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Extreme Weather and Climate Change: Population Health and Health System Implications

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Keywords

climate change, climate variability, extreme events, population health, health systems

Abstract

Extreme weather and climate events, such as heat waves, cyclones, and floods, are an expression of climate variability. These events and events influenced by climate change, such as wildfires, continue to cause significant human morbidity and mortality and adversely affect mental health and well-being. Although adverse health impacts from extreme events declined over the past few decades, climate change and more people moving into harm's way could alter this trend. Long-term changes to Earth's energy balance are increasing

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the frequency and intensity of many extreme events and the probability of compound events, with trends projected to accelerate under certain greenhouse gas emissions scenarios. While most of these events cannot be completely avoided, many of the health risks could be prevented through building climate-resilient health systems with improved risk reduction, preparation, response, and recovery. Conducting vulnerability and adaptation assessments and developing health system adaptation plans can identify priority actions to effectively reduce risks, such as disaster risk management and more resilient infrastructure. The risks are urgent, so action is needed now.

1. INTRODUCTION

Worldwide, in 2019, there were 396 disasters[1] that killed 11,755 people, affected 95 million others, and cost nearly US$130 billion (28). Asia was the most affected continent with 40% of the events, 45% of the deaths, and 74% of all people affected. Floods and storms accounted for 68% of the number of affected people worldwide. Anthropogenic greenhouse gas (GHG) emissions, land use change, and other activities impacting the global energy balance are altering the frequency and intensity of many extreme weather and climate events, with some regions experiencing increases in heat waves, floods, and droughts (84). Events influenced by climate change, particularly wildfires, also are increasing.

Risks from extreme weather and climate events arise from the intersection of the physical hazard (e.g., wind and rain), the extent of exposure to the hazard, the vulnerability of individuals and communities, and the capacity to prepare for, manage, and recover from extreme events.

A disaster generally is defined as a sudden, calamitous event that disrupts the functioning of a community or society and that exceeds its ability to cope using its own resources (81). The occurrence of an extreme event is not required for a community or region to experience extreme impacts, such as a large increase in mortality; an extreme impact can arise from a moderately strong event when it occurs in a highly vulnerable population. The converse also is true, that an extreme event may not result in extreme impacts when communities are prepared.

Roughly 20% of disasters in 2019 occurred in North America, including the Caribbean and Central America, for total damages of US$55 billion, of which US$29 billion were insured (130). Loss events included Hurricane Dorian, which caused billions of dollars in damage, especially in the Bahamas, in late August to early September. Heavy losses that year also resulted from severe weather, floods, and a winter storm in the United States. A mixture of snowmelt triggered by unusually high temperatures in March and storms with torrential rain led to sustained and extensive flooding in Nebraska, South Dakota, Iowa, and Mississippi (49).

Overall, the numbers and costs of disasters have been increasing for several decades due to increases in exposure (more people moving into harm's way and increases in the values of property and infrastructure at risk), vulnerability of people and infrastructure, and climate change (170). Since 1980, the United States has experienced 265 weather and climate disasters in which the overall damages reached or exceeded US$1 billion; the total costs were greater than US$1,775 trillion (132), with an estimated 14,223 deaths (an average of 356 per year), although the numbers of deaths are likely an underestimate (178).

Beyond the damage to infrastructure, extreme weather events and disasters can affect the health and well-being of individuals and can have catastrophic impacts on communities and health

[1]Natural disasters are not solely the consequence of biophysical, meteorological, or climatological events; human activities, such as placement of infrastructure and movement of people into vulnerable regions, also are required.

systems. People can suffer from a wide range of physical effects (e.g., heat exhaustion, injuries in severe storms, and respiratory illnesses from molds due to floods) as well as longer-term impacts on mental health. Health systems and facilities can be affected by impacts on patients and health care staff, medical and nonmedical supplies, facility operations, and critical infrastructures. To prepare for climate change, health-sector and emergency-management officials—as well as urban planners, neighborhood services staff, and others—require information about how hazards are projected to change, possible future exposures of people and property, likely changes in population health and health care infrastructure vulnerabilities, and needed capacities to prepare for and manage the events and their aftermath.

We review (*a*) the current impacts and projected risks of climate change on the health of populations and health systems from extreme weather and climate events and from wildfires, (*b*) the value of disaster management to reduce health risks from these changes, and (*c*) adaptation and mitigation measures that can explicitly address climate change in policies and planning processes.

2. EXTREME EVENTS INFLUENCED BY CLIMATE CHANGE

Global land-surface air temperature has risen 1.53°C since the preindustrial period of 1850–1900, with considerable variation in regional warming; this increase is much larger than the observed warming combined over land and oceans (0.87°C) (84). Climate models project robust differences in regional climate characteristics, including extremes.

Detection and attribution analytic methods are increasingly being applied to determine the effects of climate change on the frequency and/or magnitude of extreme events. For example, in mid-September 2019, torrential rainfall from Tropical Storm Imelda caused large-scale flooding in Southeast Texas, affecting an estimated 6.6 million people and resulting in rescues of over 1,000 people and 5 deaths (171). The recorded precipitation at the station with the highest total amount of rainfall from this event would be expected only approximately once every 1,200 years.

The 2019 Intergovernmental Panel on Climate Change Special Report on Climate Change and Land (84) concluded that warming since the period 1850–1900 has resulted in an increased frequency, intensity, and duration of extreme events in most land regions, including the following observations:

- The intensity of heavy precipitation events increased across the globe.
- The frequency and intensity of droughts increased in some regions (including the Mediterranean, West Asia, many parts of South America, much of Africa, and Northeastern Asia).
- Desertification in some dryland areas (including in sub-Saharan Africa, parts of East and Central Asia, and Australia) was associated with increased land-surface air temperature and evapotranspiration and decreased precipitation amounts in interaction with climate variability and human activities.
- The frequency and intensity of dust storms increased over the last few decades due to land use and land cover changes and climate-related factors in many dryland areas, such as the Arabian Peninsula and the broader Middle East and Central Asia.

Further, climate change is projected to continue and exacerbate these trends, including the following:

- The frequency, intensity, and duration of extreme heat events are projected to continue to increase through the twenty-first century, with all regions expected to experience unprecedented temperatures.

- The frequency and intensity of extreme rainfall events are projected to increase in many regions.
- The frequency and intensity of droughts are projected to increase, particularly in the Mediterranean region and southern Africa.

There is a range of possible futures for each additional unit of global warming. For example, regional projections of annual maximum temperatures across climate models where the Earth warms 1.5°C under a scenario of high GHG emissions indicate there may be little change in the single hottest day in a year in many regions if realized warming falls into the lower quartile of projections (154). Alternatively, increases of 3°C to 5°C in maximum temperatures could occur over most regions in the upper quartile of projections. With Earth projected to warm 1.5°C between 2030 and 2052, the next few decades could be similar to today in many parts of the world; or regions could experience significant and very rapid warming. These projections have implications for the frequency and duration of extreme heat events; the extent of increases in precipitation, including from hurricanes; and the rate of sea-level rise that affects the health of future populations (particularly but not exclusively in coastal regions) and their health systems.

2.1. Tropical Cyclones or Hurricanes

Tropical cyclones (TCs) that make landfall are among the most dramatic and costly disasters. They have different names depending on the basin where they occur (hurricanes in the northern Atlantic and northeastern Pacific, typhoons in the northwestern Pacific, and cyclones in the southern Pacific or Indian Ocean) but are the same meteorological phenomena. They cause strong winds and flooding from intense rainfall and a surge of ocean water that causes dramatic damage to buildings and infrastructure along coastlines, often including widespread utility outages. TCs have cost the United States close to US$1 trillion since 1980 (157). Low- and middle-income countries (LMICs) have suffered smaller total economic losses, but the losses are often a larger proportion of their nations' economies and arguably have greater consequences for well-being (67).

Alongside physical damages, TCs are highly detrimental to human health (107). From 1963 to 2012, there were 2,544 deaths in the United States (~50 per year) directly caused by the forces of TCs (e.g., drowning in floods caused by storm surge or extreme rainfall, or physical trauma caused by windborne debris) (142). A comparable number of TC-related deaths are indirectly caused in individuals with preexisting conditions exacerbated by the stress or strain of a storm. Hurricane Katrina alone caused 520 direct deaths and 565 indirect deaths (143). Accounts of individual TCs clearly indicate upticks in a variety of other health problems that do not necessarily result in death, including injuries, diseases, skin infections, and mental health impacts (e.g., 43, 73, 87, 141). New data sets of TC exposure history are increasing possibilities for robust, long-term epidemiological studies of these diverse health impacts from TCs (e.g., preterm birth; see 4a, 161) that will enhance our ability to predict and prepare for future TC health impacts.

A confounding challenge in projecting future TC impacts is the relatively low confidence in projections of TC changes with climate change. Projections suggest the most intense TCs will likely increase in frequency and exhibit higher precipitation rates; however, there is uncertainty whether the overall number of TCs may increase or decrease, with different trends projected depending on the modeling approach (46, 103, 154). However, other trends are clearly heightening TC risks to individuals and communities. Exposure to TCs is increasing as people move to and settle along coastlines (57), and potential damages from storm surge are increasing with sea-level rise (113).

2.2. Compound Events

Complicating projections of extreme-event impacts is the fact that many disasters are the result of combinations of extremes (sometimes called compound, interacting, interconnected, or cascading events) (140, 154). Compound extreme events consist of two or more events interacting across time and/or space, such as back-to-back extreme heat events or an extreme heat event coincident with a drought (184). The range of compound extremes that might endanger human health is large. The study of compound extremes is a nascent and rapidly evolving research area. In many cases, understanding of present and projected risks of a particular compound extreme event is lacking, including key societal drivers of vulnerability (144). We highlight a few types of compound climatic extreme events.

Heat waves are exacerbated when combined with other extreme events. Heat waves can enhance the buildup of ozone and other pollutants, leading to combinations of heat and air pollution dangerous for human health (4, 111). A particularly striking example is the combination of high temperatures, wildfire, and smoke that results in high levels of air pollution across broad geographic areas. In recent summers, the western United States has been afflicted with multiple such episodes; these are projected to become increasingly common in the future because of climate change (114).

Positive feedback loops also occur between heat waves and droughts that heighten temperature and desiccation (76, 185). Certain types of atmospheric waves can cause multiple simultaneous heat waves distributed across the Earth; this may increase the risk of multiple breadbasket failures (105). Many of the most impactful heat waves in terms of mortality might be better understood as the combination of a number of heat extremes occurring in sequence, separated by short cooler breaks—a temporally compound heat wave event. The proportion of heat wave hazards coming from these temporally compound heat waves is robustly projected to increase with global warming (7).

Past events highlight the dangers of compound extreme events involving TCs or extreme precipitation and related flooding. For example, in 2005, Hurricane Katrina led to massive flooding in New Orleans (153). Only a few weeks later, Hurricane Rita rebreached weakened levees, leading to flooding once again. These events' impacts likely added nonlinearly by affecting the vulnerability of protective infrastructures. Significant research remains to understand the dynamics of such compound hydrological extremes and to quantify risks to populations and communities (144).

3. POPULATION HEALTH AND HEALTH SYSTEM RISKS FROM EXTREME EVENTS INFLUENCED BY CLIMATE CHANGE

There is high annual variability in the numbers of deaths from all disasters, with an average of 60,000 deaths annually over the last decade, or 0.1% of all global deaths (148), with an irregular and overall declining trend. Most of these deaths were in a few intensive disasters, indicating that while the events may not be preventable, much of the loss of life can be avoided through improved forecasts and early warnings, more resilient infrastructure, and improved disaster risk management. However, there is a concern with climate change that future events may be too large or intense for effective preparation.

The next sections summarize population health and health system risks from high ambient temperatures, droughts, floods, and wildfires, followed by a discussion of the mental health risks associated with extreme events influenced by climate change.

3.1. High Ambient Temperatures

The range of health effects of high ambient temperatures include discomfort, severe illnesses requiring hospital care, mortality, and interactions with and modifications of work patterns, recreation, and other activities.

3.1.1. Morbidity and mortality from heat waves. At the global scale, the number of hot days and nights has increased since the 1950s, while cold days and nights decreased (154). Rising temperatures are directly connected to human health through heat-related illnesses (e.g., heat exhaustion, heat syncope, and heat stroke) and death, with each individual's risk highly dependent on their exposure, location, and susceptibility. There is a wide range of heat tolerance within populations and across regions. The human body can physiologically adapt to heat to a certain extent depending on individual factors, local climate, and types of heat exposure. Physiological factors (e.g., age, sex, preexisting illness, and medication or drug use) (23, 98) and behavioral or contextual factors (e.g., employment, activity, clothing, income, and housing type) (6, 118) are known to affect thermoregulation across day-to-day or hour-to-hour heat exposures. For example, in Maricopa County, Arizona, 47% (93/197) of heat deaths in 2019 involved drug use as a cause of death or contributing factor (124). Extreme heat events can disrupt health systems and services, for example, through a surge in patient volumes, by closing operating theatres in high heat and humidity conditions, or through impacts on health care professionals and patients (156).

Reducing risks to health from current and projected high temperatures—outdoors and indoors—depends not only on physiological acclimatization but also on planned adaptation by public health officials in concert with partners in other sectors. Heat action plans and early warning systems that include a proactive response to assist vulnerable populations and build awareness among the public and key stakeholders can lead to the adoption of protective behaviors and reduction in morbidity and mortality (75, 156). Common components of heat action plans and warning systems include opening of public cooling shelters, targeted messaging, wellness checks, and water distribution (e.g., 9, 19). A study by Eisenman et al. (44) found that as temperatures increased, heat-related mortality was lower in census tracts with more publicly accessible cool spaces in Maricopa County, Arizona. These and other preventative measures that may reduce heat exposures and increase coping capacity as the climate warms are important for protecting health. Over longer time scales, communities can be modified or designed with new or altered technologies and infrastructures (e.g., cool facades, green roofs, shade structures, and reflective surfacing) to reduce heat exposures in urban areas (119, 172). Heat-health adaptation measures can be cost-effective and reduce utilization of health systems (61) but should be developed and updated based on information about projected climate conditions (74).

Heat-related mortality has been declining in many industrialized countries in recent decades (56). For example, deaths attributed to heat across 105 cities in the United States declined by almost 63% from 1987 to 2005 (12). However, the extent to which continued declines could be realized (or reversals avoided) largely depends on implementing effective adaptation strategies (60). Heat-related mortality trends and optimal adaptation pathways or measures differ by country based on culture, infrastructure, technology, and communication, among other factors. Few studies have assessed heat-related mortality in LMICs due to lack of data (56, 63, 134); over half of existing studies are from China (56%) or other Asian countries (14%). LMICs typically have low-resource environments [including a lower prevalence of air conditioning (AC)] and more often rely on altering behaviors and personal cooling to stay safe. These behaviors may include application of ice or ice towels, dousing skin, or saturating clothing with water with added ventilation (fans) (26). Yet the effectiveness of these actions depends on the climate context. For example, evaporative cooling with fans is more effective in humid locations, whereas self-dousing and/or wetting of clothing when using fans are preferable strategies in certain dry climates (128). Although AC use is growing exponentially as the most popular heat-exposure reduction strategy globally (11), it is costly and financially inaccessible for many of the most vulnerable, is energy intensive, emits waste heat into the environment (150), and can increase the risk of power outages.

Heat-reduction interventions may have economic and educational cobenefits. Park (137) found that high school student test performance was reduced by 14% on days with high (~32.2°C) outdoor temperatures compared to optimal (22.2°C) outdoor temperatures in New York State. Hot school days may also disproportionately impact minority students, accounting for ~5% of the racial achievement gap in the United States, in part because of inadequate access to AC (138).

Finally, there is growing evidence linking extreme heat and rising temperatures to increased hospitalizations for mood and behavioral disorders (22, 175) and evidence of increased risk of suicide related to heat waves and rising temperatures (17, 34, 99). These risks are projected to increase with further warming. Burke et al. (17) estimated that under a high GHG emission pathway, there could be 9,000 to 40,000 additional suicide deaths throughout Mexico and the United States by 2050. Mechanisms for how high temperatures impact mental health remain poorly understood, with various nonclimatic confounders to consider (e.g., macroeconomics and social factors); yet, biologically, there may be side effects from thermoregulation and neurological responses to heat that adversely affect mental health (17).

3.1.2. Occupational health. Individuals working under heat stress are more likely to experience physiological heat strain (51) and heat-related illness, and exertional heat stroke and death can occur in young, otherwise healthy workers performing heavy physical labor (64). A global meta-analysis by Flouris et al. (51) found that individuals working a single shift under heat stress conditions were four times more likely to experience occupational heat strain than in thermoneutral conditions (based on 11,582 workers across 9 studies), with ~0.7°C higher core temperatures (1,090 workers, 17 studies) and 14.5% higher urine specific gravity (a measure of solute concentration) (691 workers, 14 studies). In the United States between 2000 and 2010, 359 occupational heat-related deaths were reported (annual mean fatality rate 0.22 per 1 million workers), with agricultural and construction workers at particularly high risk (64). Indoor workers subject to inadequate ventilation and workers exposed to point heat sources are also at risk (152). Occupational heat stress is hypothesized to contribute to the global epidemic of chronic kidney disease of unknown etiology (177) and can lead to adverse birth outcomes among heat-exposed pregnant workers (106). Working populations with the most social and economic disadvantages are often more exposed to heat and may lack adequate health care access or other means to address exposures and health effects (122).

The risk of adverse occupational health effects is likely to increase as the frequency and severity of extreme heat waves increase (83). In a study of US agricultural workers, climate change at its current pace is projected to double crop worker heat risk by the mid-century and triple by the end-of-century, absent extensive restructuring of agricultural labor (164). Increasing temperatures from local land use changes can magnify the impacts of climate change, for example, in the setting of industrial clearing of tropical forests where communities depend on subsistence agriculture and other outdoor work (183) and in areas with growing urban heat island effects (152). In tropical and mid-latitude areas of the world, Dunne et al. (38) estimated that heat stress has already reduced labor capacity by 10% relative to the 1970s and projected a reduction of 40% by the year 2100 under a pathway of high GHG emissions. Further decreases in labor productivity and associated economic impacts are projected, assuming adherence to occupational heat stress guidelines (38, 51).

3.1.3. Recreation.

High temperatures can also adversely affect people engaging in outdoor sports and recreation and represent a growing challenge for the sports industry (136). Heat is a leading cause of sudden death among athletes, and exertional heat illnesses cause thousands of debilitating health outcomes annually (18). For large events facing extreme heat (e.g., Tokyo Olympics), weather and climate data should be integrated into the decision-making process for event schedules and venue locations (79). Unpredictable disruptions from extreme weather may cost billions of dollars given the years of planning, hundreds of thousands of people involved, and global media attention, yet such safety precautions may help avoid serious risk to athletes (158). Coordination among local stakeholders in emergency medicine, public health, and events/operations is necessary to ensure that localized preparedness plans (e.g., identification of hot spots such as sun-exposed locations, expected crowds, and midday events) systematically provide adequate support for both athletic and social activities.

3.2. Droughts

The frequency and intensity of droughts are increasing with rising global temperatures and changing precipitation patterns (165). These trends and associated risks are expected to continue to intensify with climate change (77). Internationally, over the last two decades, droughts affected more than one billion people (27). Africa is a quintessential setting for examination of the roles that drought can play in human health and society, as droughts there have led to mass migration, conflict, and devastating famine (54, 58). In the United States since 1980, droughts classified as billion-dollar disasters were estimated to have caused 3,865 deaths, with most of the deaths due to heat waves accompanying drought (132).

Because of the difficulty in defining the beginning and end of a drought, the causal pathways connecting droughts to health outcomes can be complex and difficult to monitor (10, 117). The most commonly identified pathway is a reduction in water availability for societal uses, both in quantity and quality as concentrations of pollutants increase (129). Stagnant, warm waters from drought produce ideal conditions to promote growth of many freshwater pathogens (32). Simultaneously, sudden heavy rains during drought conditions can increase the likelihood of flooding.

Droughts are slowly evolving, and the disruptions to human systems can last for long periods with slow recoveries that can have delayed health impacts (159), such as through agricultural losses and environmental degradation (47). Increased particulate matter (PM) in the atmosphere resulting from drought and high winds can also lead to respiratory health issues and death (10, 29). These conditions can contribute to the spread of pathogens causing respiratory illnesses (such as coccidioidomycosis and meningitis; see 25, 53). Drought has also been linked to mental health issues and conflict (59, 173).

3.3. Floods

Based on the Emergency Events Database, from 1969 to 2018, 10,009 extreme weather events that resulted in disasters caused over two million deaths and just under four million cases of disease (83). Floods (47%) and storms (30%) were the most common extreme weather events worldwide over the period 1969–2018, with an increasing trend (97). Globally, most direct weather-related deaths were caused by storms (39%), droughts (34%), and floods (16%). Drowning is the most common cause of death after the onset of flooding (139). Morbidity continues for more than 10 days after a severe flooding event. A comprehensive review of the health impacts of worldwide flood and storm disasters between 1985 and 2014 concluded that the health impacts of these extreme events differ (151). The health impacts include increases and sometimes decreases in

- Injuries, especially wounds, and carbon monoxide and gasoline poisoning after storms;
- Cases of infectious and parasitic diseases, such as gastrointestinal illnesses, respiratory infections, and skin or soft tissue infections, after storms and floods;
- Exacerbations of noncommunicable diseases after storms and floods;
- Increased contact with health services after floods; and
- Cardiopulmonary (floods) and skin complaints (storms and floods).

The results indicate increased needs for emergency and routine health care services.

Differential vulnerabilities increase risks during and after floods and storms. During Hurricane Harvey (Texas, 2017), physical health problems primarily affected individuals who did not evacuate. Disparities exist in disaster-related flooding exposure. Older adults were more likely to live in a household exposed to flooding from Superstorm Sandy (New York, 2012) (109). Socioeconomic disparities also were present, with poorer residents having higher risk. Increases in posttraumatic stress disorder (PTSD), depression, and anxiety are associated with flooding (131, 174) and hurricanes (135). Floods also can decrease health-related quality of life (149).

Health care access and infrastructure can be severely affected by floods, including loss of records, impacts on water supplies and laboratory functions, reduced access to health care, and evacuation, with subsequent consequences for the communities served (21, 139). Health care access was particularly reduced for persons living in households where someone lost their job after Hurricane Harvey (50).

3.4. Wildfires

Many parts of the world have seen increases in the length of the wildfire season and increases in burned area (92). While there are many drivers of these increases (including historical wildfire suppression and increased intrusion of humans into wildland areas), climatic changes, including drought, have been implicated as a major contributor to changes in fire season length and acres burned (1, 179). These trends are projected to continue under a range of global climate models, with particular agreement among models in the mid-to-high latitudes (127). Globally, the mortality burden from wildfire smoke is estimated to range between 260,000 and 600,000 (90); however, this estimate could now be considered an underestimate given increases in population globally and increases in extreme wildfires in North America, Australia, Brazil, and other locations since that study's publication in 2012.

Wildfire smoke emits a variety of chemicals, including PM (suspended solid and liquid particles) and gases such as carbon dioxide, carbon monoxide, nitrogen oxides, and volatile organic compounds. Additionally, many of these chemicals react to form more PM and ground-level ozone (85). Most studies of the population-health impacts downwind from wildfires focus on PM_{10} and $PM_{2.5}$, as data on these are readily available and there is a robust literature on the health impacts of these particles. More research is needed to understand the health impacts of other components of wildfire smoke.

Wildfire smoke exposure is most consistently associated with adverse respiratory health outcomes (20, 145), with the clearest evidence for exacerbations of asthma whether measured in hospitalizations, emergency department visits, or physician visits (15, 55, 160). Many studies find that lung function among people with asthma does not decline with exposure to wildfire smoke (112, 145), but there is some evidence of lung function decline of nonasthmatics (86, 100). These contradictory findings could be due to higher medication usage among those with asthma, thus protecting them from exacerbations during exposure. Many (15, 45) but not all (91) studies that investigate the relationship between wildfire smoke exposure and refills of rescue medications often used for asthma report significant positive associations. Associations between wildfire smoke exposure and other respiratory endpoints are not as consistent, but there is increasing evidence of associations for exacerbations of chronic obstructive pulmonary disease and respiratory infections (145).

Wildfire smoke may impact specific cardiovascular endpoints such as out-of-hospital cardiac arrests (33, 93) and emergency department visits, particularly among the elderly (180). Studies with sufficient statistical power demonstrate a small but significant increase in mortality (37, 48, 89, 123). Additionally, there is increased interest in whether wildfire smoke affects birth outcomes. Babies whose gestation coincided with a wildfire had a significant but small decline in birth weight (78). An observed decline in birthweight was significantly associated with wildfire $PM_{2.5}$ across multiple fire seasons in Colorado, with increased risk of preterm birth, gestational diabetes, and gestational hypertension (2). Further, wildfires are associated with adverse mental health (16, 35).

Understanding the populations that are most affected by wildfire smoke exposure is important for targeting public health adaptations to increased wildfires under a changing climate, yet very few epidemiological studies have investigated differential risk (104). There are higher rates of emergency department visits for asthma among females compared to males (55, 160). Studies investigating differential impacts by age are not consistent except for studies of asthma exacerbations that showed the highest risks for the elderly, followed by working age adults, and the lowest risks among children (15). Very few studies have investigated differential impacts of wildfire smoke by race, ethnicity, or socioeconomic status (SES) (104, 145), but there is some evidence of stronger associations between wildfire smoke and visits to the emergency department and hospitalizations in lower-SES neighborhoods (146).

Two studies projected the health risks of air pollution from wildfires under climate change, with one focused on the western United States (115) and the other on the continental United States (52). The latter study projected that overall $PM_{2.5}$ concentrations would decrease owing to decreases in emissions from anthropogenic sources but that fire-related $PM_{2.5}$ emissions could offset some of these gains in some regions. The net result projected under high GHG emissions is that fire smoke could be the dominant source of annual average $PM_{2.5}$ exposure in all regions by the year 2100. Although $PM_{2.5}$ mortality is projected to decrease by 2100, the proportion of deaths due to wildfire-associated $PM_{2.5}$ could increase (52).

Wildfires can present many challenges to health systems and impact the operations of health facilities through increased stress on services, health risks to staff and patients, and damage to infrastructure and operations (e.g., smoke inundation of hospitals and clinics). In 2017, severe wildfires in the interior region of British Columbia, Canada, affected 19 health facilities or sites and led to the evacuation of 880 patients, caused the displacement of 700 health professionals, and cost the Interior Health Authority CAN$2.7 million (164a).

3.5. Mental Health

Extreme events and disasters can exacerbate or compound preexisting mental health needs or trigger new mental ill-health outcomes, acute or chronic and long-term (24). Substantive socioeconomic implications from destruction to homes, businesses, and communities can lead to financial stressors and community strain that can increase the likelihood for domestic or community-based violence (24). At the same time, many people exposed to extreme events demonstrate resiliency and experience very little to no mental distress (14). People exposed to extreme events also may experience a mixture of affirmative mental health outcomes like compassion, growth, and altruism as communities band together in the wake of a disaster and challenging mental health outcomes like stress, fear, anxiety, and compassion fatigue (71).

Climate change–related hazards (e.g., drought, sea-level rise, melting permafrost, and extreme weather events) affect well-being (24, 71). Impacts to mental well-being include a loss of a sense of place, referred to as solastalgia, and anxiety and grief related to a changing climate, often referred to as ecoanxiety, climate anxiety, climate trauma, ecogrief, or climate grief (3, 24, 30). These experiences are often framed as normative responses, so it is important to look broadly at the full range of mental health outcomes related to climate change and not to necessarily pathologize these outcomes (70). Those most at risk are those who already experience health inequities based on the social, environmental, and biological determinants of health (70).

Enhancing mental health literacy, access to mental health care and culturally relevant care, and a sense of community, as well as integrating mental health indicators into climate change and health assessments, support psychosocial adaptation to a changing climate (70). The cobenefits of climate change mitigation for mental well-being include active transportation that enhances mood and increased green space that can reduce stress levels and promote well-being through connections with the natural environment (80).

4. INCREASING THE RESILIENCE OF HEALTH SYSTEMS

A global adaptation gap exists in efforts by health-sector officials to prepare for climate hazards such as weather-related disasters (166). Multiple opportunities exist to increase the climate resiliency of health systems and health facilities (182). Ministries and departments of health generally have programs with responsibility for managing disaster risks. However, these programs were developed without explicitly incorporating climate change (e.g., considering the implications of projections of future risks), meaning they may be ill-equipped to manage the health impacts associated with increases in the frequency and intensity of extreme events. Furthermore, some climate-related hazards, like extreme heat, fall outside of the official or perceived domains of responsibility for professional disaster management agencies or are approached through a distributed governance model with no designated lead entity (68). The key policy levers for health-sector decision makers are climate change adaptation, GHG mitigation, and disaster risk management. To date, cross-sector adaptation efforts have been largely incremental, adjusting existing systems while maintaining their core structure and function. However, given the limitations of these systems to meet the increasing demands associated with experienced impacts or anticipated climate-related risks, transformational adaptations that seek to fundamentally change these systems are necessary (133).

Disaster risk management is often considered separately from adaptation, although there is growing integration between them to maximize protection of populations and health systems (8). Successful incorporation of climate change requires developing, implementing, evaluating, and modifying policies and programs to increase their effectiveness for what will be a very different future.

4.1. Adaptation and Mitigation

A major focus of adaptation is on promoting the development of climate-resilient health systems (182). Building blocks of such systems include (*a*) a knowledgeable health workforce with the tools needed to promote climate resilience; (*b*) health information systems that support effective management of the health risks of extreme events; (*c*) effective service delivery, including preparation for emergencies; and (*d*) adequate financing (40). Preparing health systems for climate extremes and disasters requires robust information about current impacts and projected risks to inform adaptation planning (182). A critical step is developing a health national adaptation plan (HNAP) or subnational plan, including conducting a vulnerability and adaptation assessment (181). An HNAP helps ensure that the health risks of climate change are prioritized at community to national levels of decision-making to reduce vulnerabilities and build needed capacity and resilience.

The process of developing an HNAP should be integrated with adaptation planning in other sectors (e.g., disaster risk management committees, hydro-meteorological services, agriculture, and water) and with development planning processes (181).

Vulnerability and adaptation assessments should include analyses of the ability of health systems and services to withstand extreme events and disasters; stress tests can provide information to officials to facilitate preparing for and managing more severe climate change–related shocks and stresses (39). The health impacts of extreme events can compound until a tipping point is reached, resulting in significant changes in the affected system and more severe population-health outcomes. This was illustrated in 2017 when Hurricane Maria resulted in an estimated 4,645 excess deaths in Puerto Rico, with a third of those deaths from delayed or interrupted health care (101).

Health-sector officials have a wide scope to help reduce the future magnitude and pattern of extreme weather and climate events through the reduction of GHGs given the large carbon footprint of health-related activities related to energy, food, anesthetic gases, and transportation (94). In addition, significant health cobenefits (e.g., better respiratory and cardiovascular health through improved air quality) that help build resiliency can accrue through well-designed GHG mitigation efforts (65).

4.2. Disaster Risk Management

Disaster risk management includes "strategies, policies, and measures to improve the understanding of disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, response, and recovery practices" (168). Health-emergency management policies and actions to reduce risks from climate-related hazards can contribute to adaptation and resiliency-building efforts if they are informed by climate change considerations and information. Opportunities to integrate disaster risk management and climate change adaptation include alignment of financing strategies and mechanisms; development of dual- or multipurpose government policies and strategies; integration of both disaster risk management and adaptation into national and international organizations, institutions, and programs; application of widely adopted disaster risk management participatory hazard assessment approaches; and promotion of locally led interventions or frameworks that comprehensively address disasters from all hazards and environmental problems (82). Examples of specific disaster risk management measures that may concurrently foster climate change adaptation include heat wave warning and response programs, infrastructure resilience, and overall disaster preparedness (167).

Disaster risk management strategies should consider local context and place emotional and cognitive experiences and identities that link people to places (13). Place attachment has both positive and negative relationships with natural environmental risk perception and risk coping, which have the potential to influence the effectiveness of disaster risk management strategies (13). For example, strong place attachment has been negatively associated with willingness to evacuate and relocate (13).

Community-based disaster risk management strategies are necessary to address community-specific risks, integrate priorities for vulnerable groups, and acknowledge community assets and coping strategies (155). Given the importance of implementing adaptation measures at the local level, local public health agencies are uniquely positioned to build resilience (95, 96). Public health actors are well positioned to address climate change due to their professional responsibilities, experience, and expertise (8). Prior to a disaster, community-focused public health strategies can reduce climate disaster risk by reducing human vulnerability (96). Furthermore, public health activities implemented in the context of disasters—including rapid needs assessments, surveillance, and epidemiological studies—will become more important as the frequency of climate-related hazards increases (5).

An opportunity for state and local health departments to engage in climate change adaptation activities is to build on existing all-hazards disaster preparedness and response capacity (36). A key action to close the health adaptation gap related to heat and weather extremes is to integrate disaster risk management into all health policies and to integrate health into disaster risk management plans and strategies (166). Additional collaborative opportunities, partnership, communication (within and across sectors), resources, authority, training, and capacity for state and local health department engagement in climate change adaptation activities are necessary (36).

4.3. Economic Considerations

Cross-disciplinary efforts combining population health, economics, and climate to value the adverse risks of exposures and benefits of adaptation strategies are a priority (83). While the reported estimates of economic losses associated with extreme weather events nationally (132) and globally (130) are huge, they provide limited information on the health impacts. The challenges in attributing health consequences to specific extreme events and/or variability in meteorological factors (e.g., temperature, precipitation, and humidity) limit economic valuation.

To assess the direct health costs associated with extreme events, studies used a combination of cost-of-illness measures (financial costs of utilizing medical care and pharmaceuticals) and willingness-to-pay-based estimates (e.g., value of statistical life) (147). Studies using reported medical diagnoses to estimate the changes in morbidity and/or mortality associated with a sample of climate-sensitive extreme events reported substantial health care costs (110). A statistical approach to determine the attributable fraction of morbidity and mortality associated with a specific environmental exposure, mostly extreme temperature (116), can be used in conjunction with climate and demographic projections to estimate future health care costs (108). Estimates of the economic burden in these studies are useful in informing local-level decision-making to prevent adverse outcomes (176).

Extreme temperatures impact health outcomes like labor productivity that have welfare implications for families, labor wages, and economies (102). Computable general equilibrium models can assess the economy-wide impacts of future climate scenarios based on a broader suite of human welfare indicators, such as nutrition (69). There is growing evidence of the economic impact of hurricanes on hospital evacuations and health care facilities (163).

In spite of the uncertainty and assumptions around capturing the health benefits and costs of climate impacts and solutions embedded across different sectors of the economy, these analyses provide critical inputs to policy decisions (66). The economic perspective is useful in choosing among alternatives given resource constraints. Coupled with spatially resolved information on the risk of climate hazards and vulnerable populations, this prioritization of health interventions could aid public health practitioners in implementing targeted interventions (120). Complementary to the health cobenefits of adaptation and mitigation strategies, health interventions related to water and sanitation could have larger societal benefits (121).

While the success of efforts to reduce GHGs and avoid increases in extreme weather events is uncertain, the projected economic benefits of avoided mortality are significant (169). From an equity perspective, it is important to note that the economic consequences for specific hurricane-affected communities could be substantial even though the macroeconomic consequences may appear small in these large-scale assessments of climate impacts (31).

5. CONCLUSIONS

The coming decades will be characterized by increases in the frequency and intensity of many types of extreme weather and climate events, with the potential for significant impacts on populations and health care systems worldwide. Rigorous research conducted before, during, and after disasters can improve assessments of population health and health system vulnerabilities and capacities and help evaluate the effectiveness of integrated disaster risk management and adaptation strategies (126). Such strategies can be cost-effective; examples include city-level early warning systems (42), community intervention programs (88), individual-level occupational health interventions (162), and initiatives to build health facility resilience (72). The evidence base of additional health interventions that can cost-effectively reduce the health risks of extreme events needs to be expanded.

A major challenge is the mismatch between research needs and the funding priorities of major health institutions and organizations (142). Overall funding for health adaptation is negligible (<1% of international climate adaptation finance). This led the 2018 Adaptation Gap Report to conclude "there is a significant global adaptation gap in health, as efforts are well below the level required to minimize negative health outcomes" (166, p. XIV). Research funding to understand and manage the health risks of climate change is even smaller (41, 62). Underlying reasons include the original framing of climate change as an environmental problem instead of as a whole-of-society challenge. Although the situation is changing, there is a tendency for health funders and health systems to continue to consider climate change as one of many environmental issues, such as nitrogen deposition in our waterways, where any additional cases of morbidity and mortality could be managed in the normal course of business by health care and public health institutions. Because the health risks of a changing climate are not novel, funders do not see the need for additional research and intervention. Climate change is not yet consistently viewed as core to population health and is not widely considered a current, urgent issue. Another reason funding is so low is that health funders and institutions take a primarily reductionist, top-down perspective to health issues, focusing on proximate, individual-level risk factors (125). This medical-model view of population health has been highly successful in understanding and controlling many major causes of preventable morbidity and mortality but will be insufficient to protect health and well-being in the face of the significant social and environmental changes expected over the coming decades (41). Changing these mindsets through education and capacity building is vital. Investments in research, adaptation implementation, and evaluation guided by decision maker needs can increase resilience, helping to protect the most vulnerable individuals and health care infrastructure while addressing inequities in disaster risk, even as the climate changes.

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AUTHOR CONTRIBUTIONS

K.L.E. conceptualized the article; K.L.E., J.V., J.W.B., J.E.B., D.M.H., N.A.E., K.H., C.E.R., S.S., J.S., and P.B. contributed to the writing, editing, revising, and finalizing of the manuscript.

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