioeconomic Pathways (SSPs)

SSPs are scenarios that span a range of socioeconomic changes that are likely to occur in the coming decades. SSPs were used for the Sixth Assessment Report of the IPCC for its findings.[46] The SSPs are narratives that describe possible, and plausible, trajectories of future socioeconomic developments and are designed to include a wide range of challenges to mitigation and adaptations to climate change.[23] These narratives were then used to project changes in variables sch as population, economic growth, education, urbanization, and technological development.[47] A summary of the different SSP narratives as described by Riahi et al. is as follows[23]:

"SSP1: Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)

The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2: Middle of the Road (Medium challenges to mitigation and adaptation)

The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP3: Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)

A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

SSP4: Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)

Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.

SSP5: Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)

This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.”

SSP1 and SSP5 represent scenarios with rapid economic growth and increased investments in health and education. While SSP5 envisions this through fossil-fuel based development, SSP1 does so through more sustainable means. SSP3 and SSP4 represent more pessimistic scenarios for economic growth and improvements in social development. SSP2 represents a middle of the road scenario.

Among the projections that can be made based on the SSPs are population levels by translating the SSP narratives listed above to assumptions of future fertility, mortality, migration and education scenarios for different regions.[48] The global population projections at the end of the 21st century are the lowest in the SSP1 and SSP5 scenarios with the population declining to around 7 billion. Under SSP3, the global population is projected to increase throughout the century reaching approximately 12.6 billion by 2100. Population projections for SSP2 and SSP4 are in between other pathways.

The baseline SSP scenarios, based on the narratives described above, do not account for any policies to mitigate the impact of climate change. However, each SSP describes a scenario with different levels of barriers and acceptance to, as well as need for, mitigation efforts that would allow for the achievement of emissions concentrations based on the different RCP trajectories. Although with more or less aggressive mitigation efforts, each of the different RCP targets could be reached under the different SSPs, certain RCP trajectories are more likely under the different SSPs. For example, the RCP8.5 trajectory is unlikely to occur under scenarios other than SSP5. For the Sixth Assessment Report of the IPCC, the following five SSP-RCP combination scenarios were used to assess a range of projected outcomes: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.[7]

Supplemental Methods S2 – Extreme heat days projection for the mid-century (2036-2065) period

Projections for the number of days with extreme heat in each county in the contiguous US were obtained from data made available by the Union of Concerned Scientists.[16] These projections are based on a methodology described in detail by Dahl et al.[20] Daily maximum heat index (HI) values were calculated using daily temperature and relative humidity from 2006 to 2099 from 18 statistically-downscaled climate models included in the Coupled Model Intercomparison Project Phase 5 (CMIP5). The Multivariate Adaptive Constructed Analogs (MACA) approach, which is a statistical method for downscaling Global Climate Models (GCMs) from their native coarse resolution (typically 100-300 km) to a higher spatial resolution, was used for these projections.[21] These GCMs provide projections as described in Supplemental Methods 1. The MACA approach uses a training dataset (i.e. a meteorological observation dataset) to remove historical biases and match spatial patterns in climate model output. Data were statistically downscaled to a spatial resolution of 4 kilometers. The daily maximum temperature and minimum relative humidity from the downscaled data were used to calculate daily maximum HI based on the National Weather Service HI equation.[17] The full historical model period (1950–2005) was trained to the gridMET 1979–2012 gridded meteorological observation dataset. GridMET is a hybrid spatially interpolated dataset that incorporates approaches and data from two climate datasets: the National Land Data Assimilation System Phase 2 (NLDAS-2) and Parameter-elevation Regressions on Independent Slopes Model (PRISM). These datasets are used to combine the desirable attributes of both original datasets i.e., high temporal resolution of NLDAS-2 fine spatial resolution of PRISM, into one spatially and temporally complete cohesive dataset. Bias of the downscaled model output was evaluated by comparing the multi-model mean number of days above a particular HI threshold and the equivalents for the gridMET dataset. The mean annual number of days in each US county with a HI ≥90 °F (32.2 °C), ≥100 °F (37.8 °C), and ≥105 °F (40.6 °C) as well as a "no-analog" scenario were estimated for different 30-year periods, including the mid-century (2036–2065) period. These were estimated for RCP 4.5 (intermediate increase) and RCP 8.5 (large increase) greenhouse gas concentration trajectories.

For the purposes of this analysis, we used the HI threshold of ≥90 °F (32.2 °C) for the primary analysis, but also evaluated days with HI ≥100 °F (37.8 °C), and ≥105 °F (40.6 °C) in secondary analyses. The annual projected number of extreme heat days were distributed to each of the five summer months (May to September) for each county based on the proportion of all extreme heat days that occurred in each month during the 2008-2019 period for a given county. For counties that had no extreme heat days in the 2008-2019 period, all projected extreme heat days were assigned to the month of July.

Supplemental Methods S3 – County population projections

As noted in Supplemental Methods 1, SSP scenarios have been used to project population levels for different regions. County-level population projections by age, sex, and race for the mid-century (2036-2065) period estimated by Hauer were used in the analysis.[22] The typical method for population projection is the Cohort-component method in which components of population change (fertility, mortality, migration) are projected separately for each birth cohort and then using these components to project the population size in the subsequent year.[49] However data on such components is typically unavailable at the county level, particularly for different subgroups. Hauer uses a modification of the Hamilton-Perry method which is a common alternative to the Cohort-component method and is a parsimonious method for creating population projections from multiple age-sex distributions using cohort-change ratios (CCRs).[50] To avoid the issue of impossibly large CCRs and impossibly explosive growth, particularly in cohorts with small population size, Hauer uses a blended model where county-race groups projected to grow utilize cohort-change differences (CCDs) while county-race groups projected to decline utilize CCRs. Autoregressive integrated moving average (ARIMA) models were then used to project the CCRs/CCDs. All age, sex, race, and county specific CCRs and CCDs were modeled in individual ARIMA models that populate the Leslie matrices (population projection matrices) to create projected populations. The age-structures were then controlled for the five SSPs (Supplemental Methods 1). Each SSP narrative has been previously used to create age and sex-specific projected population information. Population projections produced by Hauer from 2020-2100 were controlled using these SSP projections.

The populations were projected using the National Vital Statistics System (NVSS) U.S. Census Populations with Bridged Race Categories data set which bridges 31 race categories to four –

Hispanic, non-Hispanic Black, non-Hispanic White, and Other. To evaluate the accuracy of the projections, a base period of 1969 to 2000 was used to project age, sex, and race specific population for each county for the 2000 to 2015 period. These projections were compared against the actual county populations for this period, which showed a relatively small degree of bias.

Supplemental Methods S4: Spatial empirical Bayes smoothing

Mortality rate estimates from areas with small populations can be unstable due to potentially large changes resulting from a small change in the absolute number of deaths. This instability may lead to biased estimates of the risk of mortality in these areas. To account for this, we smoothed the monthly mortality rates using spatial empirical Bayes smoothing. This smoothing method combines the raw mortality rate with a reference rate and calculates a weighted average of the two. The weights for this average are directly proportional to the underlying population. Counties with small populations will have a greater adjustment in their rates compared to counties with a larger population. First a prior distribution is specified, and then, after observing the data, a posterior distribution is obtained.

The standard approach for Bayesian smoothing of rates is to specify a Poisson distribution for the observed counts (deaths in this case) and a Gamma distribution prior. This Poisson-Gamma mixture follows a negative binomial distribution. In an Empirical Bayes approach, parameters for the prior Gamma distribution are estimated from the actual data. The estimated prior rate can be considered the reference rate.

The empirical Bayes smoothed rate for a given county *i* is estimated using the following equation:

$$\text{Smoothed Rate}_i = \omega_i \times \text{crude rate}_i + (1- \omega_i) \times \text{reference rate}_i$$

where ω is a weight parameter calculated as follows:

$$\omega_i = \frac{\sigma^2}{(\sigma^2 + \mu/Population_i)}$$

where σ^2 and μ represent the variance and mean of the prior distribution and $Population_i$ refers to the population of county i.

μ is the reference mortality rate and is calculated as follows:

$$\sum_{i=1}^{i=n} Observed\ Deaths_i \, / \sum_{i=1}^{i=n} Population_i$$

and the σ^2 as follows:

$$\frac{\sum_{i=1}^{1=n} Population_i (crude\ rate_i - \mu)^2}{\sum_{i=1}^{i=n} Population_i} - \frac{\mu}{\sum_{i=1}^{i=n} Population_i / n}$$

where n refers to the number of counties in the reference sample.

In spatial empirical Bayes, the mean and variance of the prior are estimated from a localized group of observations rather than the global sample (i.e. all counties in the United States). In our analysis, we used all neighboring counties as the reference group for each county.

Supplemental Methods S5: Data sources and data missingness

Additional county-level publicly available data for this analysis were obtained from the following sources:

Monthly mean precipitation levels – Centers for Disease Control and Prevention's Environmental Public Health Tracking Program

Monthly number of days with elevated fine particulate matter (PM2.5), and ozone concentrations – Environmental Protection Agency.

Monthly percentage of the county population living in areas with drought – United States Drought Monitor

Monthly number of disaster declarations – Federal Emergency Management Agency

Monthly unemployment rate – Bureau for Labor Services

Total population, proportion of residents in different sub-groups based on age, gender, race and ethnicity, percentage of residents living in poverty, median household income, percentage of 18 to 64 year old adults without health insurance, and county metropolitan status – United States Census Bureau

Percentage of county land covered by forest and the percentage of land developed (low, median and high intensity development) – Multi-Resolution Land Characteristics Consortium National Land Cover Database.

Number of primary care providers – Area Health Resources Files, Health Resources & Services Administration

Number of hospital beds – American Hospital Association annual survey

Percentage of adult residents with diabetes - United States Diabetes Surveillance System, Centers for Disease Control and Prevention

All mortality and heat data were available for all counties in the contiguous US for all included years. Covariate data were available for all counties and years except as follows:

- The percentage of adult residents with diabetes in counties in the state of New Jersey were not available for 2019. Data from 2018 were used for both 2018 and 2019.
- Percentage of county land covered by forest and the percentage of land developed is available for the following years: 2008, 2011, 2013, 2016, and 2019. As forest cover and development is not expected to change rapidly from year to year, we used values for 2008 in years 2008 and 2019, values for 2011 in years 2010 and 2011, values for 2013 in years 2012, 2013, and 2014, values for 2016 in years 2015, 2016, and 2017, and values for 2019 in years 2018 and 2019.

Supplemental Methods S6: Poisson fixed effects regression model

The fixed effects, or within, estimator is an econometric technique to analyze longitudinal or panel data. This method examines the association between change in the outcome with change in the predictor variable within each subject. The inclusion of subject fixed effects (counties in this analysis) controls for both observed and un-observed time-invariant confounders. The inclusion of time fixed effects accounts for secular time trends that are common for all subjects. The following Poisson fixed effects model was used:

$$log(y_{imt}) \ = \beta_1 X_{imt} + a_i + \gamma_m + \zeta_t + \varepsilon_{imt} + log(population_{it})$$

Where y_{imt} is the number of age-adjusted, empirical Bayes smoothed deaths due to cardiovascular disease in county *I*, in month m (May, June, July, August, September), in year *t* (2008 to 2017), X_{imt} is a vector of time-varying independent variables, a_i is the county fixed effect, γ_m is the month fixed effect, ζ_t is the year fixed effect, ε_{imt} is the error term, and $\mathrm{population}_{it}$ is the annual county population (used as an offset variable).

Two separate models – for elderly and non-elderly adults – were estimated simultaneously to allow for separate estimates of the association between extreme heat days and mortality for these two sub-groups.

The model included the following monthly variables: the number of extreme heat days, mean precipitation levels, proportion of the population affected by drought, number of days with PM2.5 concentrations above national safety thresholds, number of days with ozone concentrations above national safety thresholds, the number of disaster declarations by the Federal Emergency Management Agency, and unemployment rate and annual variables: poverty rate, inflation-adjusted median household income, percentage of county residents other than non-

Hispanic White, percentage of county-residents who are elderly, percentage of adult residents with diabetes, percentage of non-elderly adults without health insurance, number of primary care providers per 100,000 residents and hospital beds per 100,000 residents, -percentage of county land covered by forest and the percentage of land developed.

Demeaned values of continuous covariates were included in the regression model.

Supplemental Table S1: ICD-10 codes used for assigning causes of death

Cause of Death	**ICD-10 codes**
Diseases of the circulatory system	I00-I99
Alternative definition for cardiovascular disorders	I00 – 109.9, I11.0 – I13.9, I20.0 – I25.9, I27.0 – I45.9, I47.0 – 147.9, I60.0 – I69.8, I70.2, I70.8, I71.0 – I73.9, I77.0 – I84.9, I86.0 – I98.9

Supplemental Table S2: Alternative Poisson fixed effects models and goodness of fit statistics. Outcome – Monthly cardiovascular mortality rate (all adults)*

Model	**Bayesian information criterion†**	**Psuedo-R²‡**	**Deviance goodness of fit statistic§‖**	**Pearson goodness of fit statistic§‖**
Original model	1161438	0.8985	Chi-square: 82615.6 df: 372896 Prob>Chi-square=1.00	Chi-square: 84519.34 df: 372896 Prob>Chi-square=1.00
Including number of extreme heat days as quadratic term	1161448	0.8985	Chi-square: 82599.46 df: 372892 Prob>Chi-square=1.00	Chi-square: 84504.76 df: 372892 Prob>Chi-square=1.00
Including all covariates as linear splines with 5 knots	1162433	0.8986	Chi-square: 82250.91 Prob>Chi1(372790) 1.00	Chi-square: 84129.46 Prob>Chi1(372790) 1.00

* Multivariable model includes all other covariates listed in Supplemental Methods 4

† Lower value indicates better model fit

‡ McFadden's pseudo-R^2. Values greater than 0.2-0.4 indicate excellent model

§ Prob>Chi-square>0.05 indicates adequate model fit

‖ Based on a Poisson Least Square Dummy Variable regression model with the same covariates as the Poisson fixed effects model and with county, month, and year fixed effects.

Supplemental Table S3: Estimated excess cardiovascular deaths associated with extreme heat days in the current (2008-2019) and mid-century (2036-2065) periods in the contiguous United States using alternative heat index thresholds among all adults*

	Current	**SSP2-4.5†**		**SSP5-8.5†**	
Heat threshold	Estimated excess deaths number of deaths, (95% CI)	Estimated excess deaths number of deaths, (95% CI)	Percent change compared to current period %, (95% CI)	Estimated excess deaths number of deaths, (95% CI)	Percent change compared to current period %, (95% CI)
≥100 °F (37.8 °C)	1043.2 (761.6, 1324.9)	3915.5 (2903.5, 4927.5)	275.3 (252.4, 298.2)	5771.5 (4284.0, 7259.1)	453.2 (418.4, 488.1)
≥105 °F (40.6 °C)	461.7 (297.9, 625.6)	2420.0 (1601.8, 3238.2)	424.1 (388.1, 460.0)	4169.4 (2759.3, 5579.5)	803.0 (738.5, 867.4)

* Estimated excess deaths based on Poisson fixed effects model with monthly and annual covariates from the 2008-2019 period (Supplemental Methods S6). Excess deaths were then estimated by calculating the difference between the number of predicted deaths in each county with all covariates at their observed value and the number of predicted deaths if there were no

extreme heat days. For the projected number of excess deaths in the mid-century period, the number of extreme heat days and county population were replaced with projected values when calculating the difference while keeping the regression coefficients the same.

† SSP - Shared Socioeconomic Pathways. SSP2-4.5 refers to a “Middle of the road” scenario for socio-economic changes and an intermediate increase in greenhouse gas emissions trajectory. SSP5-8.5 refers to a “Fossil-Fueled Development” scenario for socio-economic changes and a large increase in greenhouse gas emissions trajectory.

Supplemental Table S4: Estimated excess cardiovascular deaths associated with extreme heat days in the current (2008-2019) and mid-century (2036-2065) periods in the contiguous United States using an alternative cardiovascular mortality definition*†‡

	Current	**SSP2-4.5§**		**SSP5-8.5§**	
Population	**Estimated excess deaths number of deaths, (95% CI)**	**Estimated excess deaths number of deaths, (95% CI)**	**Percent change compared to current period %, (95% CI)**	**Estimated excess deaths number of deaths, (95% CI)**	**Percent change compared to current period %, (95% CI)**
All adults (20 years and older)	1084.0 (274.6, 1893.4)	2751.3 (547.1, 4955.6)	153.8 (121.9, 185.7)	3493.7 (692.0, 6295.3)	222.3 (181.0, 263.6)

* Extreme heat defined as maximum daily heat index ≥90 °F (32.2 °C)

† Estimated excess deaths based on Poisson fixed effects model with monthly and annual covariates from the 2008-2019 period (Supplemental Methods S6). Excess deaths were then estimated by calculating the difference between the number of predicted deaths in each county with all covariates at their observed value and the number of predicted deaths if there were no extreme heat days. For the projected number of excess deaths in the mid-century period, the

number of extreme heat days and county population were replaced with projected values when calculating the difference while keeping the regression coefficients the same.

‡ Alternative definition of cardiovascular mortality based on International Statistical Classification of Diseases and Related Health Problems, 10th Revision codes listed in Supplemental Table S1.

§ SSP - Shared Socioeconomic Pathways. SSP2-4.5 refers to a “Middle of the road” scenario for socio-economic changes and an intermediate increase in greenhouse gas emissions trajectory. SSP5-8.5 refers to a “Fossil-Fueled Development” scenario for socio-economic changes and a large increase in greenhouse gas emissions trajectory.