

Climate Change and Extreme Heat Events

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Abstract: The association between climate change and the frequency and intensity of extreme heat events is now well established. General circulation models of climate change predict that heatwaves will become more frequent and intense, especially in the higher latitudes, affecting large metropolitan areas that are not well adapted to them. Exposure to extreme heat is already a significant public health problem and the primary cause of weather-related mortality in the U.S. This article reviews major epidemiologic risk factors associated with mortality from extreme heat exposure and discusses future drivers of heat-related mortality, including a warming climate, the urban heat island effect, and an aging population. In addition, it considers critical areas of an effective public health response including heat response plans, the use of remote sensing and GIS methodologies, and the importance of effective communications strategies.
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Introduction

Extreme heat events, characterized by stagnant, warm air masses and consecutive nights with high minimum temperatures, are a significant public health problem in the U.S. that will be exacerbated by the synergistic effects of a warming climate, urbanization, and an aging population. In fact, extreme heat events (EHE), or heatwaves, are the most prominent cause of weather-related human mortality in the U.S.,¹ responsible for more deaths annually than hurricanes, lightning, tornadoes, floods, and earthquakes combined.

Although all heat-related deaths and illness are preventable, many people succumb to extreme heat every year. Over a 5-year period, from 1999 to 2003, a total of 3442 heat-related deaths were reported in the U.S. (an annual average of 688).² Extreme heatwaves, such as that witnessed across Europe in 2003, can result in a significantly higher mortality.³

Despite the high mortality associated with EHE and projections of a warming climate, there is a lack of public recognition of the hazard of extreme heat exposure,⁴ and U.S. metropolitan areas generally lack preparedness measures such as heatwave-response plans.^{5,6} Part of the problem lies in the fact that heatwaves are silent killers—natural disasters that do not leave a trail of destruction in their wake. Like other natural disasters they are sporadic phenomena, but unlike hurricanes, which leave lasting reminders of the

devastation, memories of the heatwave disappear once cooler weather arrives.

This article reviews the clinical and epidemiologic features of heat-related deaths in the U.S. and discusses the potential impacts of climate change, urbanization, and demographic trends on EHE-related mortality. It also discusses individual- and community-level approaches to preventing heat-related illness and death, as well as the application of new methodologies for identifying locations and populations at greatest risk of exposure to extreme heat stress and their contribution to efforts to bolster public health preparedness for heatwaves.

Heat-Related Illness: Clinical and Epidemiologic Aspects

Prolonged exposure to high temperatures can cause heat-related illnesses, including heat cramps, heat syncope, heat exhaustion, heat stroke, and death.⁷ Heat exhaustion is the most common heat-related illness.⁸ Signs and symptoms include intense thirst, heavy sweating, weakness, paleness, discomfort, anxiety, dizziness, fatigue, fainting, nausea or vomiting, and headache. Core body temperature can be normal, below normal, or slightly elevated, and the skin can be cool and moist.^{1,7,9} If unrecognized and untreated, these mild to moderate signs and symptoms may progress to heat stroke.⁸ Heat stroke is a severe illness clinically defined as core body temperature $\geq 40.6^\circ\text{C}$ ($\geq 105^\circ\text{F}$), accompanied by hot, dry skin and central nervous system abnormalities, such as delirium, convulsions, or coma.^{7,9}

Those at particularly high risk of adverse health effects from extreme heat exposure include the

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elderly, those living alone, and people without access to air conditioning.¹⁰ In addition, people with chronic mental disorders or pre-existing medical conditions (e.g., cardiovascular disease, obesity, neurologic or psychiatric disease), and those receiving medications that interfere with salt and water balance (e.g., diuretics, anticholinergic agents, and tranquilizers that impair sweating), are at greater risk for heat-related illness and death. Drinking alcoholic beverages, ingesting narcotics (e.g., cocaine or amphetamines), and participating in strenuous outdoor physical activities (e.g., sports or manual labor) in hot weather also are risk behaviors associated with heat-related illnesses.⁹⁻¹²

U.S. Heat-Related Morbidity and Mortality

Several dramatic events, such as the 1995 Chicago and the 2003 European heatwaves, have demonstrated the stunning lethality of extreme heat exposure. Estimating the death toll of less extreme heatwaves is difficult in the U.S. because heat-related illnesses such as heat stroke and heat exhaustion are not notifiable conditions (i.e., conditions requiring reporting to public health agencies by hospitals and healthcare providers) and because heat-related deaths are often misclassified or unrecognized.

In the U.S., many causes of death also increase during heatwaves. In addition to classic heat stroke, deaths from cardiovascular and respiratory diseases have been shown to rise.^{10,13,14} Because heat-related illnesses can cause various symptoms and exacerbate a wide variety of existing medical conditions, the etiology can be difficult to establish when the illness onset or death is not witnessed by a physician.

Although many medical examiners accurately document heat-related deaths, the criteria used to determine heat-related causes of death vary among states and can lead to underreporting of heat-related deaths, or to the reporting of heat as a factor contributing to death rather than the underlying cause.¹⁵ Therefore, estimates of mortality from hyperthermia likely underdocument the true magnitude. Often, medical examiners attribute heat exposure as a primary or contributing cause of death only if they record a core body temperature $>40.6^{\circ}\text{C}$ ($>105^{\circ}\text{F}$). In the National Association of Medical Examiners' revised criteria, a death also can be classified as heat-related if the person is "found in an enclosed environment with a high ambient temperature without adequate cooling devices and the individual had been known to be alive at the onset of the heatwave."¹⁵

Few studies have attempted to assess the impact of EHEs on morbidity. Semenza and colleagues¹⁰ ana-

lyzed hospital admissions in Chicago during the July 1995 EHE and estimated that it was responsible for over 1000 excess hospital admissions, particularly among people with pre-existing diabetes, respiratory illnesses, and nervous system disorders. Schwartz and others found an association between elevated temperatures and short-term increases in cardiovascular-related hospital admissions for 12 U.S. cities.¹⁶ Similarly, a recent analysis of emergency medical services dispatch data in Phoenix concluded that the greatest incidence of heat-related medical dispatches occurred during the times of peak solar irradiance, maximum diurnal temperature, and elevated heat indices (combined temperature and relative humidity).¹⁷ Analysis of short- and long-term outcomes of heat-stroke patients who survived the 2003 heatwaves in France demonstrated that heat-stroke victims suffered a dramatic reduction in functional status that restricted discharge to home and resulted in early mortality.³

As a result of differences in climate and the prevalence of adaptations such as air conditioning, heat-related mortality rates can be expected to vary among cities. In fact, studies of mortality following EHEs in the U.S. show significant regional variation.¹⁸ Historically, EHEs have had the greatest impact in the Northeast and Midwest and the least impact in the South and Southwest.¹⁹ These findings may suggest

that populations in vulnerable cities are less acclimated to high temperatures and have reduced prevalence of adaptations such as air-conditioning.

Extreme heat event-related mortality is characterized by temperatures and humidities substantially greater than the mean for a specific time of year.²⁰ Relative humidity is a critical factor in the impact of heat on human health, because of its effect on the body's ability to cool by evaporation.²¹ When relative humidity is high, the rate of evaporative cooling of sweat on the skin is reduced, making thermoregulation more difficult. Because residents adapt to warmer temperatures over the summer, heatwaves occurring early in the summer pose an increased risk of adverse health outcomes.²¹ The duration of the EHE and the number of days of elevated minimum temperatures are additional meteorologic conditions associated with high mortality.^{22,23}

High ambient heat also affects human health through its effect on air pollution. A positive association has been found between temperatures $>32^{\circ}\text{C}$ ($>90^{\circ}\text{F}$) and ground-level ozone production,²⁴ and increasing evidence suggests that ozone and high temperature affect mortality synergistically.²⁵ Similarly, heatwave mortality is greatest on days with high PM_{10} (particulate matter with diameter under $10\mu\text{m}$).²⁶

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Future Drivers of Heat-Related Mortality

Climate Change

Mounting evidence that the earth's climate is changing has led the UN Intergovernmental Panel on Climate Change (IPCC) to conclude that "warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising of global average sea level."²⁷ In fact, climate model simulations project that, for the first half of the twenty-first century, year-round temperatures across North America will warm approximately 1°–3°C (2°–5°F).²⁸ Late in the twenty-first century, projected annual warming is likely to be 2°–3°C (3°–5°F) across the western, southern, and eastern continental edges, but more than 5°C (9° F) at high latitudes,²⁹ where many U.S. urban areas that have been affected by lethal heatwaves are located.

The impact of climate change on U.S. heatwaves may have already begun, as observed by the significant upward trend in the frequency of heatwaves from 1949 to 1995 ($p < 0.01$) for the eastern and western U.S., indicating approximately a 20% overall increase in the number of heatwaves during that period.³⁰ For the twenty-first century, the IPCC projects with high confidence that extreme heat events will intensify in magnitude and duration over portions of the U.S. where they already occur.³¹ As a consequence, populations in Northeastern and Midwestern U.S. cities are likely to experience the greatest number of illnesses and deaths in response to changes in summer temperatures.¹⁹

Analyses of U.S. climate change scenarios through General Circulation Models (GCMs) project that, for the period 2080 to 2099, Chicago will experience a 25% increase in the number of heatwaves,³² and the number of annual heatwave days in Los Angeles, for the 2070 to 2099 time period, will increase from 12 to 44–95.³³ In a study on the impact of future climate scenarios on mortality in 44 cities, Kalkstein and Greene³⁴ estimate that by 2020, under a business-as-usual emissions scenario, excess annual summer deaths will increase from 1840 to 1981–4100 (depending on the GCM used), and by 2050 up to 3190–4748 excess deaths will occur each summer.

The Urban Heat Island Effect

Cities and climate are co-evolving in a manner that will certainly amplify both the health effects of heat and the vulnerability of urban populations to heat-related death. More than half the world's population now lives in cities, up from 30% only 50 years ago.³⁵ This rapid urbanization has quickly transformed environments from native vegetation to an engineered infrastructure that increases thermal-storage capacity, resulting in significant change in the urban climate compared with

adjacent rural regions, known as the urban heat island (UHI) effect.

The UHI effect can be a powerful force in local climate. The combined effect of the high thermal mass provided by concrete and blacktop roads, the low ventilation ability of the urban "canyons" created by tall buildings, and "point-source" heat emitted from vehicles and air conditioners, magnifies the temperature increases created by climate change.³⁶ In real terms, relative to the surrounding rural and suburban areas, the UHI effect can add from 1°C to 6°C (2° to 10°F) to ambient air temperature.^{21,37} More importantly, the UHI effect serves to absorb heat during the daytime and radiate it out at night, raising the nighttime minimum temperatures, which have been linked epidemiologically with excess mortality.³⁸

Other features of the built environment and urban sociodemographics have been shown to increase the risk of heat-related death, including access to transportation, medical care, and cooling centers as well as crime, housing type, and neighborhood land use. In a study looking at the role of the urban form in mitigating exposure to extreme heat within the UHI, Harlan and colleagues³⁴ compared eight neighborhoods within metro Phoenix and looked for differences in exposure to heat stress and availability of adaptive resources such as air conditioning. They found statistically significant differences in thermal stress among the study neighborhoods, which were amplified during a heatwave. High settlement density, typified by apartment buildings, sparse vegetation, and lack of green space in the neighborhood were significantly correlated with higher temperatures and thermal comfort index. Lower socioeconomic and ethnic minority groups were more likely to live in warmer neighborhoods and not only have greater exposure to heat stress but also lack resources to cope with it. In sum, people in warmer neighborhoods were more vulnerable to heat exposure because they had greater exposure to heat and fewer social and material resources.

Demographic Trends

Advanced age represents one of the most significant risk factors for heat-related death in the U.S.⁹ In addition to having diminished thermoregulatory and physiologic heat-adaptation ability, the elderly are more likely to live alone, have reduced social contacts, and experience poor health.^{40–42} The prevalence of these social and physiological vulnerabilities to extreme heat will increase as the elderly become an increasingly larger proportion of the U.S. population.

Analysis of demographic trends in the U.S. project that the number of adults aged ≥ 65 years will nearly triple from 35 million in 2000 to almost 90 million by 2060.⁴³ Similarly, the proportion of the total U.S. population aged ≥ 65 years will increase from 12.4% in

2000 to over 20% in 2060.⁴³ Another demographic trend affecting vulnerability to extreme heat is population movement toward urban areas, which are gaining an estimated 67 million people globally per year—about 1.3 million every week. By 2030, approximately 60% of the projected global population of 8.3 billion will live in cities.³⁵ In addition to the impact the UHI effect has on electrical use, large cities' demands on power during heatwaves can severely tax the power grid infrastructure leading to rolling brown-outs or a large-scale power failure, as was observed in the 2006 heatwave in New York City.

The Public Health Response and Adaptation Measures

Public health efforts to prevent heat-related illness during EHEs require attention to both individual- and community-level risk factors. During heatwaves, elderly, disabled, or homebound people should be checked frequently for sign of heat-related illnesses, or transported to emergency cooling shelters for respite. Even a few hours spent daily in an air-conditioned environment has been shown to be a strong protective measure in reducing heat-related illnesses and death.¹⁰

If exposure to heat cannot be avoided, preventive measures should include reducing, eliminating, or re-scheduling strenuous activities; frequently drinking water or non-alcoholic fluids; frequently taking showers; wearing lightweight and light-colored clothing; and avoiding direct sunshine. Parents should never leave children alone in cars, and should ensure that children cannot lock themselves in an enclosed space, such as a car trunk. Relatives, neighbors, and caretakers of people at risk for heat-related death should frequently evaluate heat-related hazards, recognize symptoms of heat-related morbidity, and take appropriate preventive action.

The use of fans indoors, in rooms without air conditioning, should be strongly discouraged during an EHE.³⁸ Although fans provide a cooling effect by evaporating sweat, fan use can pose a significant risk when the heat index exceeds 37°C (99°F), because it serves to increase heat stress by blowing air that is warmer than body temperature over the skin surface.⁴⁴

Heat Response Plans

Despite the high morbidity and mortality associated with extreme heat exposure, U.S. cities, with few exceptions, are not adequately prepared for heatwaves.⁶ As with other natural disasters, heat response plans (HRPs) are central elements in the public health and emergency management response to heatwaves. HRPs, written plans that detail actions local government agen-

cies and nongovernmental organizations (NGOs) can take when extreme heat is predicted, have been shown to be effective in reducing heat-related mortality.³⁸ For example, an Extreme Weather Operations Plan developed by the City of Chicago following the 1995 heatwave probably reduced the death toll during the 1999 Chicago heatwave by increasing the number of daily contacts for the elderly during the event.^{45–47}

In their evaluation of existing HRPs, Bernhard and McGeehin⁵ have identified five essential criteria that should be considered during plan development:

1. Identify a lead agency and other all participating agencies.

Successful response to heat emergencies requires close collaboration of many local government agencies and NGOs. Plans must identify a lead agency and describe specific and detailed roles and responsibilities of the lead agency and all supporting agencies and NGOs. Plans should be revisited annually, before warm weather begins, to review response protocols and to confirm participation of lead personnel.

2. Identify criteria for activation and deactivation of the HRP.

An HRP should be activated in advance of a heatwave to inform the public about the risks from exposure to extreme heat. Activation of the HRP should be based on city-specific factors that affect the relationship between local weather and mortality. These factors may include ambient temperature, relative humidity, extremes in daytime highs, nighttime lows, and deviations from local norms.

3. Develop a communication plan and public education tools.

Coordination of local agencies is essential to define a clear communication strategy and pathway from the lead agency to first responders, the public, and the media. This communication strategy must be defined before the heat emergency and should be maintained throughout activation of the HRP.

4. Define risk factors, high-risk populations, and methods to reach those populations.

A key factor in the success of an HRP is identification of risk factors for heat-related mortality specific to each locale, which guides the development and implementation of intervention strategies. These findings should be used to develop HRP interventions for use during extreme heat events. Examples of such interventions include daily well-person checks of the elderly by community police or social service agency personnel; radio, television, and print media messages warning of

the dangers of heat; and provision of transportation for the elderly to air-conditioned “cooling centers” set up in public spaces, such as libraries and community centers.

5. Establish a method for evaluation and plan revision.

Post-heat event meetings with all participating agencies should be scheduled to review response activities and key HRP elements such as activation and deactivation thresholds, communication plans, outreach activities, and to correct deficiencies in the HRP. Evaluations also should examine surveillance data on morbidity and mortality in relation to weather data.

Although HRPs are central elements in the community-wide response to extreme heat events, people should also take appropriate individual action to reduce their risk for heat-related illness and death. Plans that effectively incorporate these individual-level risk reduction measures into outreach education efforts are likely to have the most success at reducing heat-related morbidity and mortality.

Environmental Design Strategies for Cool Cities

In addition to heat response plans, cities can mitigate the effects of extreme temperatures by engaging in efforts to reduce the UHI effect created primarily by the lack of vegetation and the high thermal absorbance of engineered urban surfaces. These “cool cities” initiatives⁴⁸ to reduce the UHI effect are gaining in importance because of their potential not only to reduce heat-related illness and mortality, but also to reduce energy demand, greenhouse gas emissions, air-conditioning costs, and air pollution.

Principle strategies of cool cities initiatives include promoting the installation of cool roofs and pavements, which use highly reflective and lighter colored materials to increase the reflectance, or *albedo*, of these surfaces,⁴⁹ and the promotion of green roofs which use roof-top plantings to cool building through *evapotranspiration* (the release of water from plants to the surrounding air). In addition to the energy savings from cooler buildings, green roofs aid in stormwater management and are popular for their aesthetic benefits. A “whole building” approach to energy efficiency and sustainability is promoted by the U.S. Green Buildings Council through their Leadership in Energy and Environmental Design (LEEDS) certification program.⁵⁰ LEEDS buildings make use of numerous design features, including high albedo surfaces and green roofs, to minimize a building’s thermal capacity and reduce energy consumption.

Additional strategies to promote cool cities include increasing tree plantings, especially to shade buildings, as well as increasing the relative amount of green spaces in urban areas. Even plantings that don’t provide shade

to buildings have been shown to have significant energy savings, because they cool the air through evapotranspiration.⁵¹ To reduce costs, cities should promote policies of replacing low-albedo surfaces with high-albedo surfaces during routine maintenance of roads and buildings.⁵²

Communicating Risk and Effecting Behavior Change

At a fundamental level, the success of public health efforts to prevent morbidity and mortality during heatwaves hinges on their ability to effect behavior change in individuals during these events. Despite the lethality of heat and heatwaves, public recognition of the hazard of extreme heat exposure is still lacking. Recent studies suggest that although extreme heat advisories are effective in alerting the public to the dangers of these events, many at-risk individuals are unaware, or unwilling, to take appropriate preventive measures.⁴ A survey of individuals aged ≥ 65 years in four North American cities found that, whereas community knowledge of heatwave advisories was high, knowledge about appropriate preventive actions was low.⁴

Bridging the gap between EHE planning efforts and individual action requires serious attention to health communication activities, including audience segment analysis and message testing.

Heatwaves pose a unique challenge to health communicators for several reasons. First, as noted above, heatwaves are less dramatic and conspicuous than other natural disasters. Second, whereas most natural disasters pose a sudden and abrupt risk to human health, the danger of hyperthermia gradually increases with duration of exposure, as a person’s ability to withstand excessive heat gradually diminishes over time; the epidemiologic evidence for this can be seen in the 2- to 3-day lag in mortality following the start of a heatwave. Additionally, although individuals might be willing to adjust their activities for the first day or two of an extreme heat advisory, an individual’s perceived threat of the heatwaves diminishes the longer the event lasts.

Along with individual perceptions of the risk of heat stroke during hot weather, economic factors also play a role. The high costs of running air conditioners during a heatwave imposes a significant economic burden, especially on the elderly living on a fixed income, many of whom decide to endure the heat rather than incur large bills. Sheridan and colleagues⁴ report in their survey that more than a third of study respondents considered cost as a factor in deciding whether to run the air conditioning in their home. Reflecting the under-appreciation of heat exposure as a health hazard, many state-run energy assistance programs, including the Low Income Home Energy Assistance Program (LIHEAP), provide energy assistance only for heating costs, not cooling costs. In fact, in 2007, only 16 states

offered cooling-related energy assistance programs under LIHEAP.⁵³

Vulnerability Mapping

One important finding of epidemiologic investigations of EHE-related morbidity and mortality is that poor and minority populations, located in urban neighborhoods, are disproportionately affected.^{42,54} Techniques to characterize the UHI and surface temperature, through the use of satellite remote sensing instruments, now have a degree of spatial resolution that allows for the characterization on a neighborhood scale.⁵⁵ These high-resolution remote sensing technologies enable the mapping of vegetation, land use, and thermal profiles,^{38,39,56,57} and can be integrated, through GIS, with indicators of social vulnerability such as demographic profiles, income, housing stock, prevalence of air-conditioning, and access to transportation infrastructure.^{58,59} The refinement of these mapping techniques ultimately will provide local emergency response personnel with novel tools to improve planning and preparation for heatwaves, by allowing for better resource allocation and tailoring of health communication messages to specific ethnic or demographic groups. Additionally, state and local energy policy managers can apply these mapping techniques to prioritize locations for suspension of electricity shut-offs, or for provisioning of LIHEAP cooling assistance during EHEs.

Conclusion

Heatwaves are a significant public health threat in the U.S. Although climate change, urbanization, and demographic trends will continue to contribute to risk, preventive approaches can help reduce the morbidity and mortality associated with these events. Public health practitioners can play an active role in developing adaptation measures such as city-specific heat response plans. The development and implementation of these plans should be guided by the best evidence, generated by epidemiologic studies and ecologic models, on the relationship between hazard and health outcomes.

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