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Temperature Extremes and Health: Impacts of Climate Variability and Change in the United States

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Learning Objectives

- Discuss the evidence (and limitations of evidence) relevant to assessing the health impacts of extreme temperatures.
- Review the physiologic effects, mortality burden, and factors affecting vulnerability to the health effects of cold and hot temperatures.
- Demonstrate familiarity with the likely impact of climate change on temperature and health, including the factors that will affect temperature-related morbidity and mortality.

Objective: *We evaluated temperature-related morbidity and mortality for the 2007 U.S. national assessment on impacts of climate change and variability on human health.* ***Methods:*** *We assessed literature published since the 2000 national assessment, evaluating epidemiologic studies, surveys, and studies projecting future impacts.* ***Results:*** *Under current climate change projections, heat waves and hot weather are likely to increase in frequency, with the overall temperature distribution shifting away from the colder extremes. Vulnerable subgroups include communities in the northeastern and Midwestern U.S.; urban populations, the poor, the elderly, children, and those with impaired health or limited mobility.* ***Conclusions:*** *Temperature extremes and variability will remain important determinants of health in the United States under climate change. Research needs include estimating exposure to temperature extremes; studying nonfatal temperature-related illness; uniform criteria for reporting heat-related health outcomes; and improving effectiveness of urban heat island reduction and extreme weather response plans.* (J Occup Environ Med. *2009;51:13–25*)

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Exposures to temperature extremes have been associated with both mortality and morbidity. At the population level, the distribution and magnitude of these health impacts depend on intrinsic factors, including population and regional vulnerabilities; social and cultural context; the built and natural environment; public health infrastructure; and health and social services. Other determinants of variations in the magnitudes of the impacts between temperature and health, in both space and time, include the public's perception of risk; availability of human and financial resources and technological options; and the political will for policy action. This larger context within which temperature affects health is important to consider in developing and determining the likely efficacy of adaptation measures to reduce exposures and prevent and/or minimize the impact of health outcomes. Assessing the direct temperature-related health impacts of global change requires both analysis of existing literature based on past associations of health events with temperature, as well as considerations of health impacts under future climate scenarios projected by scientists and modelers; economic development; future population demographics, and planned adaptive and mitigative actions. This assessment does not address uncertainties in climate modeling or demographic changes. Rather, it focuses on describing estimated health associations, and expressing a level of confidence in them, based on their strength, consistency, and plausibility, given possible ranges of demographic and climate projections available from current state-of-the art modeling and forecasting efforts.

First National Assessment

The First National Assessment of the Potential Impacts of Climate Variability and Change was undertaken by the U.S. Global Change Research Program and published in 2000 in a special issue of Environmental Health Perspectives. The section on temperature-related morbidity and mortality concluded that, based on climate change projections, the impacts of heat on human health were likely to outweigh those of cold.[1] Research completed since the first National Assessment has largely confirmed those conclusions.[2] The assessment identified vulnerable subgroups including communities in the northeastern and Midwestern U.S.; urban populations, the poor, the elderly, children, and those with impaired health or limited mobility. Research was called for on methods for representing exposure to temperature extremes; nonfatal temperature-related illness; uniform criteria for reporting heat-related health outcomes; effectiveness of heat-response plans; and urban design and characteristics for reducing urban heat island effects and health consequences[1] The present section discusses progress in filling these gaps by assessing literature published since the first assessment, focusing on U.S.-based research except where studies from other regions illustrate important advances in substantive understanding of temperature-health links or illustrate approaches that can enhance understanding of impacts in the United States.

Temperature and Health: Definitions and Study Approaches

The primary health outcomes evaluated in temperature epidemiology are mortality and morbidity. Mortality data are commonly obtained from population-wide vital statistics records on a regional basis or taken from specific areas or hospitals, when examining a particular heat event. Temperature-related morbidity may be represented by hospital admissions, doctor visits for heat stroke, or calls for assistance to ambulances and health "hotlines." Cause-specific morbidity and mortality are often evaluated; causes other than those attributed directly to temperature exposure may be affected by temperature. "Extremes" of temperature should be understood in a relative context. An extreme cold temperature in Arizona will differ from an extreme cold temperature in Minnesota, because populations can acclimate or adapt to prevailing weather conditions.

Two analytic approaches are commonly employed. One is evaluate the impact of a discrete heat event, such as the 1995 Chicago heat wave.[3,4] Because no standard definition of a "heat wave" exists,[5] they are often defined in terms relative to the prevailing temperature conditions, even within a season, both in research[6,7] and in practice.[8] This suggests that the definition of "unusually hot" may shift in a warming planet. Studies using a second analytic approach, evaluating associations between temperatures and health events over several years, have shown that the effect of temperature on mortality is nonlinear and effects are observable even below temperatures that would be characterized as "extreme." One analysis of this type used 22 years of data to characterize the J or U shaped dose-response with mortality for the full range of the temperatures in 11 U.S. cities (Fig. 1).

Epidemiologic Study Designs

Epidemiologic study designs to evaluate effects of temperature on health include descriptive studies (mapping studies, case-control), case-crossover, and case-only, useful for evaluating effect modification, and time series, which may use multiple years of mortality or morbidity data to evaluate trends over decades[9,10] Since the 2000 assessment, several studies have confirmed the associations of extreme temperatures with mortality. Comparable effects were seen for heat and mortality among elderly in 20 large U.S. cities using time series and case-crossover designs,[11] suggesting effects are robust to analytic approach. Effect modification has been explored using biomedical characteristics (eg, underlying medical conditions); demographic characteristics (race, age, educational attainment); housing characteristic; and community or geographical characteristics (eg, latitude; percent people with high school education). These effect modifiers are described in subsequent sections as "vulnerability factors."

Estimating Exposure to Temperature

Ways of estimating exposure to temperature in epidemiology studies are shown in Table 1. The table provides examples of these various methods, from the following references.[6,12–24]

All these metrics can provide important information on how thermal extremes may affect health under a changing climate. The diurnal temperature range (difference between minimum and maximum) is especially relevant because of evidence that high night-time temperatures can increase the risk of adverse health effects[25] Because climate models present scenarios of mean changes in temperature,[26] and do not forecast humidity or heat events, studies that assign exposure based on simple outside air temperature are of more utility for projecting future impacts of climate change, though physiologically based indices and synoptic modeling may be useful for developing heat wave and health warning systems. High-resolution remote sensing technology enables mapping of vegetation and thermal profiles,[15,27–29] and geographic in-

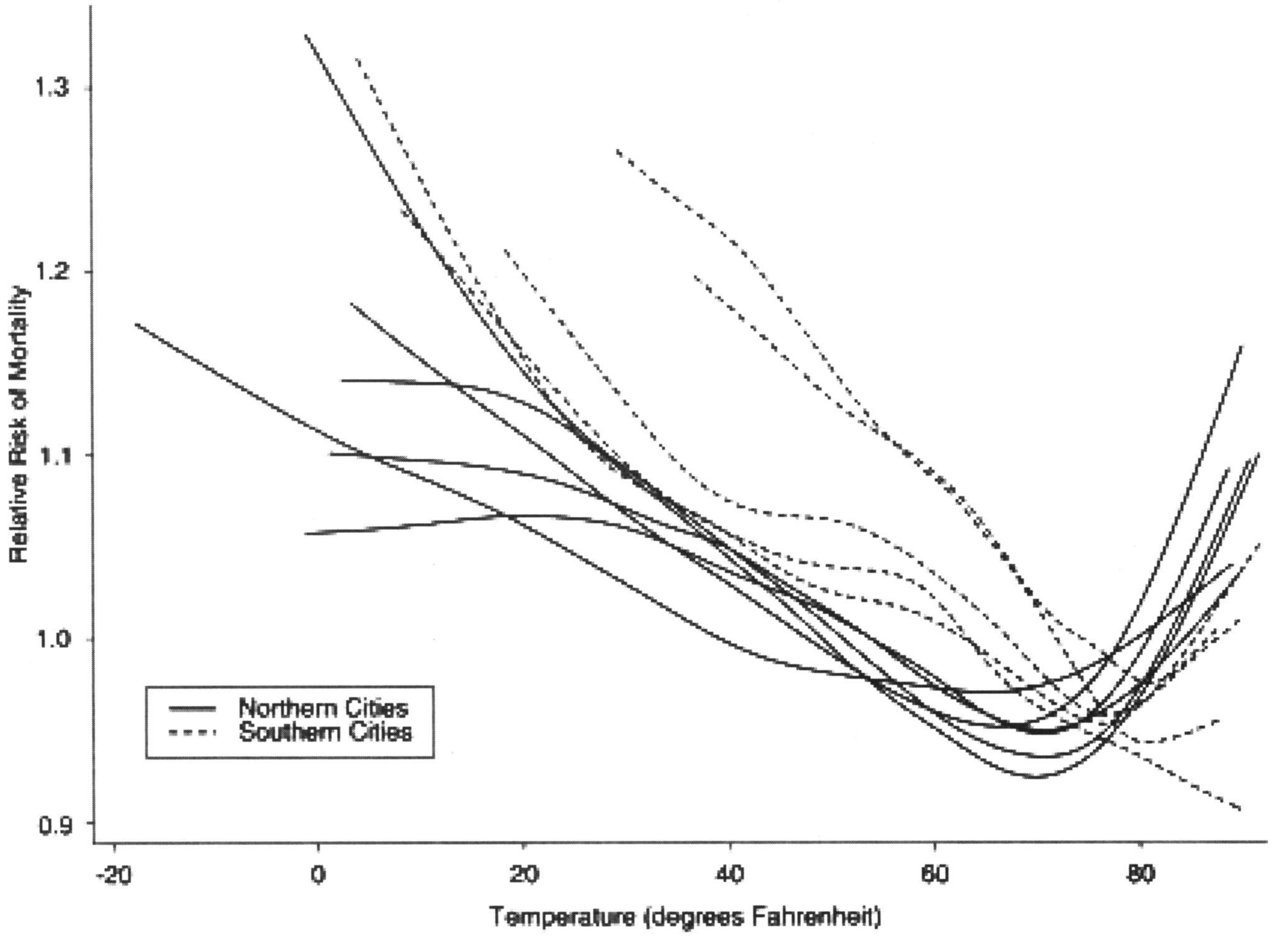

Fig. 1. Temperature-mortality relative risk functions for 11 US cities, 1973–1994. Northern cities: Boston, Mass; Chicago, Ill; New York, NY; Philadelphia, Pa; Baltimore, Md; and Washington, DC. Southern cities: Charlotte, NC; Atlanta, Ga; Jacksonville, Fla; Tampa, Fla; and Miami, Fla. °C = 5/9 × (°F − 32). Reprinted with permission from *Am J Epidemiol.*[13]

formation systems allow superimposition of temperature profiles with indicators of social vulnerability,[30,31] bringing the dimension of "space" into research on temperature and health.[32] Similarly, information on temperature microclimates within urban areas is being used to evaluate socioeconomic differences in heat exposure, and parameters (including vegetation) that influence these exposures[15] Synoptic air masses can be used in health research by using days that fit predefined meteorological categories to define exposure.[24,33] Estimated health associations may differ by location of the monitor (airport vs city center).[34] Such differences may result from spatial variability in thermal profiles. The urban heat island effect is when air temperatures in cities can be 2°F to 10°F higher than the surrounding suburban and rural areas, due to absorption of heat by dark paved surfaces and buildings, lack of vegetation and trees, heat emitted from buildings, vehicles, and air conditioners, and reduced airflow around buildings.[28,35–37] Mitigation efforts including planting of trees and vegetation can reduce urban heat island effects.[38] As Fig. 2 shows, individuals spending time in rural zones may experience substantially lower outside temperatures than those in city centers, resulting in exposure misclassification if a single monitor is used in health studies covering a thermally heterogeneous geographic area. However, urban areas may not experience significantly greater heat-related mortality compared with rural, at least in Ohio.[39]

The next sections discuss the health effects of hot and cold temperatures with a specific focus on the mortality literature. Temperature-related mortality is directly-quantifiable, and multiple studies conducted since 2000 confirm significant associations with both heat and cold.[7,9,10,18,40,41] Because morbidity is a much less well-studied health outcome, with less consistent observed effects, a separate section on temperature-related morbidity follows.

Cold Temperatures

Physiological Effects

Early signs of cold exposure, which can particularly be dangerous

TABLE 1
Exposure Metrics for Temperature and Health Studies, With Selected Citations Showing Their Application

	Temperature and Related Exposure Indices: a) ambient Air Temperature;[6,12–16] b) Apparent Temperature, Humidex, Heat Index;[17–20] c) Physiologically Equivalent Temperature[21,22]	Remote Sensing Thermal Profiles[23]	Synoptic Air Masses[19,20]
How measured or calculated	Airport, government outdoor monitors, home/personal monitors (dewpoint, humidity, temperature), cloud cover, solar radiation, clothing, activity, other (for c)	Satellite images of thermal emissivity, land surface temperatures vegetative cover	Meteorological forecasting models: use temperature, dewpoint pressure, wind, cloud cover
Statistical forms used in studies	Continuous (minimum, maximum, mean, diurnal range, variance) Discrete ("extreme" temperature days, defined heat waves) Various lags of above, from day of health event to several weeks before	Frequently displayed in maps, but same statistical forms as 3 previous can also be applied	Categorical (moist tropical, dry tropical, etc)
Advantage(s)	Easily obtained, temperature is predicted in GCMs so studies with temperature useful for projections Easily calculated, may represent thermal stress better than temperature May better represent physiological experience of thermal stress	Can show finer geographic resolution thermal variability	May reflect thermal stress better than temperature alone; used in heat watch warning systems
Disadvantage(s)	May not reflect physiologically relevant exposure Not as useful as temperature for future climate/health projections Not practical for large scale studies or projections	Available only for selected times when satellite is launched and passing over geographic area	May be difficult for public health professionals or lay public to understand, limited use for projections

GCM indicates general circulation models.

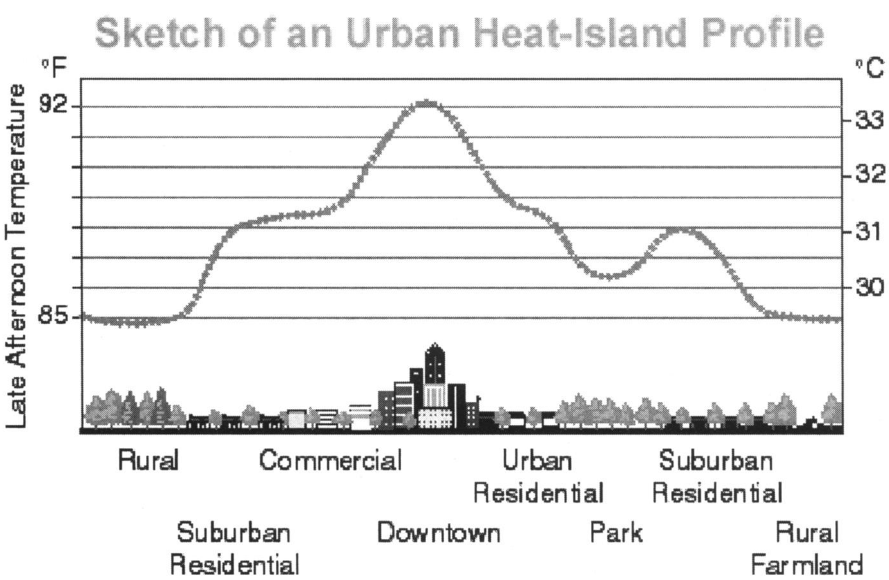

Fig. 2. Urban Heat Island Source: EPA. *Heat Island Effect*. U.S. Environmental Protection Agency; 2005 http://www.epa.gov/heatisland/about/index.html.

for the elderly, very young, mentally ill, and homeless people, include shivering and exhaustion, confusion or fumbling hands; memory loss and slurred speech; drowsiness, bright red, cold skin, and very low energy[42] Cold exposure can result in a loss of plasma fluid which can lead to thrombosis,[43] and seasonal variations in cardiovascular risk factors as well as intake of antioxidant vitamins (with changes in availability of certain foods, such as fresh fruits, during winter) may also stem directly from or affect responses to cold exposure[44–47] There is evidence that not solely age but fitness and body composition, and level of activity are important determinants of how the human body responses to exposure to thermal extremes.[48–51]

Burden of Cold-Related Mortality in the United States

From 1979 to 2002, an average of 689 deaths per year (range: 417 to 1021), totaling 16,555 over the period, were attributed to exposure to excessive natural cold (International Classification of Diseases (ICD)-9 codes E901.0, E901.8, and E901.9; ICD-10 code X31).[52] Black males had a higher death rate compared with white males. Alaska, New Mexico, North Dakota, and Montana experienced higher overall death rates, along with milder states that experience rapid temperature changes (North and South Carolina) and western states with greater ranges in nighttime temperatures (eg, Arizona.)[52] Cold contributes as well to other causes of death (respiratory, cardiovascular) so the overall burden of cold on mortality is likely to be underestimated by the methods of counting only deaths where "cold exposure" is recorded as a contributing or primary cause. Associations of both morbidity and mortality with cold temperatures have been seen to endure for periods of days to weeks,[13,53,54] with evidence that cold temperatures do not contribute much to short-term mortality displacement when compared with heat-related mortality.[41]

Vulnerability Factors

Cold weather has a strong association with cardiovascular disease deaths, both the United States and abroad.[16,55,56] Cold-related mortality, when not classified specifically as hypothermia, is attributed to respiratory causes as well as coronary thrombosis.[57] Demographically, cold-associated deaths occurred disproportionately among blacks and the less educated[18] in the United States, and among women and those with preexisting respiratory illness in the United Kingdom;[58] use of protective clothing was related to levels of cold-related mortality in Europe.[59] In the United Kingdom, housing characteristics and socioeconomic deprivation were not strong modifiers of the cold-mortality association.[58] Across Europe, however, income inequality, fuel poverty, and residential thermal standards were related to the risk.[60] In the United Kingdom, the elderly living in nursing and care homes were more vulnerable to cold-related mortality.[61]

Hot Temperatures

Physiological Effects

Heat exposure's physiological effects range from symptoms such as dizziness, weakness, fatigue, cramps, and syncope (fainting); to multiorgan failure, coma and death, in the case of heat stroke. Athletes, the elderly, children, the mentally ill, and people on medications such as diuretics are known to be affected.[62–68]

Burden of Heat-Related Mortality in the United States

Heat has been consistently associated with elevated mortality in a variety of studies and the burden in the United States is substantial.[10] During 1979 to 2002, 4780 U.S. deaths were classified as heat related (caused by exposure to excessive natural heat, ICD-10 X30, ICD-9 E-900) and an additional 1203 had hyperthermia as a contributing factor (ICD-10 T67, ICD-9 E-992) to cardiovascular, metabolic, and other cause-deaths[69] During this period, heat waves, which had the highest toll of mortality among people over age 65, occurred in 1980 (St. Louis and Kansas City, MO), 1995 (Chicago, IL), and 1999 (Cincinnati, OH, and Chicago). During 1999 to 2003, Arizona had the highest average annual hyperthermia-related death rate, followed by Nevada and Missouri[69] Heat is expected to contribute to the exacerbation of chronic health conditions, so including deaths with hyperthermia as an underlying cause can increase the number of heat-attributed deaths by substantial amounts (54% during the period 1999–2003).[70] A number of analyses have looked at cause-specific mortality-cardiovascular, renal, respiratory, diabetes, nervous system disorders and other causes, not specifically described as heat-related, as these deaths are also heat-associated.[16,71,72]

Vulnerability Factors

Excess deaths occur during heat waves,[5] on days with higher-than-average temperatures, and in places where summer temperatures vary more.[13] Populations living in places where extreme heat is rare seem to have higher estimates of heat-related deaths possibly because they are less acclimated to high temperatures.[73] Vulnerability to heat-related mortality is marked by a variety of characteristics, including being elderly, very young, city-dwellers, having diabetes, being less educated, socially isolated, black or of "non-white" race, lacking access to air-conditioning, outdoor laborers.[1,3,74–76,12,18,77–79,4,80–83] The elderly in nursing and care homes in the United Kingdom were more vulnerable to heat-related mortality;[61] this relationship may differ in the United States where air-conditioning may be more prevalent. A sociological analysis of the 1995 Chicago heat wave found that people living in neighborhoods without public gathering places and active street life were at higher risk of dying during the heat wave; this research sheds light into the important role that community and societal characteristics can play in determining vulnerability during extreme weather.[75]

Temperature-Related Morbidity

As noted in the 2000 assessment, there is less information on temperature-related morbidity than mortality, although Environmental Protection Agency (EPA) is now funding three efforts to fill these research gaps.[84] Studies evaluating hospitalizations associated with temperature,[4,82,83] have found less consistent associations than for mortality. Although short-term increases in cardiovascular-cause hospital admissions in 12 U.S. cities were associated with both hot and cold temperatures,[83] consistent associations with these particular causes, including cardiovascular and cerebrovascular, were not seen in an analysis of hot weather and hospital admissions in London,[82] where heat was associated with respiratory and renal-cause admissions only, and not with total hospital admissions. A recent multicity European analysis of temperature and hospital admissions only saw associations between hot and cold temperatures and respiratory-cause hospital admissions, and concluded that these results are not consistent with those of mortality studies.[85] One possible explanation for the lack of coherence between studies of daily mortality and hospital admissions during extreme weather, at least in Europe, is that cardiovascular-cause mortality occurs rapidly before the individuals have time to seek care, but confirmatory studies looking at morbidity and mortality concurrently would be necessary to evaluate this question.[86] Particular medical conditions, including diabetes, emphysema, and nervous system disorders, have been shown to affect risk of hospitalization.[4] Factors related to housing also affect vulnerability to morbidity outcomes; for example, heat stroke risk is higher among individuals with no access to air-conditioning or with few trees and shrubs shading their dwellings,[87] and respiratory morbidity was shown to be related to energy-inefficient housing in the United Kingdom.[88]

Other indicators of morbidity that have not yet been evaluated in the United States but may be of potential use for surveillance and research include calls to health hotlines and ambulance calls.[89,90] Increases in primary care consultations are also potential important tools for surveillance; U.K. doctor visits for respiratory complaints among elderly people were increased following 2-week exposures to cold temperatures (below 5°C).[91] Carbon monoxide poisoning is also a potentially fatal hazard-related cold weather, due to the use of combustion devices indoors for heating and cooking,[92] as well as blockage of vehicle exhaust pipes by snow.[93] Similarly, the burden of in-home carbon monoxide poisonings is disproportionately higher among non-English speakers and other racial/ethnic minorities.[94–96]Preventive messages have the capacity to reduce the toll of this cold-related cause of death.[94,97] Slips, falls, vehicle accidents, and other injuries related to ice and snow are also an important health consequence of cold weather,[98] but are not direct consequences of cold exposure or efforts to reduce that exposure.

Heat Waves and Heat Events

Prevention programs designed to reduce the toll of hot weather on the public have emphasized the idea of a discrete heat "event"[99] or heat "wave," which may often involve multiple deaths or hospitalizations for heat-related causes. Follow-up investigations were triggered by the 1995 Chicago heat wave,[3,4,75] and the 2003 European heat wave, estimated to have contributed to tens of thousands of premature deaths.[100] The prediction for more frequent, intense and longer duration heat waves suggests a need for continued vigilance and emphasis on warning the population during such events,[101] and these programs appear to reduce the toll of hot weather on public health[102–104] However, a survey of individuals aged 65 year and older in four North American cities (Dayton, OH; Philadelphia, PA; Phoenix, AZ; and Toronto, Ontario, Canada) suggests that the public is unaware of appropriate preventive actions to take during heat events.[105] Although respondents were aware that there were heat warnings, the majority did not consider that they were vulnerable to the heat, or did not consider hot weather to pose a significant danger to their health, and only 46% modified their behavior on the heat advisory days. Although many individuals surveyed had access to home air-conditioning, their use of it was influenced by concerns about energy costs. Precautionary steps recommended during hot weather, such as increasing intake of liquids, were reported to be followed by very few of the respondents.[105] Some respondents reported using a fan indoors with windows closed and no air-conditioning, a situation that can increase heat exposure and be potentially deadly. Further, simultaneous heat warnings and ozone alerts were a source of confusion, since "not driving" recommendations conflicted with the suggestion to seek cooler locations if the residence was too warm.[105] Relatively few other studies have evaluated the effectiveness of public warning and prevention programs on health, although EPA's Urban Heat Island program may be one opportunity to evaluate the impact of community level programs.[106] One pilot study done in Philadelphia tested a culturally appropriate intervention program among isolated older adults, mostly African-American women,[107] who also did not perceive themselves as being vulnerable to heat, but the effects of these programs, which are now beginning to be deployed on a wider scale in both Europe and the United States,[108,109] require continued critical evaluation. A recent evaluation of heat and mortality in three European cities suggested that simply targeting specific heat events is not adequate to prevent health consequences of hot weather.[6] These findings suggest that the guidance provided in such recent publications as the "Extreme Heat Events Guidebook"[99] might be expanded to include messages that raise general public awareness of ways to avoid heat exposure, and improve resiliency (through increased liquid intake, for example) and not just during declared weather "emergencies." Additional public education, including education in schools, would also help raise awareness. In addition, more rigorous evaluation of which components of heat wave and health warning systems can reduce mortality would be useful.

Temperature and Air Pollution

Air pollution can be both a confounder and effect modifier for studies of temperature and health, and results vary by location[54,110–113] Because of frequent high correlations between pollution and temperature, carefully modeled estimates are needed for the purpose of accurate risk assessment.[114] Further, because air pollution may increase in local areas due to increasingly stagnant air masses related to climate change, the toll of joint exposures of temperature and pollutants may increase in the future.[115,116]

Projecting Future Impacts of Climate Change on Temperature and Health

Climate change will affect temperature distributions as well as the hydrological cycle. Exposure to climate variability and change over the next few decades is inevitable because of inertia in the climate system and the long duration of greenhouse gases in the atmosphere.[26] Carbon dioxide (CO_2), the main anthropogenic greenhouse gas, is not destroyed chemically; natural processes, primarily transient storage in land and ocean reservoirs, remove about half of anthropogenic CO_2 each year, with the balance remaining in the atmosphere for more than 100 years.[26] Therefore, atmospheric CO_2 will continue warming the planet for at least several decades after stabilization of concentrations. As a result, the only way to reduce the impacts of climate change on health over the next decades is through preparedness. Diurnal temperature ranges decreased from 1950 to 1993, in part due to land use (eg, reforestation) and urbanization practices (paving and roof surfacing choices)[117] among other factors.[35] However, new observations suggest that this decrease did not occur from 1979 to 2004 since day- and night-time temperatures have been rising at similar rates, though the trends vary by region.[26]

The degree to which climate change may affect the health burden of extreme temperatures on the population is somewhat more straightforward to quantify than for indirect health impacts, such as vector-borne disease. Drivers of the temperature and health association, now and in the future, include overall trends in global temperature; determinants of temperature variability at the local scale; demographic characteristics of the population; and policies that affect the social and economic structure of communities, including urban design, energy policy, water use, and transportation planning. Land use is a key determinant of variations in exposures to temperature, since, for example, multistory buildings and materials use in pavement and construction can affect temperature exposure at the microscale[15] and as the population continues to grow, residential and industrial development will continue to affect the temperature profile at the population level.

Population demographics are also shifting. The proportion of elderly people in the U.S. population is increasing; over 13% of the U.S. population is expected to be over age 65 by the year 2010, and by 2030, 20% will be over 65, representing over 50 million people.[118] Older people are physiologically and socially vulnerable[75,119] to heat waves and hot weather, and the majority of evidence suggests that older people are also more sensitive to cold-related mortality.[18] The proportion of the U.S. population comprised of both very young and older adults is also anticipated to grow from approximately 15% to over 25% by the year 2100.[2] The increasing size of this vulnerable segment of the population may mean that the health burden of temperature extremes on the population will also rise. With the trends in increasing obesity and related medical conditions including diabetes,[120,121] and evidence that those with diabetes are at greater risk of heat-related mortality,[77] the population level reduced fitness and higher fat body composition may lead to an increased burden of temperature-related illness and death.

A final important driver of temperature-related morbidity and mortality is the social and economic context. Physical features of communities, including housing quality and green space;[87] social programs that affect access to health care, aspects of population composition (level of education, racial/ethnic composition), and social and cultural factors can all affect differential vulnerability to exposure to temperature extremes.[9,32,75] Trends in changing poverty and racial/ethnic composition of the population are less consistent on a national level than the age structure changes (U.S. Census 2005). Further, community features and policies relevant to temperature and health often differ by locality, so changes in these parameters may be difficult to forecast on a national scale.

Some efforts to project future impacts of climate change on health in various locations illustrate attempts to capture projected trends in these drivers and link them to estimates of temperature and health in specific locations. All of these efforts used some sort of downscaled climate models to estimate the temperature distributions in the particular geographic region of interest. Projecting these impacts is challenging, in part due to the uncertainties about the population's ability to adapt, and modeling efforts differ in their approaches to account for adaptation and/or acclimatization ability in the populations under study. Several such efforts are described in Table 2.[122–125]

Of particular note is that the Lisbon projected impacts were more sensitive to the choice of regional climate models than the method used to calculate excess deaths, and the author described the challenge of extrapolating health effects at the high end of the temperature distribution, for which data are sparse or nonexistent.[122]

In addition to these modeling efforts, longer-term time-series studies can shed light on potential future patterns of association between temperature and health. Three studies conducted using decades of data on mortality and temperature from U.S. cities,[126–128] heat-attributable mortality appeared to be declining; this trend, for both cold and heat-related mortality, was also observed in London over the last century.[129] The authors speculate that these declines

TABLE 2
Examples of Projections of Future Climate Change Impacts on Temperature-Related Mortality

Location	Period	Adaptation Considered	Projected Impact on Heat-Related Deaths
Lisbon, Portugal[122]	2020s, 2050s compared with 1980–1998	Yes	Increase of 57%–113% in 2020s, 97% to 255% in 2050s, depending on adaptation
8 Australian cities[123]	2100 compared with 1990s	No	Increase of 1,700 to 3,200 deaths, depending on policy approach followed and age structure of population
New York, NY[124]	2050s compared to 1990s	Yes	Increase 47% to 95%, but reduced by 25% under adaptation
California[125]	2090s compared with 1990s	Yes	Depending on emissions, mortality increase 2–7 times from 1990 levels, reduced 20% to 25% with adaptation
Boston, MA*	Projections to 2100 compared with 1970–1992	Yes	Declines in heat-related mortality after 2010, due to adaptation

*From CLIMB, 2004.[152]

are due to increasing prevalence of air-conditioning (in the U.S.), improved health care, and other adaptations at the population level. The results of this work suggest that increases in heat-related mortality may not occur in the United States,[130] even under various scenarios of global warming in which temperature distribution shifts upward and temperature variability is increased, along with the frequency of heat waves.[99] However, the problem of using the slopes estimated in the studies is that this requires the assumption that mortality will continue to decline at the same rate, which is unlikely to be true.

Furthermore, studies examining population subgroups may reveal that these trends do not apply to all sectors of the population equally. Heat-related mortality and other climate-sensitive health impacts have been shown to affect poor and minority populations disproportionately,[16,18] in part due to lack of access to air-conditioning[131] and research and action focusing on the role that climate change may play in health disparities has been urged in several recent publications.[132–134] A further concern is that widespread adoption of air-conditioning, although likely to reduce heat-related health impacts,[135] also has trade-offs, including the indirect impact of increasing fossil fuel consumption and the associated emissions of air pollutants and greenhouse gases, and potentially contributing to illnesses related to air-conditioning usage, such as Legionnaire's disease and allergic illness that may be associated with biological contaminants present in air-conditioning equipment. Further, the elderly and other vulnerable people may not feel vulnerable, and choose not to use their air conditioners due to concerns about increased energy bills.[105] Regionally, U.S. populations show differences in terms of their vulnerability to heat and cold,[9] though urban versus rural risks were not substantially different in a study in Ohio.[39]

Mortality Displacement

Mortality displacement (or "harvesting") refers to the idea that deaths associated with exposure to extreme temperature are deaths already expected among a frail subset of the population that are only advanced by a few days, and hence do not represent a substantial shortening of life at the population level. This concept is critically important for estimating the overall population burden associated with exposure to extreme temperatures, as well as estimating the potential economic impact of climate change on temperature-related health outcomes, mortality being among the most commonly used health outcomes. The problem of extrapolating estimates derived from time-series studies that evaluate short-term effects of environmental exposures on mortality to annual excess death estimates has been discussed at length in the air pollution literature,[136,137] but the same principle applies to temperature studies. Study designs that explicitly evaluate whether the temperature effects represent mortality displacement are valuable for predicting future impacts of temperature extremes. Such studies have been conducted in the United States, and others in Europe, with inconsistent results. Some studies suggested that temperature had longer-term effects on health,[54,138] but others did not show evidence of this.[139] In Delhi, India, heat exposure had longer-term effects on mortality, compared with deaths in Sao Paulo, Brazil, and London, England.[140] This was attributed to a differing profile in the populations at risk, in which child mortality and infectious disease-related mortality present a larger burden in India.[140] In 12 U.S. cities, heat-related mortality reflected some mortality displacement whereas the effects of cold temperatures on mortality persisted for several weeks.[13,41] This was also seen in a study in Ireland, which found delayed effects of cold temperature.[54] Given the differential impacts of temperature on mortality observed in subgroups of the population, defined by demographic, community, or biomedical characteristics, eg,[9,16,18,131] and the findings of heterogeneity in mortality displacement in cities with very different demographic, socioeconomic, and health profiles,[140] further examination of whether temperature-related mortality displacement is heterogeneous by U.S. population subgroups is warranted. Several current efforts using health data from Europe attempt to project the burden of climate change under various future scenarios and the possible influence of adaptive activities on temperature-related mortality, but as of yet nothing is in the peer-reviewed literature[141,142]

Priority Research Needs and Data Gaps

Differential Impacts in Vulnerable Populations

Further research is needed to evaluate how subpopulations in the United States, defined by geographic location, biomedical and demographic characteristics, and community context, may respond differently to exposure to temperature extremes.

Air Pollution and Temperature

Additional research on how coexposures to air pollution and extreme temperatures influence health will be useful for taking preventive action that comprehensively addresses both preventing exposures and reducing pollution emissions at the source.

Evaluations and Changes to Current Public Health Interventions

Rigorous evaluation of heat wave and health warning systems, especially as they become implemented on a wider scale in the United States,[109] is needed to ensure preventive messages and activities are effective. Further, data from epidemiologic studies can guide whether the use of various parameterizations of temperature and weather exposure (minimum, maximum, mean, diurnal changes, apparent temperature, synoptic air masses, etc.) provide the most predictive power for mortality and thus would be optimal triggers for preventive action. The question of whether a focus of these systems should be on heat events versus heat exposure generally should be addressed in design and evaluation.

Motivating Appropriate Behavioral Change During Heat Events

In light of the survey results of elderly people, it is clear that public health warning systems are not effectively inspiring adaptive behavior changes; further research is needed to understand how messages will be more effective. In addition, understanding which components of these systems are effective is important.

Evaluation of Mortality Displacement

More studies of this phenomenon will allow improved estimates of future potential impacts of climate change.

Understanding Morbidity Impacts of Extreme Ambient Temperatures and Heat Events

The literature to date on morbidity impacts is sparse and results inconsistent; prevention efforts will be better served if a robust evidence base is available, and inconsistencies between the literature are better understood in the context of population and exposure heterogeneity.

Thresholds

If climate change in certain regions drastically changes the frequency or intensity of extreme temperature events, a possibility under the current state of the science,[143] there are likely to be physiological limits to how fast the population can acclimatize and to how high a temperature adaptation is possible. Further research on this issue can help guide mitigative and adaptive strategies.

Conclusions

Given recent research on climate change,[143,144] including forecasts that heat waves are projected to become more frequent, intense, and of longer duration in the twenty-first century,[101,145] it is likely that the burden of heat-related morbidity and mortality will increase. Although the first national assessment described "multiple levels of uncertainty that preclude any definitive statement on the direction of potential future change for each of the health outcomes assessed"[146] and much uncertainty still exists,[2] progress has been made that can guide adaptive action.

Several of the research gaps identified in the first assessment have been partially filled by studies that address differential health effects by community, demographic, and biological characteristics; improve our understanding of the exposure-response relationships, and attempt to address the challenges of estimating and preventing the public health burden posed by extreme temperatures under a changing climate. The uncertainties in this literature preclude definitive statements about the effects of future climate change on health effects associated with temperature extremes. These uncertainties derive from the inconsistencies in results across a relatively large number of studies on temperature and mortality; the relative paucity of data on morbidity outcomes and the effects of preventive intervention and adaptation strategies, and the nascent stage and complexity inherent in efforts to project the future impact of climate change on these health outcomes. What is certain is that temperature extremes have historically represented and continue to represent an important health risk. Preventive efforts are needed to reduce exposures to these extremes among those most vulnerable, and to create equitable and health-promoting circumstances at the individual and community levels, regardless of the uncertainties in the degree to which climate change influences these relationships.

Local governments are showing an increasing interest in preparing for and preventing temperature and climate-related health impacts.[147–149]

Their ability to adapt to these health threats depends on the range of technological options, public health infrastructure, public risk perception and awareness, and local leadership and public support. As the recent EPA Extreme Heat Events guidance shows, cities such as Philadelphia and Phoenix have developed capacity to act preventively and proactively[150] in the face of extreme weather, but this capacity is not uniform or widespread.[151] The opportunity to rigorously design and evaluate these adaptive capabilities, in light of lessons learned from cities and regions that have historical experience with these programs, will be a critical step toward protecting public health in the most effective and economical manner.

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