Appendix E. Temperature Mortality

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1. Introduction

Rising temperatures due to climate change will lead to an increase in heat-related illnesses and deaths.[1] Extreme temperature days, or days that are hotter than the average seasonal temperature in summer or colder than the average seasonal temperature in winter, cause increases in illnesses and death by compromising the body's ability to regulate its temperature.[2] There are two types of approaches that are typically used to understand the relationship between extreme temperature (or heat and cold stress) exposure and mortality. One approach, which is more data intensive, simulates associations between temperatures and mortality to assess whether there is evidence of excess mortality during periods of extreme hot or cold weather. A second approach uses death certificates to analyze whether the cause of death may be due to hot or cold weather - this approach tends to underestimate excess mortalities due to extreme temperatures because death certificates often lack this information.[3]

In addition to temperature-related mortality, temperature-related health impacts include heat stroke, heat exhaustion, heat syncope, heat cramps, and hyperthermia for hot weather, and hypothermia and

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[1] Ebi KL, Balbus JM, Luber G, Bole A, Crimmins A, Glass G, Saha S, Shimamoto MM, Trtanj J, and White-Newsome JL. 2018. Human Health. In *Impacts, Risks, and Adaptation in the U.S.: Fourth National Climate Assessment*, Volume II [Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK, and Stewart BC, (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 539–571. doi: 10.7930/NCA4.2018.CH14.

[2] USGCRP. 2016. *The Impacts of Climate Change on Human Health in the U.S.: A Scientific Assessment*. Crimmins A, Balbus J, Gamble JL, Beard CB, Bell JE, Dodgen D, Eisen RJ, Fann N, Hawkins MD, Herring SC, Jantarasami L, Mills DM, Saha S, Sarofim MC, Trtanj J, Ziska, L. U.S. Global Change Research Program, Washington, DC, 312 pp. http://dx.doi.org/10.7930/J0R49NQX

[3] Berko J, Ingram DD, Saha S, Parker JD. 2014. Deaths Attributed to Heat, Cold, and Other Weather Events in the U.S., 2006-2010. National Health Statistical Reports No. 76, July 30, 2014, 15 pp. National Center for Health Statistics, Hyattsville, MD. http://www.cdc.gov/nchs/data/nhsr/nhsr076.pdf

frostbite for cold weather.[4] Exposure to extreme heat may result in death because it exacerbates pre-existing conditions, including cerebral, respiratory, and cardiovascular diseases, and because it has greater impact on those who are taking prescribed or other drugs that may already change their heat regulatory system.[5] Studies have analyzed future temperature-related mortality related to climate change, and though there is no standard for defining temperature exposures, these studies provide consistent evidence of an increase in mortality from high temperatures due to warming climate.[6,7,8]

The relationship between exposure to extreme temperatures and socially vulnerable populations has been examined across hundreds of studies, reports, and guidance documents.[9,10,11] Vulnerability has been defined by the U.S. EPA as the "differential exposure, differential preparedness, and differential ability to recover".[12] This definition introduces the idea of adaptive capacity, which is the ability of an individual or community's social, political, and economic institutions to 1) adjust to change or changes, 2) regulate associated damage, 3) take advantage of resulting opportunities, and 4) cope with the outcomes.[13] Health impacts associated with extreme temperature exposure can be at least partially offset by an individual or community's adaptive capacity.[14]

This appendix analyzes the relationship between the risk of health impacts associated with increased extreme temperatures from climate change and the socially vulnerable groups who currently live in areas with the highest projected changes in premature mortality due to climate-driven changes in extreme temperature. This analysis considers mortality from changes in both extreme heat and cold. Previous studies on the U.S. have shown that the net effect of both heat stress and cold stress is

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[4] USGCRP. 2016. *The Impacts of Climate Change on Human Health in the U.S.: A Scientific Assessment*. Crimmins A, Balbus J, Gamble JL, Beard CB, Bell JE, Dodgen D, Eisen RJ, Fann N, Hawkins MD, Herring SC, Jantarasami L, Mills DM, Saha S, Sarofim MC, Trtanj J, Ziska, L. U.S. Global Change Research Program, Washington, DC, 312 pp. http://dx.doi.org/10.7930/J0R49NQX

[5] Berko J, Ingram DD, Saha S, Parker JD. 2014. Deaths Attributed to Heat, Cold, and Other Weather Events in the U.S., 2006-2010. National Health Statistical Reports No. 76, July 30, 2014, 15 pp. National Center for Health Statistics, Hyattsville, MD. http://www.cdc.gov/nchs/data/nhsr/nhsr076.pdf

[6] Sanderson M, Arbuthnott K, Kovats S, Hajat S, Falloon P. 2017. The use of climate information to estimate future mortality from high ambient temperature: A systematic literature review. *PLoS ONE* 12(7): e0180369. https://doi.org/10.1371/journal.pone.0180369

[7] Basu R, and Samet JM. 2002. Relation between Elevated Ambient Temperature and Mortality: A Review of the Epidemiologic Evidence. *Epidemiol Rev* 24:190-202.

[8] Botzen WJW, Martinius ML, Brode P, Folkerts MA, Ignjacevic P, Estrada F, Harmsen CN, Daanen HAM. 2020. Economic valuation of climate change-induced mortality: age dependent cold and heat mortality in the Netherlands. *Climate Change* 162:545-562.

[9] Berko J, Ingram DD, Saha S, Parker JD. 2014. Deaths Attributed to Heat, Cold, and Other Weather Events in the U.S., 2006-2010. National Health Statistical Reports No. 76, July 30, 2014, 15 pp. National Center for Health Statistics, Hyattsville, MD. http://www.cdc.gov/nchs/data/nhsr/nhsr076.pdf

[10] Ho HC, Knudby A, Chi G, Aminipouri M, Yuk-FoLai D. 2018. Spatiotemporal analysis of regional socio-economic vulnerability change associated with heat risks in Canada. *Appl Geogr* 95: 61-70.

[11] Manangan AP, Uejio CK, Saha S, Schramm PJ, Marinucci GD, Brown CL, Hess JJ, Luber G. 2014. Assessing Health Vulnerability to Climate Change: A Guide for Health Departments." In *Climate and Health Technical Report Series*. Atlanta, GA: Centers for Disease Control and Prevention.

[12] U.S. Environmental Protection Agency. 2003. Framework for Cumulative Risk Assessment. Washington, D.C.

[13] IPCC, Climate Change. 2007. Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA. Cambridge and New York: Cambridge University Press.

[14] Manangan AP, Uejio CK, Saha S, Schramm PJ, Marinucci GD, Brown CL, Hess JJ, Luber G. 2014. "Assessing Health Vulnerability to Climate Change: A Guide for Health Departments." In *Climate and Health Technical Report Series*. Atlanta, GA: Centers for Disease Control and Prevention.

dominated by the former.[15] While this chapter and its methods evaluate effects from both extreme heat and cold temperatures, it uses the term heat stress for convenience.

The analysis aims to quantify how climate change will affect extreme temperature mortality with respect to socially vulnerable populations. Section 2 describes the motivation and background for investigating these factors. Section 3 describes the methods used to perform the analysis, while Section 4 explains the results. Section 5 provides limitations about the results.

2. Populations who are Socially Vulnerable to Extreme Temperature Mortality

Studies analyzing the relationship between extreme temperature and related adverse health impacts focus on an array of different types of social vulnerabilities. These studies include both analysis of heat stress-related impacts and extreme cold-related impacts.

Evidence of the relationship between social vulnerability determinants and extreme temperature mortality

Most frequently, studies analyze extreme temperature-related impacts on the elderly population, or those aged 65 and up, and the infant population, or those under age 5.[16,17,18,19,20] Elderly individuals tend to experience worse health outcomes than those of other age groups due to cardiac strain created by exposure to heat, while babies and young children sweat less than older people, limiting their body's ability to naturally cool.[21,22]

Studies also examine the relationship between extreme temperature mortality and residence in an urban environment, poverty, identifying as a member of racial and ethnic groups including Black and African American and Hispanic and Latino individuals, suffering from social isolation, or working

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[15] See Chapter 5: Extreme Temperature Mortality, and in particular Table 5.2 in EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001, available at: https://www.epa.gov/cira/multi-model-framework-quantitative-sectoral-impacts-analysis

[16] Madrigano J, Jack D, Anderson GB, Bell ML, Kinney PL. 2015. Temperature, ozone, and mortality in urban and non-urban counties in the northeastern U.S. *Environmental Health*. 14:3.

[17] Eisenman DP, Wilhalme H, Tseng CH, Chester M, English P, Pincetl S, Fraser S, Vangala S, Dhaliwal SK. 2016. Heat Death Associations with the built environment, social vulnerability and their interactions with rising temperature. *Health & Place*, 41: 89-99.

[18] Berko J, Ingram DD, Saha S, Parker JD. 2014. Deaths Attributed to Heat, Cold, and Other Weather Events in the U.S., 2006-2010. National Health Statistical Reports No. 76, July 30, 2014, 15 pp. National Center for Health Statistics, Hyattsville, MD. http://www.cdc.gov/nchs/data/nhsr/nhsr076.pdf

[19] Ho HC, Knudby A, Chi G, Aminipouri M, Yuk-FoLai D. 2018. Spatiotemporal analysis of regional socio-economic vulnerability change associated with heat risks in Canada. *Appl Geogr* 95: 61-70.

[20] Wainwright SH, Buchanan SD, Mainzer HM, Parrish RG, Sinks TH. 1999. Cardiovascular mortality—the hidden peril of heat waves. *Prehospital and disaster medicine* 14.4: 18-27.

[21] Kenney WL, Craighead DH, Alexander LM. 2014. Heat waves, aging, and human cardiovascular health. *Med Sci Sports Exerc*. 46(10): 1891-1899.

[22] Natural Disasters and Severe Weather. 2017. Centers for Disease Control and Prevention, National Center for Environmental Health. https://www.cdc.gov/disasters/extremeheat/heat_guide.html

outdoors.[23,24,25,26,27] Madrigano et al. (2015) examined temperature, ozone, and mortality in 91 urban and non-urban counties within the Northeastern region of the U.S. Contrary to previous studies, authors found that extreme temperature impacts were not limited to urban areas. An increase in temperature from 70 to 90°F was associated with an 8.88% increase in mortality in urban counties, while that same temperature increase was associated with an 8.04% increase in mortality in non-urban counties. Importantly, characteristics of both urban and non-urban counties related to the percentage of elderly residents, families living in poverty, and population density impacted these results.[28]

Berko et al. (2014) evaluated death certificates for individuals whose deaths were attributed to heat, cold, and other weather events in subpopulations across the U.S. between 2006 and 2010. Using logistic regression with other demographic details, authors found that the counties in the highest quartile of median household income had the lowest rates of death due to any weather-related cause. The authors also found that subpopulations with increased mortality risk from heat stress include older adults, young children, Black and African American individuals, and males. Increased mortality risk from extreme cold was associated with older adults, young children, Black and African American individuals, males, and those with preexisting conditions. Non-Hispanic and Latino and Black and African American individuals had higher rates of both heat- and cold-related mortality than other race and ethnicity groups, experiencing heat stress-related mortality at a rate 2.5 times that for non-Hispanic white individuals, and 2 times that for Hispanic white individuals. Age-adjusted weather-related death rates varied by urban versus non-urban areas.[29]

Using air conditioning for cooling has an impact on the relationship between heat stress and mortality, as air conditioning contributes to an individual's adaptive capacity.[30] However, an individual's income, neighborhood, or other social vulnerability factors may prevent them from being able to readily access air conditioning in either their home or a local public setting. Eisenman et al. (2016) analyzed the relationship between adaptive capacity and social vulnerability in Maricopa County, Arizona, which includes the city of Phoenix. Study authors found that in Census tracts with more publicly accessible air-conditioned spaces, mortality from heat stress increased less than in those without publicly accessible cooled spaces. Performing a principal components analysis, authors found social vulnerability factors contributing to heat stress mortality risk included socioeconomic vulnerability, social isolation, older age, and working in an agriculture or extraction industry. Socioeconomic vulnerability was defined as

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[23] Basu R and Samet JM. 2002. Relation between Elevated Ambient Temperature and Mortality: A Review of the Epidemiologic Evidence. *Epidemiol Rev* 24:190-202.

[24] Basu and Samet, 2002.

[25] Berko J, Ingram DD, Saha S, Parker JD. 2014. Deaths Attributed to Heat, Cold, and Other Weather Events in the U.S., 2006-2010. National Health Statistical Reports No. 76, July 30, 2014, 15 pp. National Center for Health Statistics, Hyattsville, MD. http://www.cdc.gov/nchs/data/nhsr/nhsr076.pdf

[26] Ho HC, Knudby A, Chi G, Aminipouri M, Yuk-FoLai D. 2018. Spatiotemporal analysis of regional socio-economic vulnerability change associated with heat risks in Canada. *Appl Geogr* 95: 61-70.

[27] Åström DO, Bertil F, Joacim R. 2011. Heat wave impact on morbidity and mortality in the elderly population: a review of recent studies. *Maturitas* 69.2 (2011): 99-105.

[28] Madrigano J, Jack D, Anderson GB, Bell ML, Kinney PL. 2015. Temperature, ozone, and mortality in urban and non-urban counties in the northeastern U.S. *Environmental Health*. 14:3.

[29] Berko J, Ingram DD, Saha S, Parker JD. 2014. Deaths Attributed to Heat, Cold, and Other Weather Events in the U.S., 2006-2010. National Health Statistical Reports No. 76, July 30, 2014, 15 pp. National Center for Health Statistics, Hyattsville, MD. http://www.cdc.gov/nchs/data/nhsr/nhsr076.pdf

[30] Eisenman DP, Wilhalme H, Tseng CH, Chester M, English P, Pincetl S, Fraser S, Vangala S, Dhaliwal SK. 2016. Heat Death Associations with the built environment, social vulnerability and their interactions with rising temperature. *Health & Place*. 41: 89-99.

homes with female householder, householder living alone, foreign born, those working in outdoor occupations (e.g., agriculture, forestry, and mining), annual income below the poverty level, and those uninsured.[31] Mortality rates increased as temperatures increased in Census tracts that have higher proportions of Hispanic households with income under the poverty line and without health insurance.[32]

This study focuses on four determinants of social vulnerability to extreme temperature-related mortality. These social vulnerability determinants include many of those described by the relevant literature but may not be defined in the same manner. Social vulnerability metrics analyzed in this document include income (those making less than two times the federal poverty level); race and ethnicity (those who identify as Black and African American, Native American, Pacific Islander, Asian, or Hispanic/Latino); educational attainment (individuals with less than a high school diploma); and age over 65. While these characteristics have individual impacts on heat stress and the resulting risk of premature mortality, they are often observed in combination with one another and with other factors.

3. Methods for Assessing Social Vulnerability Dimensions of Climate Change-Related Changes in Extreme Temperature Exceedance Days

This analysis assesses two dimensions of extreme temperature impacts that could disproportionately influence socially vulnerable populations. The first recognizes that changes in extreme temperature days may be geographically concentrated in areas with higher or lower proportions of people who are socially vulnerable. The second focuses on differential health impacts due to higher baseline mortality rates among socially vulnerable populations, despite equal changes in extreme temperatures. The analysis is based on the approach in Mills et al. (2014), which employs a proportional hazard model whereby a given change in temperature exceedance days results in a percentage change in mortality risk relative to baseline incidence.[33]

This analysis builds upon an approach developed by Mills et al. (2014) and updated for U.S. EPA (2017), described here briefly. Mills et al. (2014) assessed extreme heat and extreme cold mortality over the 21st century in 33 U.S. cities. The analysis published in 2014 was subsequently updated to include 49 cities, and then further expanded to reflect heat and cold stress effects limited to populations in counties that correspond to 49 large U.S. cities.[34] The use of these 49 cities does not mean that individuals in other areas are not affected by extreme temperature mortality, but rather that the data are not available for those other locations to be included in this analysis.

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[31] "Householder," in these cases, refers to the head of household or single earner.

[32] Eisenman et al. 2016.

[33] Mills D, Schwartz J, Lee M, Sarofim M, Jones R, Lawson M, Duckworth M, Deck L. 2014. Climate change impacts on extreme temperature mortality in select metropolitan areas in the U.S. *Climatic Change*, 131, 83-95.

[34] U.S. EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, Washington, D.C.

To evaluate health effects under a wide-range of future temperatures, the methods were applied to daily maximum and minimum temperature inputs from six climate models (CanESM2, CCSM4, GISS-E2-R, GFDL-CM3, HadGEM2-ES, and MIROC5) under a higher greenhouse gas scenario (RCP8.5).[35]

U.S. EPA's Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE) is used in this analysis to quantify the impact of climate change on mortality from both extreme heat and extreme cold days. BenMAP-CE quantifies health impacts resulting from changes in environmental conditions such as air quality, as described in Technical Appendix D, or in this case temperature "exceedance days". This analysis uses datasets provided by the authors of Mills et al. (2014) that were updated for the U.S. EPA (2017) analysis, resulting in the full set of counties associated with 49 cities.

The following general function is applied in BenMAP-CE to calculate the increase in annual deaths due to the number of extreme temperature exceedances over the year (Equation 1):

$$\text{Excess Mortality} = \text{Incidence}*\text{Population}*\text{Beta}*\text{DeltaQ}$$

City-specific excess mortality estimates (the beta value in Equation 1) reflect multipliers on baseline daily mortality associated with each unique daily exceedance of a hot or cold threshold. The beta value is an important component that accounts for variability in mortality across cities based on local infrastructure and building types, market penetration of adaptive measures such as air conditioning, and the susceptibility/adaptability of human populations to heat and cold stress. The city-specific extreme hot and extreme cold threshold (DeltaQ) is another important parameter in the mortality effect function; excess mortality effect is not estimated below the extreme heat threshold or above the extreme cold threshold. These inputs, as well as baseline incidence and population, are summarized in Table 1. The relation of these inputs is presented in Figure 2.

Table 1. Components of Extreme Temperature Mortality Analysis

INPUT	DESCRIPTION AND SOURCE
Excess Mortality	Increase in extreme temperature-related annual deaths attributable to climate change (outcome variable)
Incidence	BenMAP-CE mortality incidence (2007-2016) stratified by White and non-White populations (see section D.1.3 of the BenMAP User Manual)[36]
Population	County-level population from the 2010 U.S. Census
Beta	The city-specific marginal mortality impact of an extreme temperature day as a decimal value
DeltaQ	City-specific change in heat or cold exceedance days between projected era (climate model-specific) and 1996 baseline period

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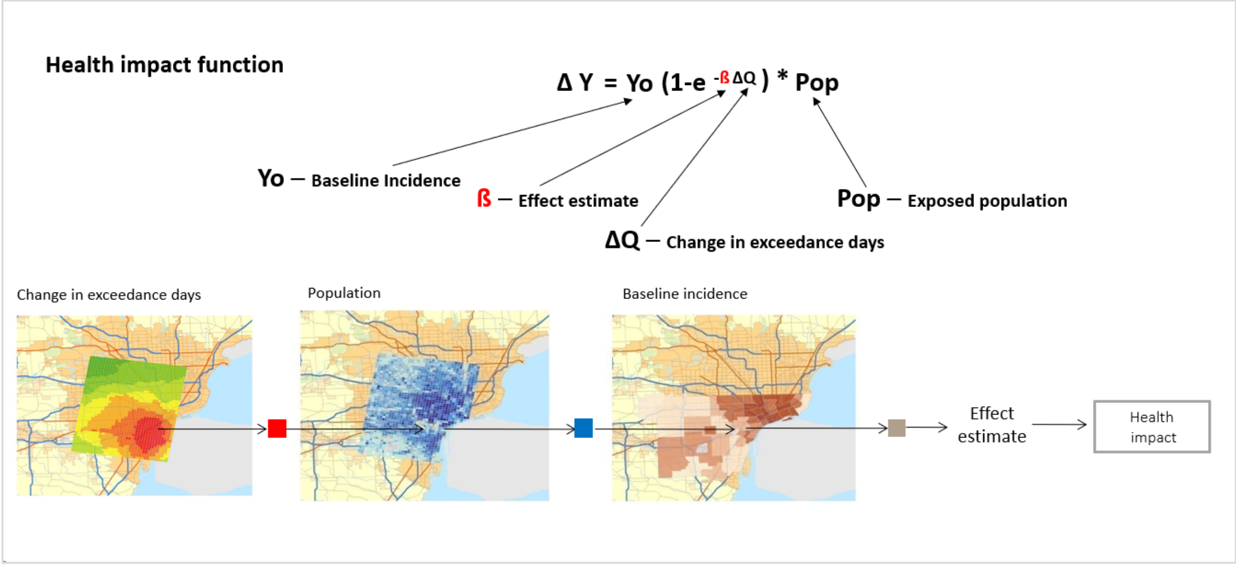
[35] RCP8.5 was selected to assess a wide range of future climates, but this does not imply a judgement regarding the likelihood of that scenario. As shown in this section, extreme temperature-related health impacts stemming from integer levels of future warming are derived from this trajectory of radiative forcing.

[36] U.S. EPA. 2018. Environmental Benefits Mapping and Analysis Program: Community Edition (BenMAP-CE) v 1.4.14. Washington, DC.

Figure 2. Components of Health Impacts Analysis Performed in BenMAP-CE



The resulting set of concentration-response (C-R) functions includes 78 county-specific extreme heat functions corresponding to 41 cities, and 83 county-specific extreme cold functions corresponding to 42 cities.[37]

Each temperature (heat or cold exceedance), climate model, and degree combination scenario is processed and city-specific county level C-R functions using BenMAP-CE are applied to generate estimated health effects for the vulnerable populations of interest.

City-specific model parameters are presented in Table 2. Cold and heat temperature thresholds indicate the temperature below which or above which a day is counted as an extreme temperature day, respectively. Beta values indicate the marginal mortality impact of an extreme temperature day.

Table 2. City-Specific Model Parameters

CITY	TEMPERATURE THRESHOLDS (°C)*		BETA VALUES	
	COLD	HEAT	COLD	HEAT
MIDWEST				
Canton, OH	-9.4	21.7	0.018	0.059
Chicago, IL	-10.6	23.3	0.017	0.098
Cincinnati, OH	-7.2	22.8	0.018	0.057
Cleveland, OH	-8.3	22.8	0.016	0.060
Columbus, OH	-7.8	22.8	0.016	0.056

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[37] Based on the observed period of the underlying empirical study, not every city meets both hot and cold exceedance thresholds. Specifically, cities where the minimum temperature for the 99 percentile hottest day is equal to or below 20°C (8 cities), or cities where the maximum temperature for the 1 percentile coldest day is greater than or equal to 10°C (7 cities) are excluded from analysis of heat or cold exceedance, respectively.

CITY	TEMPERATURE THRESHOLDS (°C)*		BETA VALUES	
	COLD	HEAT	COLD	HEAT
Detroit, MI	-8.9	22.8	0.017	0.068
Milwaukee, WI	-11.7	22.8	0.018	0.062
Minneapolis, MN	-17.2	22.2	0.018	0.059
St. Louis, MO	-7.8	26.1	0.018	0.058
Terre Haute, IN	-10	22.8	0.018	0.058
Youngstown, OH	-8.9	21.1	0.018	0.059
NORTHEAST				
Baltimore, MD	-3.3	23.9	0.017	0.059
Boston, MA	-6.1	23.3	0.018	0.059
Jersey City, NJ	-3.9	25	0.018	0.060
New Haven, CT	-7.2	21.7	0.019	0.056
New York, NY	-3.9	25.6	0.015	0.080
Philadelphia, PA	-3.9	25	0.018	0.065
Pittsburgh, PA	-7.8	21.7	0.017	0.058
Washington DC	-2.2	25	0.018	0.058
NORTHWEST				
Portland, OR	1.7	-	0.018	-
Seattle, WA	2.2	-	0.018	-
Spokane, WA	-7.2	-	0.018	-
SOUTHEAST				
Atlanta, GA	2.2	24.4	0.017	0.056
Birmingham, AL	2.2	24.4	0.018	0.057
Charlotte, NC	1.7	24.4	0.018	0.057
Fort Lauderdale, FL	-	27.8	-	0.050
Greensboro, NC	-0.6	23.3	0.019	0.059
Miami, FL	-	27.8	-	0.055
Nashville, TN	-2.2	24.4	0.018	0.055
New Orleans, LA	7.2	26.1	0.018	0.059
Orlando, FL	-	25	-	0.056
Tampa, FL	-	26.7	-	0.052
SOUTHERN GREAT PLAINS				
Austin, TX	5	25.6	0.018	0.057
Dallas, TX	1.7	27.2	0.017	0.055
Houston, TX	6.1	26.1	0.018	0.052
Kansas City, KS	-10	24.4	0.016	0.057
Oklahoma City, OK	-2.8	25	0.018	0.053
Tulsa, OK	-3.3	26.7	0.017	0.056
SOUTHWEST				
Albuquerque, NM	0.6	21.7	0.016	0.056
Boulder, CO	-8.9	-	0.018	-
Colorado Springs, CO	-8.9	-	0.018	-

CITY	TEMPERATURE THRESHOLDS (°C)*		BETA VALUES	
	COLD	HEAT	COLD	HEAT
Denver, CO	-8.9	-	0.017	-
Los Angeles, CA	-	21.1	-	0.064
Phoenix, AZ	-	32.2	-	0.056
Provo, UT	-3.9	22.8	0.018	0.058
Sacramento, CA	6.1	-	0.018	-
Salt Lake City, UT	-3.9	22.8	0.017	0.054
San Diego, CA	-	21.7	-	0.056
San Francisco, CA	9.4	-	0.017	-
*Cities with unlisted heat or cold thresholds and beta values do not meet exceedance criteria.				

To further understand the mortality impacts from extreme temperature exceedance days associated with degree increases in global mean temperature, this analysis uses the health effect estimates calculated in BenMAP-CE and follows the four steps outlined in Figure 3.

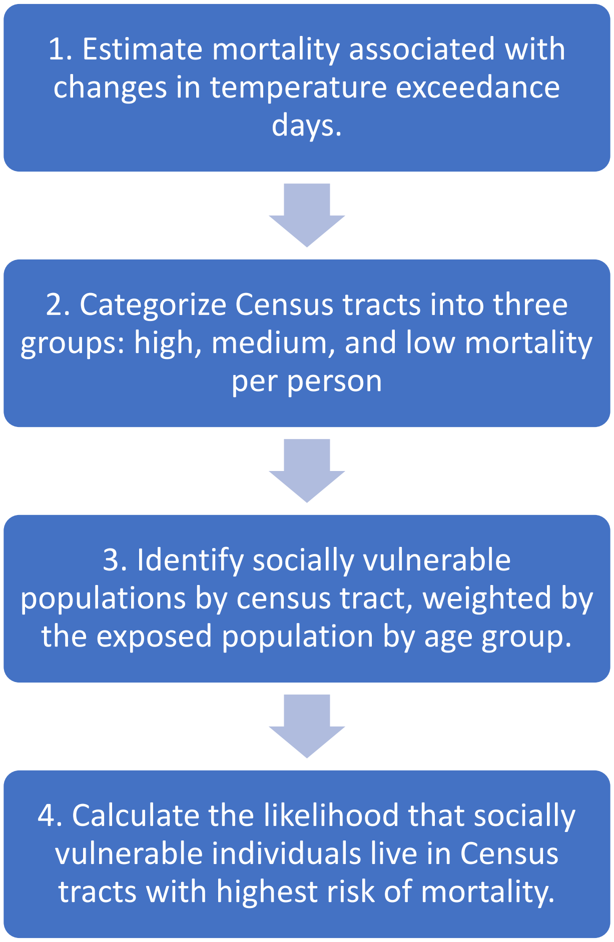
Step 1: Estimate the mortality rate effects associated with each degree increase in global mean temperature (from BenMAP results). The BenMAP analysis estimates excess mortality associated with increased hot and cold exceedance days due to increasing global mean temperature. For more on the climate projection methods, see Appendix C. BenMAP results are binned by integer degree of warming, averaged across climate models, and summed across impact type (heat-related mortality and cold-related mortality) in post-processing. These results are disaggregated to Census tract spatial resolution by calculating per capita mortality rate for each county and assigning that rate to each associated Census tract. Displaying results at the Census tract level allows for better application of social vulnerability factors.

Step 2: Categorize Census tracts into three groups: high, medium, and low mortality rates per person per year. The output from Step 1 is used to categorize Census tracts into three evenly sized groups, or terciles. The high impact group comprises Census tracts with the highest mortality rates; the low impact group includes Census tracts with the lowest mortality rates. This analysis focuses on the composition of populations found in the high impact tercile.

Step 3: Identify socially vulnerable populations by Census tract. This analysis does not observe exactly which individuals both experience extreme temperature-related mortality and are socially vulnerable. Instead, it relies on data from the American Community Survey (2012-2016) at the Census tract level to (1) count the number of individuals in socially vulnerable groups relative to non-socially vulnerable groups then (2) weight the proportions by the total population being analyzed. All-cause mortality rates associated with temperature exceedance days for those aged 0-99 based on Mills et al. (2014) as updated by U.S. EPA (2017) was quantified. The four measures of social vulnerability included in this analysis are: individuals who experience low income; ethnic or racial minority, or simply minority, which denotes Black and African American, Native American, Pacific Islander, Asian, and Hispanic and Latino individuals; individuals with no high school diploma; and individuals who are age 65 or older.[38,39,40]

Step 4: Calculate the likelihood that socially vulnerable individuals currently live in Census tracts with highest projected increases in premature mortality. These likelihoods are expressed relative to the respective non-socially vulnerable population and are calculated at the national and regional level. The likelihood measures are separately calculated for each social vulnerability metric.

Figure 3. Four steps for assessing extreme temperature-related mortality effects on socially vulnerable populations



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[38] Individuals who experience low income are defined as those who earn less than two times the federal poverty limit in income each year. Further details can be found in footnote 8 in Section 1 of this technical appendix.

[39] Black and African American, Native American, Pacific Islander, Asian, and Hispanic/Latino-identifying individuals make up the group that this report refers to as of “minority” or “minority status” in accordance with the 2020 federal environmental justice glossary. This description nonetheless may serve to further marginalize these historically marginalized groups and aim to describe these individuals based on their characteristics.

[40] No high school diploma refers to individuals who have not attained a high school diploma or its equivalent.

4. Results and Discussion

Section 4 describes the results of the analytic methods described in Section 3. First, this section provides maps showing the changes in the number of days over 90ºF in the current climate and expected to be experienced with 2ºC and 4ºC of warming. Next, this section presents a table of extreme temperature-related mortality by city. Then, this section presents maps of the geographic distribution of vulnerable populations across the Census tracts included in this analysis, along with maps of extreme temperature-related mortality impacts by degree – limited to the counties within the spatial domain of this heat and cold stress analysis. Next, this section describes the sorting of results into terciles of premature death and national-level likelihood of premature mortality impacts by social vulnerability factors. Finally, the section presents results for the likelihood that each socially vulnerable group currently lives in high-impact areas relative to their reference populations.

Figure 4 presents the number of days with temperatures 90°F or higher under current climate and with global warming of 2°C and 4°C. Each city has a distinct threshold for extreme heat mortality impacts, but these maps provide a general indication of the changes in extreme heat using a consistent metric across the contiguous U.S.

Table 3 depicts projected net extreme temperature-related excess deaths (considering the net effect of both heat stress and cold stress) per 100,000 population in each city for each degree increase of global mean temperature.[41] Excess deaths are measured from the baseline period, and the table also includes the baseline (or "0ºC") baseline mortality rate. Also included in the table are the cold temperature and hot temperature thresholds for each city. It shows that climate change is projected to result in increasingly higher rates of mortality as global mean temperature increases.

Generally, mortality rates in the cities analyzed are expected to increase with warming, especially in southern and eastern regions that are projected to experience the largest increase in extremely hot days. Cities that only experienced extreme cold in the historic period, notably those in the Northwest region, do not show an increase in extreme-temperature related mortality in this analysis. This result is an artifact of the methodology, which relies on observed temperature thresholds based on a historic period – it is likely that many of these Northwestern cities could show heat-related mortality outcomes under a different methodology. The results show the Midwest is projected to exhibit high mortality rates associated with extreme temperature, but currently available data do not reveal the reasons for this difference, they only suggest that at the population level the Midwest cities included in the analysis are more sensitive to extreme heat stress than other locations examined by this work.

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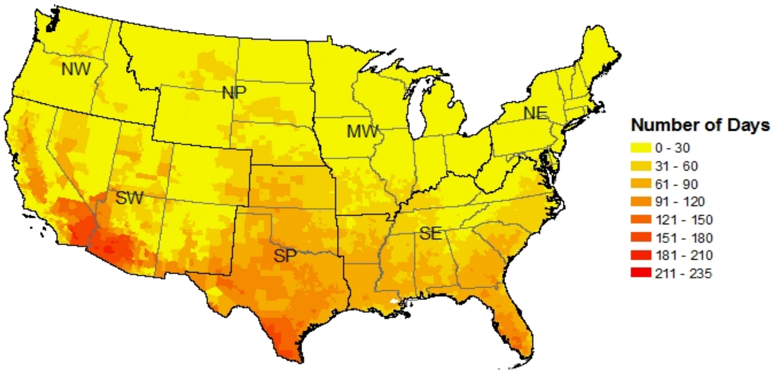
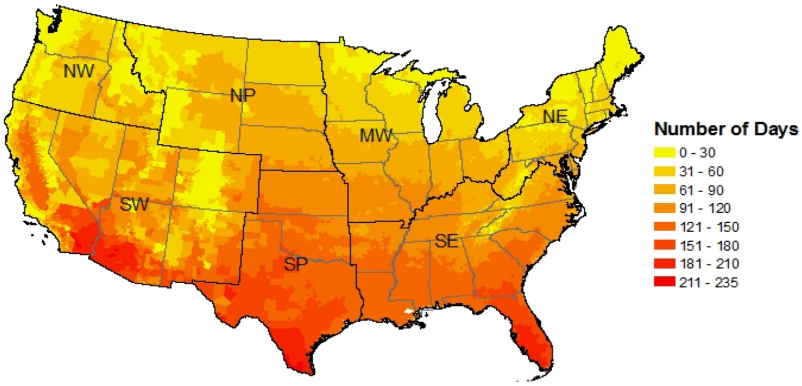
[41] Mortality impacts reported in Table 3 reflect the sum of heat and cold impacts in all census tracts that encompass each city, as described in section 3 of this Appendix (Methods).

Figure 4. Number of Days Above 90°F in Current Climate and with 2°C and 4°C of Global Warming

Current climate



2°C of Global Warming



4°C of Global Warming

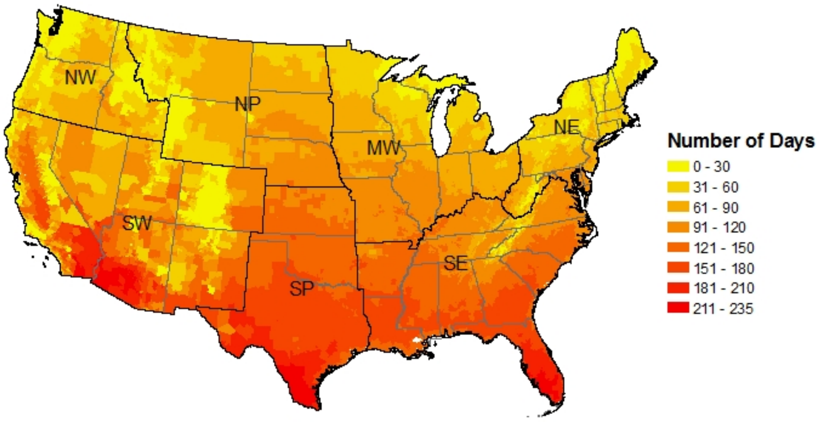


Table 3. Baseline and Excess Mortality Rates Per 100,000 by City at 1°C through 5°C of Global Mean Temperature Increase. Color Gradations Express the Range of Excess Mortality Risk Values by City, from Lowest (pink) to Highest (red).

CITY	BASELINE MORTALITY PER 100,000	EXCESS (ABOVE BASELINE) MORTALITY PER 100,000				
	0°C*	1°C	2 °C	3 °C	4 °C	5 °C
MIDWEST						
Canton, OH	0.36	1.99	4.50	7.63	10.45	15.98
Chicago, IL	0.60	1.50	3.36	5.14	7.71	13.02
Cincinnati, OH	0.53	2.03	4.24	6.66	9.23	13.51
Cleveland, OH	0.47	1.33	3.17	5.49	7.99	13.00
Columbus, OH	0.55	1.10	2.67	4.61	6.43	9.93
Detroit, MI	0.45	0.78	2.00	3.42	5.75	10.63
Milwaukee, WI	0.52	0.75	2.36	4.37	6.52	10.40
Minneapolis, MN	0.78	1.30	2.57	3.95	5.73	8.84
St. Louis, MO	0.38	0.79	2.33	4.27	6.66	10.72
Terre Haute, IN	0.55	2.12	4.36	6.55	8.53	12.23
Youngstown, OH	0.48	1.69	4.09	7.11	10.11	16.38
NORTHEAST						
Baltimore, MD	0.45	1.24	3.32	6.16	8.73	13.23
Boston, MA	0.56	0.24	0.91	2.25	3.22	6.04
Jersey City, NJ	0.41	0.36	1.28	2.64	3.73	6.02
New Haven, CT	0.70	0.82	2.23	4.31	5.81	9.62
New York, NY	0.71	0.67	2.22	4.42	6.20	9.61
Philadelphia, PA	0.51	0.69	2.28	4.65	6.76	10.93
Pittsburgh, PA	0.42	1.93	4.93	8.56	11.61	17.75
Washington DC	0.59	1.28	3.42	5.86	7.65	10.77
NORTHWEST						
Portland, OR	0.02	-0.01	-0.03	-0.05	-0.05	-0.06
Seattle, WA	0.02	0.00	-0.02	-0.05	-0.05	-0.05
Spokane, WA	0.05	0.00	-0.04	-0.08	-0.09	-0.08
SOUTHEAST						
Atlanta, GA	0.34	0.78	2.18	4.03	5.68	7.93
Birmingham, AL	0.90	0.78	2.46	4.88	7.47	12.66
Charlotte, NC	0.13	0.94	2.74	4.78	6.34	8.97
Fort Lauderdale, FL	0.04	0.29	1.08	2.22	4.26	8.63
Greensboro, NC	0.61	1.80	4.31	7.01	8.93	12.51
Miami, FL	0.08	0.92	3.01	6.11	9.34	13.60
Nashville, TN	0.44	1.32	3.69	6.42	8.55	11.88

CITY	BASELINE MORTALITY PER 100,000	EXCESS (ABOVE BASELINE) MORTALITY PER 100,000				
	0°C*	1°C	2°C	3°C	4°C	5°C
New Orleans, LA	0.51	2.13	5.09	8.76	11.49	15.45
Orlando, FL	0.18	1.98	5.20	7.96	9.70	11.35
Tampa, FL	0.55	1.08	3.38	6.49	8.86	11.91
SOUTHERN GREAT PLAINS						
Austin, TX	0.46	0.99	2.65	4.90	6.37	7.73
Dallas, TX	1.14	0.54	1.69	3.58	5.25	7.07
Houston, TX	0.20	1.27	3.47	6.07	7.59	9.35
Kansas City, KS	3.09	1.90	4.01	5.72	7.26	9.38
Oklahoma City, OK	0.43	1.71	4.03	6.58	8.86	10.93
Tulsa, OK	1.05	1.32	3.21	5.64	7.95	10.64
SOUTHWEST						
Albuquerque, NM	0.23	1.14	3.15	4.75	6.13	8.63
Boulder, CO	0.01	-0.03	-0.04	-0.04	-0.04	-0.05
Colorado Springs, CO	0.01	-0.01	-0.03	-0.04	-0.04	-0.05
Denver, CO	0.03	-0.02	-0.03	-0.04	-0.04	-0.05
Los Angeles, CA	0.00	0.55	1.24	2.27	3.35	6.01
Phoenix, AZ	0.11	0.22	0.76	1.55	2.40	5.34
Provo, UT	0.30	0.31	0.75	1.21	1.86	2.90
Sacramento, CA	0.09	-0.02	-0.04	-0.06	-0.07	-0.07
Salt Lake City, UT	0.35	0.44	1.09	1.75	2.69	4.20
San Diego, CA	0.00	0.60	1.63	3.19	4.20	7.07
San Francisco, CA	0.01	-0.02	-0.04	-0.06	-0.06	-0.06

*0°C references deaths per 100,000 attributable to extreme temperature in the baseline climate (1986-2005). All other columns represent the change in mortality rates incremental to the baseline due to global temperature change.

Figure 5 shows the proportion of socially vulnerable individuals in the four populations analyzed that currently live in the Census tracts included in the analysis. Populations are assumed to remain constant under the different levels of global warming analyzed.[42]

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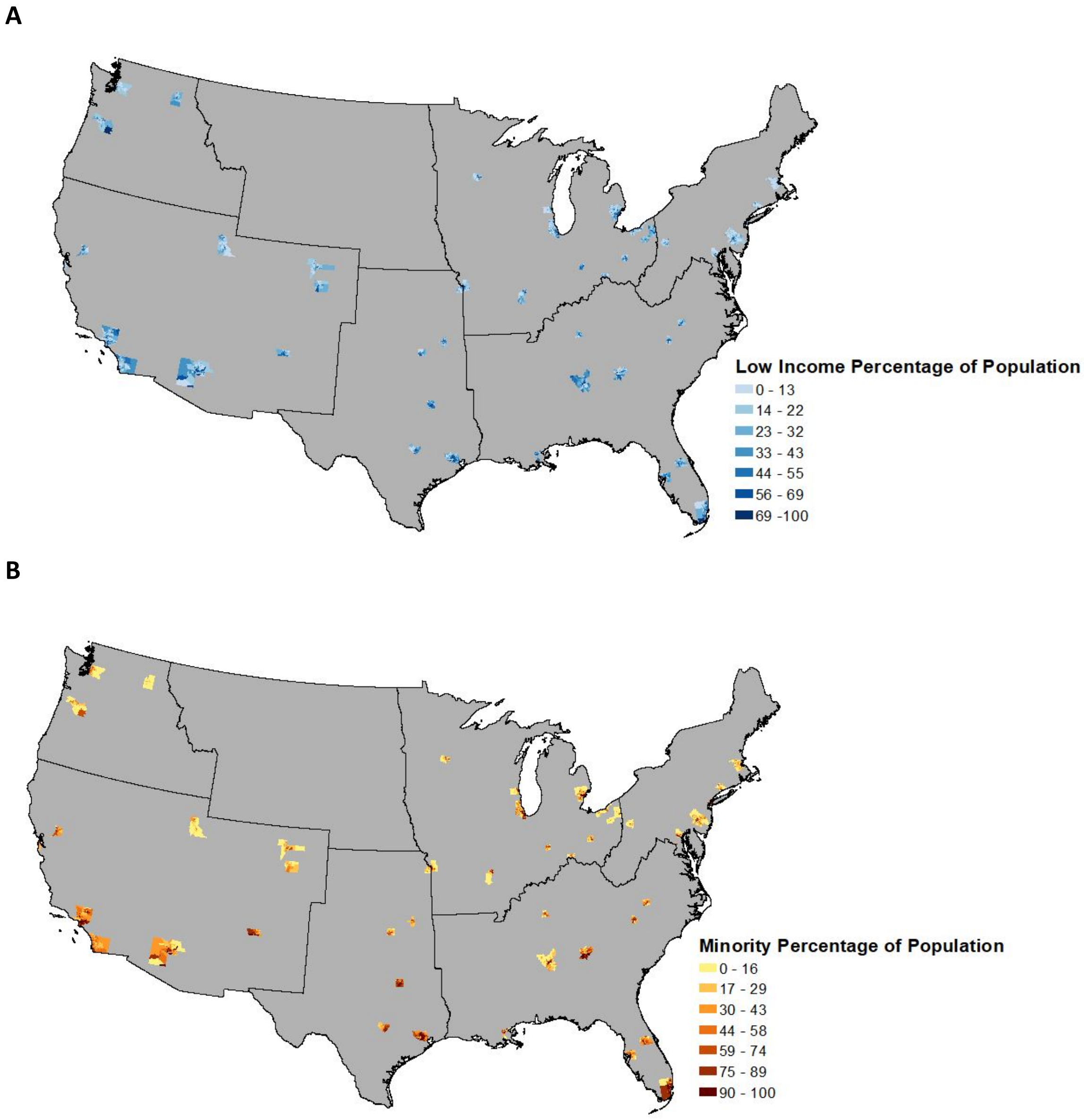
[42] This assumption may be flawed. As global mean temperatures increase, those living in cities that already experience many days with extreme temperatures may leave for cities with fewer extreme temperature days. This flight phenomena is likely to occur more frequently with greater increases in global mean temperature.

Figure 5. Socially Vulnerable Populations within Study Area



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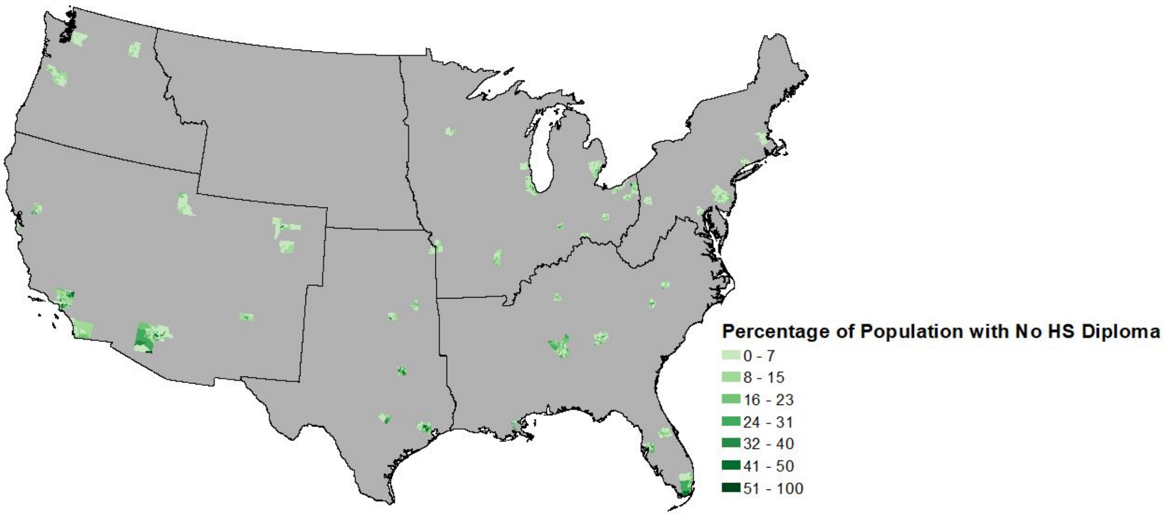

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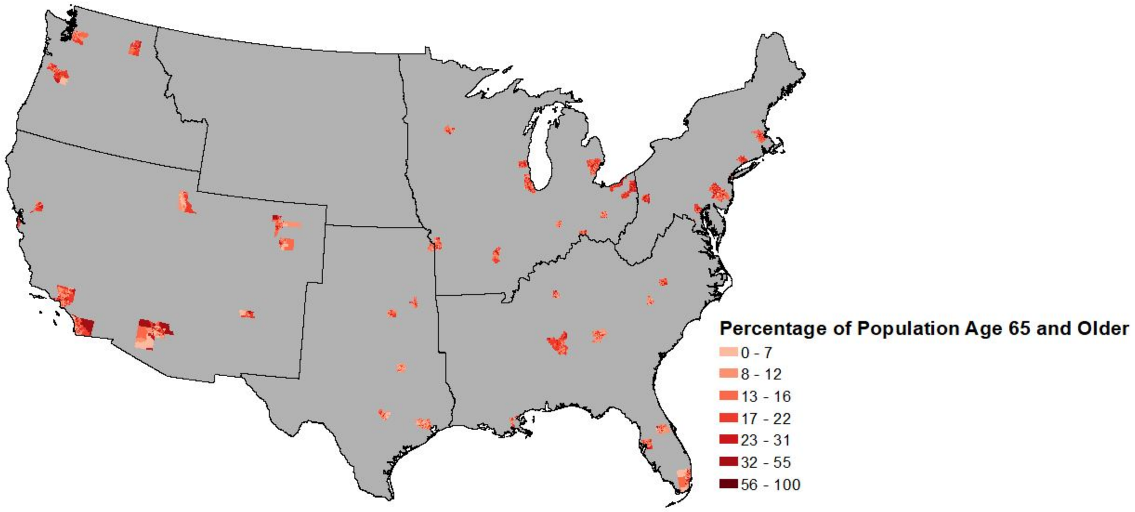
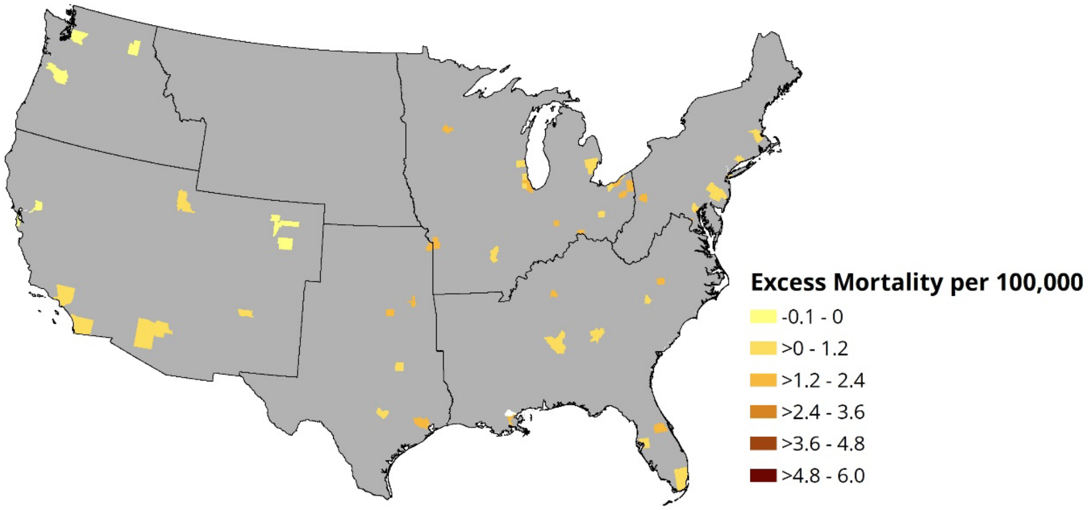


Figure 5a shows that most cities included in this analysis have heterogenous income profiles across Census tracts, with slightly higher percentages experiencing low income in the southern and western regions. The percentage of the population experiencing low income is slightly lower in cities in the Midwest and the Northeast than in the rest of the cities. Figure 5b shows Census tracts with the percentage of individuals who identify as Black and African American, Native American, Pacific Islander, Asian, or Hispanic and Latino. Generally, the southern regions have Census tracts with higher percentages of Black and African American, Native American, Pacific Islander, Asian, or Hispanic and Latino individuals than northern regions. Figure 5c shows the percentage of the population in each Census tract with no high school diploma. Cities in the southern regions have slightly greater percentages of individuals who have no high school diploma compared to northern regions. Figure 5d shows little difference in the percentage of population that are age 65 or older, though there is slightly more variation among Census tracts that make up the urban area of each city. There is not significant variability across regions, but there is variability within Census tracts that make up each urban area. This trend highlights the heterogeneity of urban populations across factors of vulnerability.

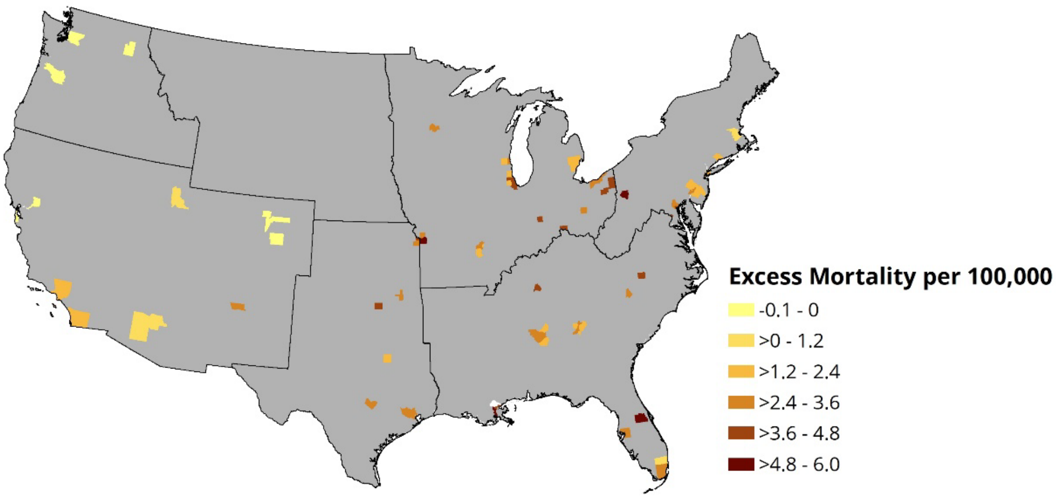
To better understand the projected regional patterns of extreme temperature-related mortality, Figure 6 shows maps of extreme temperature-related excess mortality rates associated with 1°C through 5°C increases in global mean temperature.

Figure 6. Extreme Temperature-Related Premature Mortality by Census Tract at Different Levels of Global Mean Temperature Change[43]

1°C Global Warming



2°C Global Warming



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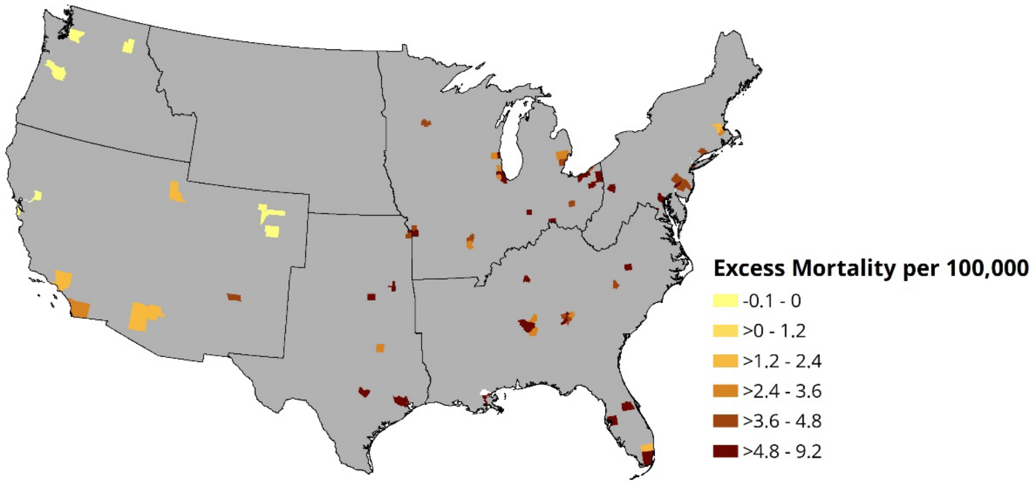
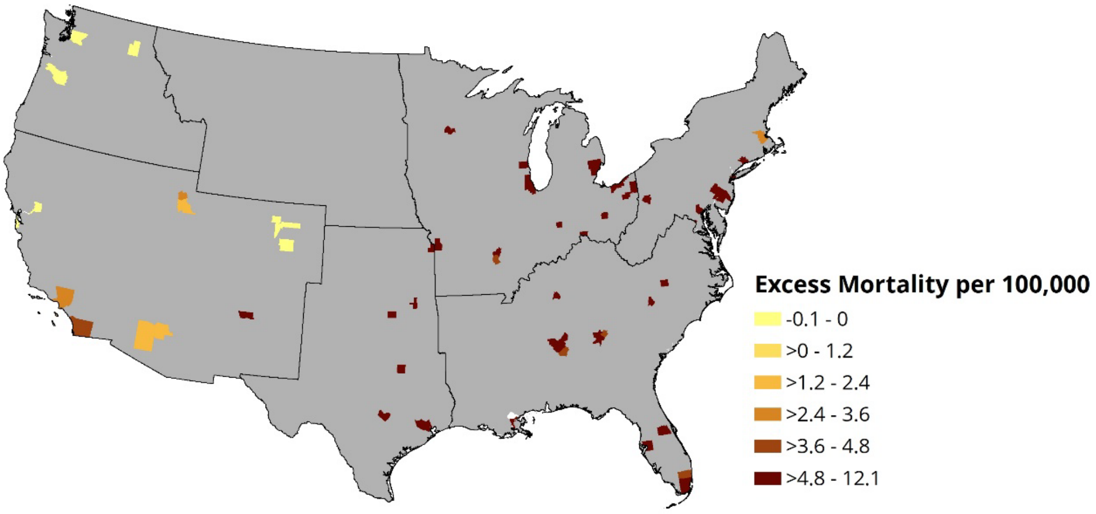
[43] Only census tracts that correspond to the cities evaluated within this analysis are included.

3°C Global Warming



4°C Global Warming



5°C Global Warming

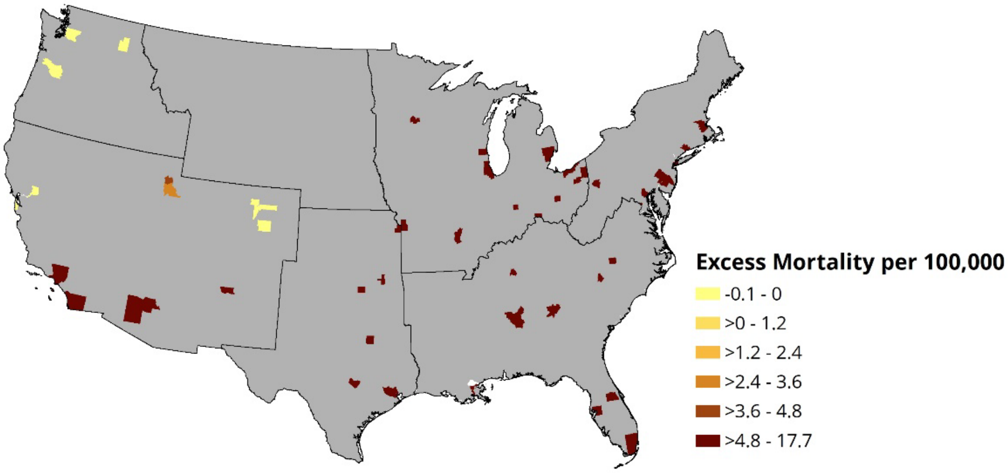


Figure 6 shows increasing rates of excess mortality across cities as global mean temperatures increase from the baseline. Regardless of social vulnerability factors, cities in the Northwest experience comparatively lower mortality rates consistently as global mean temperature increases, as the unique climate and topography of the Northwest makes cities less likely to experience extreme temperature days. Extreme temperature mortality in the Northwest is minimized by decreasing extreme cold deaths with warming temperatures. As noted above, the result for the Northwest is an artifact of the underlying methodology in Mills et al. (2015) – with a different methodology the analysis might find greater heat impacts in this region.

As seen in Figures 5 and 6, cities in the Midwest, Northeast, and Southeast regions generally experience greater mortality rates at 2°C of warming in Census tracts with a higher percentage of individuals who experience low income (e.g. Chicago, Philadelphia, Birmingham, Tampa). This pattern is not observed in the cities of the Northwest and Southwest, where Census tracts with high percentages of individuals who experience low income experience lower mortality rates. Individuals who experience low income are particularly susceptible to extreme temperature-related health impacts because they may not have reliable access to adaptive measures that alleviate heat stress, such as air conditioning, when compared with non-vulnerable individuals.

The figures also show that in cities of the Southeast and Southern Great Plains regions, individuals who are classified as one or more of the minority racial and ethnic categories defined in this document are projected to have greater numbers of deaths caused by extreme temperatures than individuals in the modeled cities of the northern regions. This is especially true in Houston and Miami, where over 75% of the population identifies as Black and African American, Native American, Pacific Islander, Asian, or Hispanic/Latino and deaths exceed 3 people per 100,000 at 2°C of warming. In contrast, the Midwest and Northeast have higher percentages of white, non-Hispanic or Latino individuals, but also experience higher extreme temperature-related mortality rates after 2°C of warming – the results in Table 3 above provide evidence that cities in the Midwest and Northeast region are generally more susceptible to increased warming, perhaps because those cities are less well acclimated to extreme heat events.

The percentage of the population age 65 and older is distributed fairly uniformly across urban areas included in this analysis, while greater mortality rates are concentrated in southern and eastern regions.

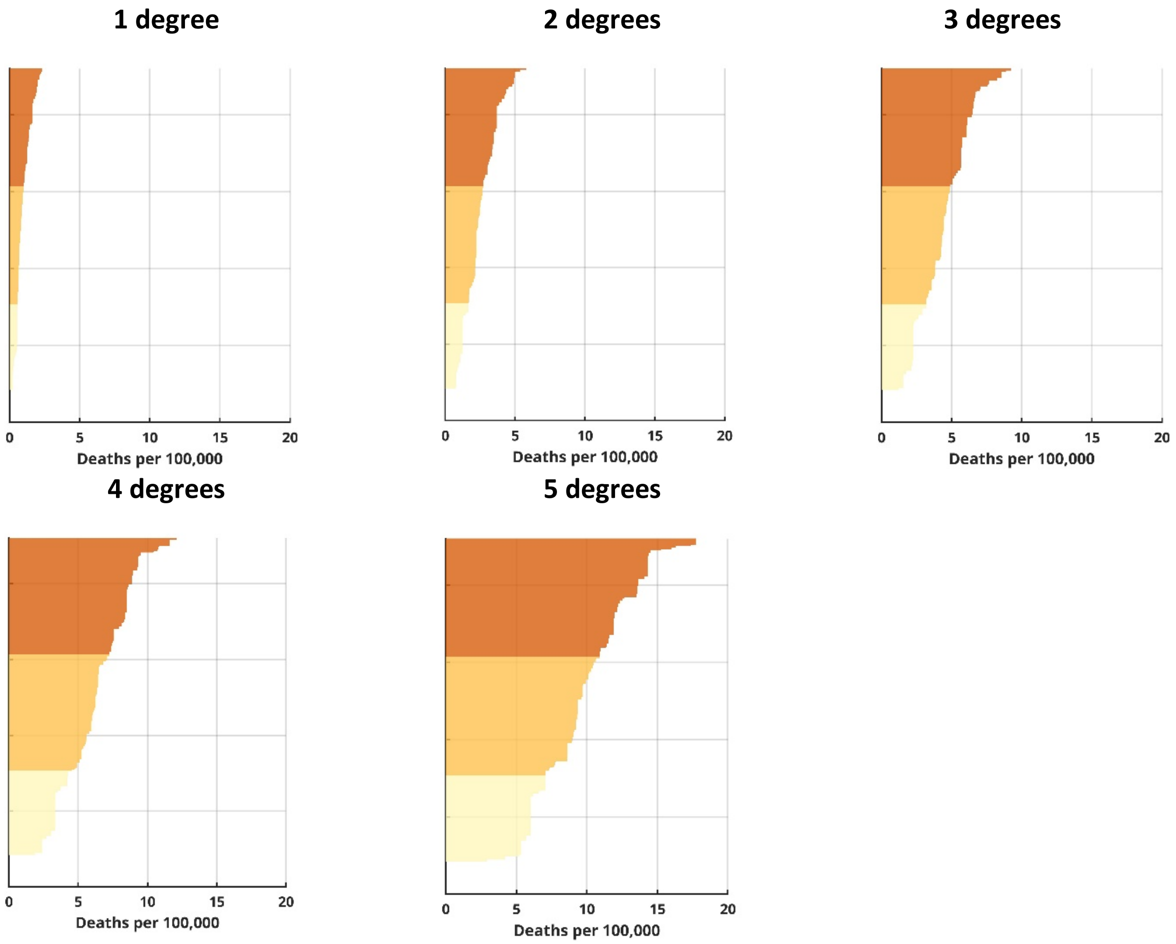
Some cities in the Southwest have greater percentages of individuals age 65 and older, but do not experience higher mortality rates. This implies that the distribution of deaths at 2°C of warming is more temperature-driven than correlated to the percentage of the population age 65 and older. This could be due to the mitigating effect of decreased extreme cold-related deaths in northern and western regions, as elderly individuals are vulnerable to experience worse health outcomes than those of other age groups due to heat-related cardiac strain and diminished thermoregulatory control. Based on the epidemiological and observational studies described in Section 2, elderly individuals are likely to be more vulnerable to extreme temperature days irrespective of their location.

Figure 7 shows the distribution of extreme temperature-related mortality rates per 100,000 people by Census tract and degree of warming. The distribution is sorted into high, medium, and low impact terciles at 1°C through 5°C of global mean temperature increase. Together, the panels in Figure 7 show a relatively uniform increase in excess mortality impacts across Census tracts analyzed, with the exception of the top five percent of tracts which show an unusually high rate of increase compared to lower impact tracts (at two degrees of global mean temperature increase and above). In the Census tracts at the top of the distribution, impacts are projected to surpass five deaths per 100,000 at two degrees of warming and ten deaths per 100,000 at four degrees of warming.

Figure 8 presents the likelihood that socially vulnerable individuals currently live in areas with the highest increases in mortality due to climate-driven changes in extreme temperatures, compared to individuals in their reference populations. With 2°C of global warming, those with low income are 11% more likely than those with higher income to currently live in high-impact areas. With 4°C of global warming, the risk for this population increases to 16%. With 2°C and 4°C of global warming, minorities are 8% and 14% more likely, respectively, to live in high-impact areas relative to non-minorities. Those with no high school diploma and those over age 65 are not projected to be more likely to live in high-impact areas relative to their reference populations.

In general, the likelihood that socially vulnerable individuals live in areas with the greatest risk of extreme temperature-related death increases as global mean temperature increases from one to four degrees. Directional changes of risk at five degrees of warming for Black and African American, Native American, Pacific Islander, Asian, and Hispanic/Latino individuals, as well as those with no high school diploma, is likely attributed to the changing composition of the climate model suite after four degrees of warming.

Figure 7. Distribution of Projected Annual Extreme Temperature-Related Deaths Per Person by Census Tract (Nationally) Associated with Degree Increases (in Celsius) in Global Mean Temperature. Excess Premature Mortalities are Shown as the Count Per 100,000.



1 degree

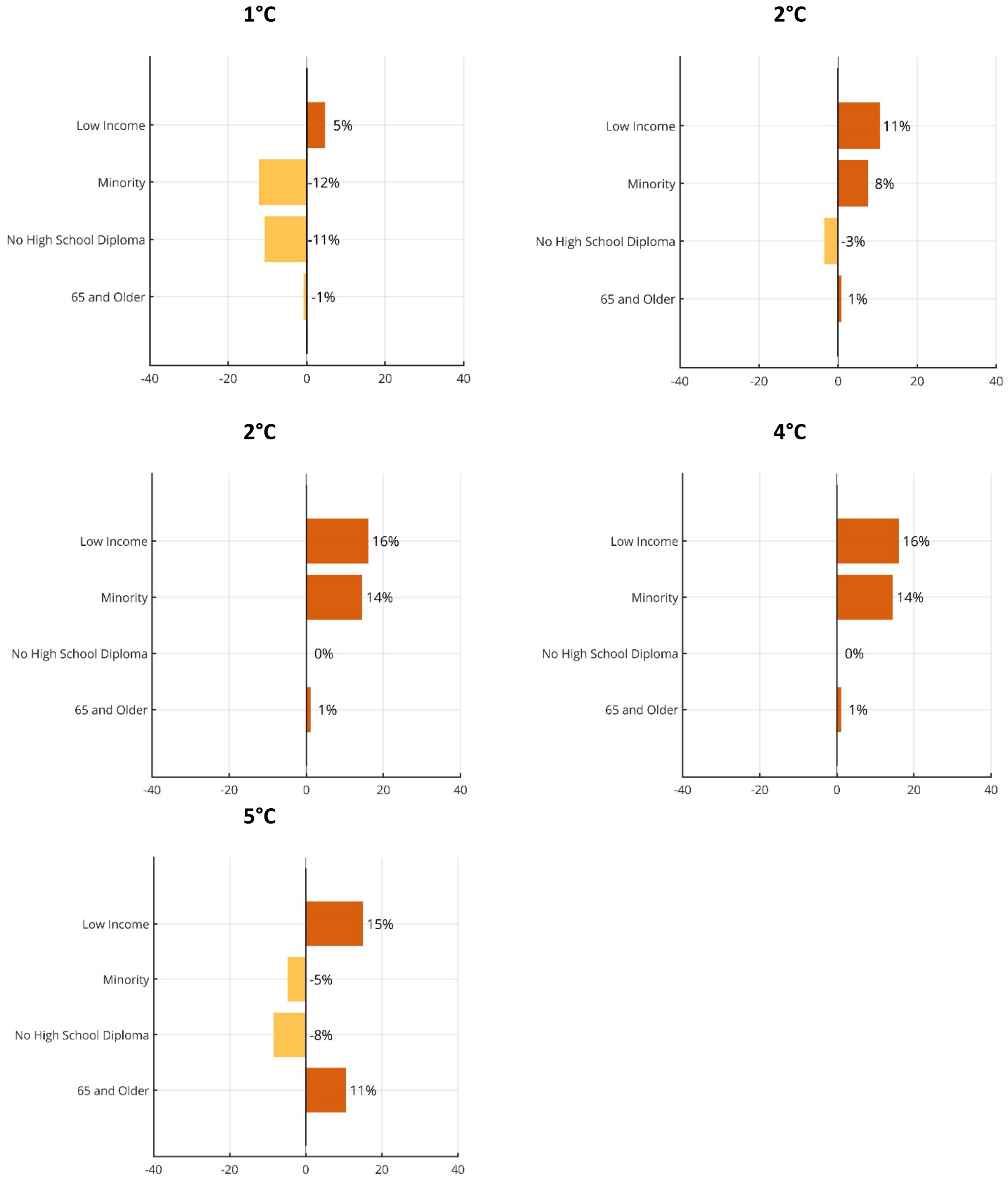
2 degrees

3 degrees

4 degrees

5 degrees

Figure 8. Likelihood that Those in Socially Vulnerable Groups Currently Live in Areas with the Highest Projected Increase in Extreme Temperature-Related Deaths Relative to Their Reference Populations



1°C

2°C

2°C

4°C

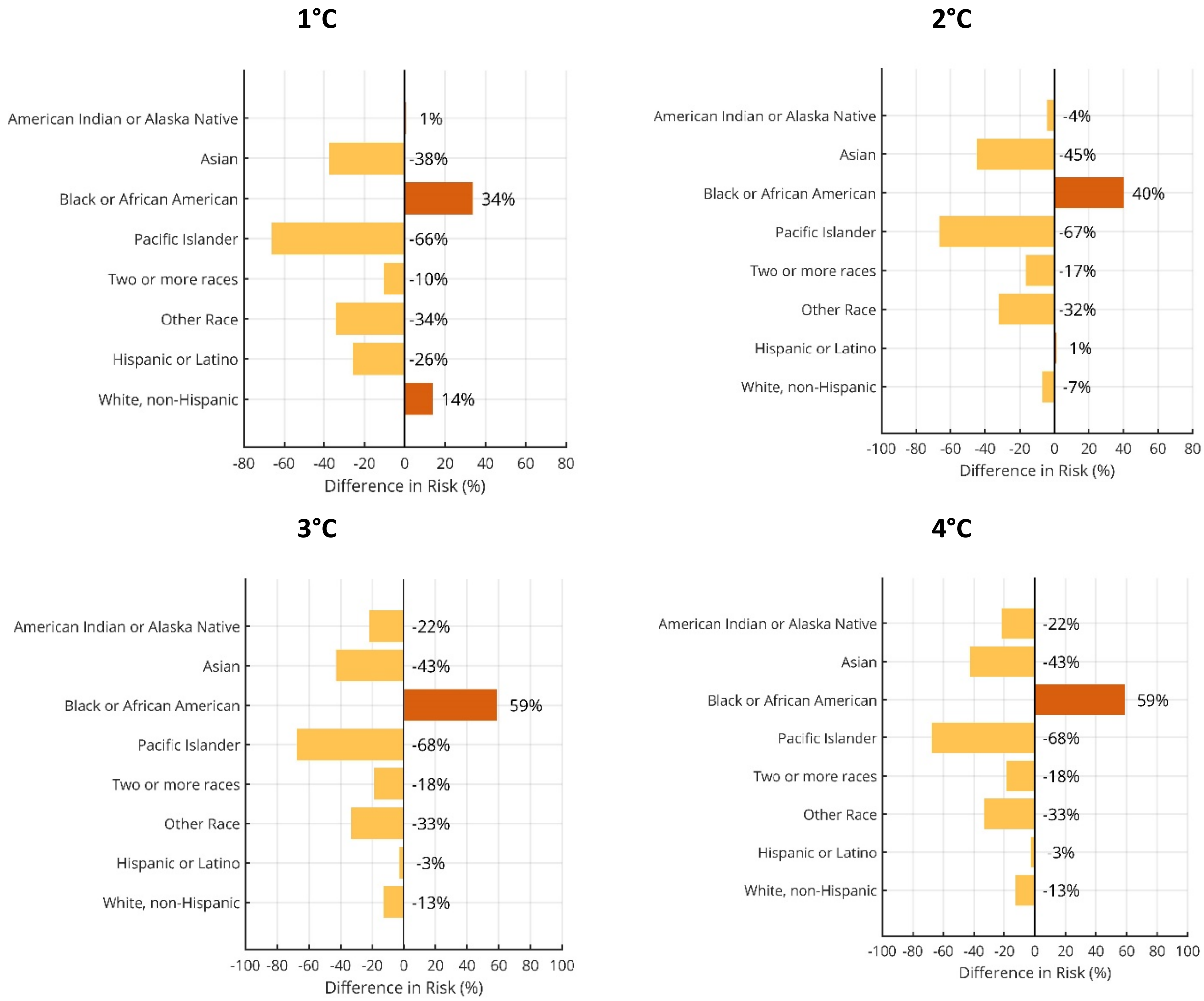
5°C

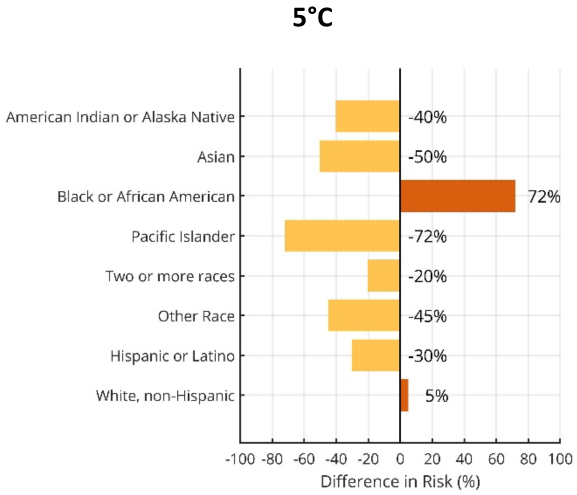
Figure 9 presents results for individual racial and ethnic groups that comprise the minority population group, as well as white, non-Hispanic individuals. Of the racial and ethnic groups analyzed, Black or

African American individuals have the most disproportionately high risk of living in areas with the highest projected increases in premature mortality due to climate-driven changes in extreme temperature. Those in other racial and ethnic groups have a relatively lower likelihood of living in high-impact areas relative to their reference populations.

Figure 9.

Likelihood that Those in Individual Racial and Ethnic Groups Currently Live in Areas with the Highest Projected Increase in Extreme Temperature-Related Deaths Relative to Their Reference Populations





5. Analytical Limitations

This analysis represents a high-level evaluation of how socially vulnerable populations may be disproportionately at risk of living in areas with the highest projected increases in premature mortality associated with climate-driven changes in extreme temperatures. The following limitations must be considered along with the findings of this analysis:

- This analysis is restricted to a limited group of urban areas and the counties that contain those urban areas and does not draw conclusions about heat stress-related health impacts in smaller urban, suburban, or rural areas. The Northern Great Plains region is excluded because no cities in the region were included in the original epidemiological study upon which this analysis is based. Changes in extreme heat and cold-related deaths would be expected in this region that are not quantified here. The Northwest and Southern Great Plains have limited representation within the 49 cities and may have higher associated uncertainties due to the smaller number of Census tracts as part of the analysis.[44]
- This national analysis relies on county/urban-scale estimates of daily temperature exceedances. Extreme temperature analyses conducted at the neighborhood scale, such as Harlan et al. (2006),[45] have identified a significant "heat island" effect, which amplifies disproportionate effects on socially vulnerable groups. Harlan et al. found that for the 2003 summer season in eight Phoenix neighborhoods, the impact of neighborhood-scale heat island phenomena amplifies social disparities in heat stress that leads to illness and mortality. Certain socioeconomic and ethnic minority groups were more likely to live in warmer neighborhoods with greater exposure to heat stress. High settlement density, low vegetation density, and low open space in the neighborhood were significantly correlated with higher temperatures and a heat stress index. Some of these neighborhood-level findings were further supported by a later study which looked at the 2000-2008

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[44] Note also that some research suggests that extreme temperature mortality may also occur outside of urban areas of the U.S. (see Madrigano J, Jack D, Anderson GB, Bell ML, Kinney PL. Temperature, ozone, and mortality in urban and non-urban counties in the northeastern U.S. *Environmental Health*, 2015. 14:3, cited earlier in this appendix), but the evidence outside urban areas remains limited for the U.S. as a whole.

[45] S.L. Harlan, A.J. Brazela, L. Prashada, W.L. Stefanov, and L. Larsen. 2006. Neighborhood microclimates and vulnerability to heat stress. *Social Science and Medicine*, 63: 2847-2863.

period.[46] If these conditions are common in other urban environments in the U.S., the inability of this analysis to prospectively assess neighborhood scale heat island effects very likely means that this analysis underestimates the degree of disproportionate effects on lower income, minority, and low educational achievement socially vulnerable populations.

- Due to limitations in the underlying epidemiological methods, this analysis does not quantify morbidity rates/health outcomes related to heat stress, which are likely to increase as temperature increases.[47] Temperature extremes can provoke hospital admissions for cardiovascular and respiratory disorders, cause heat exhaustion or heat stroke, and worsen cardiovascular disease, respiratory disease, and other chronic conditions. Corresponding reductions in morbidity may be associated with decreases in extreme cold.
- Extreme heat impacts and extreme cold impacts are represented as summed numbers of death and mortality rates in this analysis. As the global mean temperature increases, extremely cold days are projected to decrease and associated cold mortality rates will decrease compared to the baseline period, while extremely hot days and associated heat mortality rates are projected to increase. Patterns in the net effect of both heat and cold stress therefore may be a more complex function of changes in temperature than the function for each weather impact type separately.
- This analysis assumes the percentage of socially vulnerable individuals by Census tract will remain constant in relation to increase in global mean temperature. It is possible that those living in cities that already experience many days with extreme temperatures may migrate to cities with fewer extreme temperature days over time as global mean temperatures increase.
- The BenMAP-CE analysis was run using county-level incidence and population data and then disaggregated to the Census tract level for likelihood estimates. Thus, the likelihood results reflect patterns of the spatial allocation of socially vulnerable populations that are more detailed than the spatial precision of the county-level health effect estimates.
- The BenMAP-CE analysis was run using city-level Beta values, which were assigned to each county that surround the metropolitan area of each city, consistent with the underlying EPA (2017) analysis. Some error may be introduced by assigning city-level Beta values across all counties in the domain of Mills et al. (2015) and updated by EPA (2017).

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[46] S.L. Harlan, J.H. Declet-Barreto, W.L. Stefanov, and D.B. Petitti. 2013. Neighborhood Effects on Heat Deaths: Social and Environmental Predictors of Vulnerability in Maricopa County, Arizona. *Environ Health Perspect* 121:197–204. http://dx.doi.org/10.1289/ehp.1104625

[47] See for example Lin S, Hsu W-H, Van Zutphen AR, Saha S, Luber G, and Hwang S-A. 2012. Excessive Heat and Respiratory Hospitalizations in New York State: Estimating Current and Future Public Health Burden Related to Climate Change. *Environmental Health Perspectives*, 120 (11), 1571-1577.

6. Data Sources

DATA TYPE	**DESCRIPTION**	**DATA DOCUMENTATION AND AVAILABILITY**
Climate modeling	Six LOCA bias-corrected and downscaled GCM climate projections. Climate models from fifth phase of the Coupled Model Intercomparison Project (CMIP5): GFDL_CM3, CanESM2, CCSM4, GISS_E2_R, HadGEM2_ES, and MIROC5.	Taylor, K.E., Stouffer, R.J., Meehl, G.A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society,* 93, 485-498. U.S. Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and U.S. Geological Survey, 2016: Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs. Data available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/
Extreme temperature exceedances	Daily threshold exceedances of hot and cold extreme thresholds for 49 cities, for six GCMs, grouped by GCM-specific 11-year bins.	U.S. EPA. (2017). *Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment*. Washington, D.C.
Baseline health effect incidence rates	Race-stratified county-level baseline mortality incidence rates (2007-2016) were obtained from BenMAP-CE, disaggregated by age, race, and ethnicity.	U.S. EPA. (2018). *Environmental Benefits Mapping and Analysis Program: Community Edition (BenMAP-CE) User Manual and Appendices*. Washington, DC.
Population projections	2010 U.S. Census population data was obtained from BenMAP-CE at the county level, disaggregated by age, race, and ethnicity.	U.S. EPA. (2018). *Environmental Benefits Mapping and Analysis Program: Community Edition (BenMAP-CE) User Manual and Appendices*. Washington, DC. U.S. Census Bureau, cited 2017: Population Estimates Program. Available online at https://www.census.gov/programs-surveys/popest.html