Improving Societal Outcomes of Extreme Weather in a Changing Climate: An Integrated Perspective

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Abstract

Despite hazard mitigation efforts and scientific and technological advances, extreme weather events continue to cause substantial losses. The impacts of extreme weather result from complex interactions among physical and human systems across spatial and temporal scales. This article synthesizes current interdisciplinary knowledge about extreme weather, including temperature extremes (heat and cold waves), precipitation extremes (including floods and droughts), and storms and severe weather (including tropical cyclones). We discuss hydrometeorological aspects of extreme weather; projections of changes in extremes with anthropogenic climate change; and how social vulnerability, coping, and adaptation shape the societal impacts of extreme weather. We find four critical gaps where work is needed to improve outcomes of extreme weather: (*a*) reducing vulnerability; (*b*) enhancing adaptive capacity, including decision-making flexibility; (*c*) improving the usability of scientific information in decision making, and (*d*) understanding and addressing local causes of harm through participatory, community-based efforts formulated within the larger policy context.

Contents

Extreme weather: weather conditions and weather-related events that are rare at a particular location and time or can cause significant impacts

Vulnerability: the susceptibility of people or systems to damage or harm

Climate change mitigation: human intervention to reduce emissions and/or concentrations of carbon dioxide and other greenhouse gases

Adaptation: long-term or fundamental changes people make to systematically reduce potential harm (or take advantage of opportunities) from changing weather stressors

1. INTRODUCTION

Extreme weather events have captured the interest of scientists, the media, and members of the public (1–7). Humans have always been interested in and influenced by extreme weather. As human societies have evolved, our ability to anticipate such events and reduce negative outcomes has improved substantially. Yet over the past few decades, losses from hazardous weather have grown dramatically, and catastrophic weather disasters have occurred more frequently (4, 8, 9). Population and property at risk from extreme weather are increasing, and continued property development, coastal migration, and urbanization are expected to further increase societal vulnerability (4, 10–14).

Moreover, weather extremes have been changing, and anthropogenic climate change is projected to cause some types of extreme weather to further increase in frequency and magnitude and to affect new areas (6, 15, 16). Consequently, scientific studies, media reports, and public perception are increasingly connecting extreme weather events with anthropogenic climate change, and extreme weather is a growing concern for climate change science and policy (2, 3, 6, 7, 16). Extremes such as floods, droughts, and heat waves have even unfortunately been referred to as "useful catastrophes" (e.g., 17) that might motivate action on climate change.

Within the climate change community, extreme weather is of growing interest to physical scientists who are projecting changes in extremes as well as to social, environmental, and health scientists who are examining the impacts of changes and the potential for systems to adapt. The weather, natural hazards, and disaster communities have also built a large body of knowledge on extreme weather. Here, we discuss selected findings from these literatures and integrate knowledge across them, with an emphasis on understanding how to improve societal outcomes in the short and long term. The societal outcomes of extreme weather result from interactions among multiple components of physical and human systems, across spatial and temporal scales. Consequently, if the ultimate goal is to protect lives and reduce losses, then we must understand hydrometeorological aspects of weather extremes, the social and environmental conditions that make people vulnerable to extremes, and strategies for managing risk, as well as the interactions among them.

Although weather extremes and changes in extremes can be beneficial and they have important effects on the environment, here we focus primarily on reducing the harm they cause to human systems. We synthesize relevant knowledge on key physical science, social science, and policy aspects of extreme weather and add to it by examining how these aspects interact across multiple spatial scales and timescales to create or reduce harm. Much of the current work in this area focuses on macroscale issues, such as national- and international-level disaster impacts, risk management strategies, and climate change mitigation and adaptation. Because the impacts of and responses to extreme weather events often occur at the local (household and community) level, we emphasize interactions between weather, societal characteristics, and decisions at local scales, within the larger-scale context that shapes them.

The article is organized around key topics rather than types of extreme weather events, with important points illustrated using relevant examples from specific event types. From a physical science perspective, we discuss what weather extremes are, their hydrometeorological bases, and how they might change with projected anthropogenic climate change (Sections 2 and 3). [Because weather and climate are interconnected, the weather extremes discussed here include events sometimes referred to as "climate extremes" (e.g., 2) and "climatic hazards" (e.g., 18).] From a societal perspective, we discuss how extreme weather conditions affect society and the environment and also how social vulnerability (including exposure, sensitivity, and adaptive capacity) shapes the effects different people experience (Sections 2 and 4). Building on this knowledge and incorporating a policy perspective, we then discuss strategies for improving societal outcomes related to weather extremes, in general and in the context of climate change (Section 5). This includes the roles of natural hazard and disaster risk management, weather and climate predictions and warnings, climate projections, climate adaptation, and vulnerability reduction. Finally, we synthesize major issues and present recommendations for research to fill critical gaps in the knowledge needed to improve societal outcomes of extreme weather, particularly for more vulnerable populations.

Current discussion about weather extremes in scientific communities and policy contexts often focuses on climate change projection, mitigation, and adaptation. Yet every day, people make decisions that affect risk from extreme weather, whether the risk is influenced by anthropogenic climate change or not. Thus, we find that one cannot discuss strategies for adaptation to weather extremes in a changing climate without considering how people cope with weather extremes more generally. Predictions and longer-term projections of weather extremes can be useful in identifying and managing risk. However, such information is unavoidably uncertain, and gaps often exist between the production of scientific knowledge and its usability for decision making (19–21). To address these gaps, scientists are increasingly focusing on generating predictions and projections of weather extremes linked to decision makers' needs, including improved estimation and communication of uncertainty. But science and engineering cannot eliminate all losses, and expending resources on loss prevention involves trade-offs with other activities. Thus, if the goal is to improve societal outcomes, it is critical to reduce societal vulnerability to weather extremes, especially for more vulnerable populations. Doing so requires understanding the interactions underlying the specific extreme weather challenges experienced at local levels and then using that knowledge to help households and communities build resilience to those challenges within the context of the societal and climatic changes and other stressors they face. This includes improving our understanding of how to leverage local strengths and build adaptive capacity to provide flexibility in coping and adaptation decisions. Because of the nature of extreme events and human attitudes toward them, this in-depth contextual knowledge must be complemented with (*a*) work on how local choices interact with larger-scale drivers and policies as well as with (*b*) a broader view of how decisions that build resilience can be motivated.

Exposure: conditions of the natural and built environment that position a system to be affected by weather stressors

Sensitivity: the degree to which a system is affected by weather stressors

Adaptive capacity: the ability of a system to modify its features and behaviors to better manage existing and anticipated weather stressors

Climate projections: estimates of future climate usually derived from climate model simulations, using one or more scenarios of future greenhouse gases and other forcings

Coping: adjustments people make to deal with existing weather stressors

2. AN OVERVIEW OF WEATHER EXTREMES AND THEIR IMPACTS

Because extreme weather is a broad concept that is studied from multiple disciplinary perspectives, there is not agreement on one definition (3, 5). Some researchers define weather as extreme from a climatological perspective; examples include weather conditions that exceed a certain threshold (e.g., temperature below freezing) or are in the tails of the climatological distribution for a location (e.g., temperature above the 90th percentile) (2, 5, 22, 23). Others define weather as extreme from a societal perspective, as hazardous weather-related events that produce significant damage or disastrous outcomes (e.g., high-impact heat waves or storms) (9, 24). Yet these two approaches often overlap. For example, scientists often use information about societal impacts of weather to help select climatological measures of extremes (see Section 3, below) (2, 3, 25–27). And because typical weather is generally inside a population's "coping range," i.e., the range of conditions that people can deal with or recover from (28, 29), weather that has significant impacts is usually climatologically rare. To reflect these interrelated perspectives, we take a holistic approach, discussing extreme weather events as integrated physical-societal phenomena in their broader context.

Here we discuss weather conditions and weather-related events that are rare at a particular location and time or can cause significant impacts. Types of extreme weather include:

1. Temperature extremes, i.e., heat and cold;
2. Precipitation extremes, i.e., heavy precipitation and associated floods, anomalously low precipitation and associated drought; and
3. Storms and severe weather, i.e., tropical cyclones (including hurricanes and typhoons), strong thunderstorms, tornados, major winter storms, and other high-wind events.

Closely related hazards include landslides and wildfires. Some of these are extremes in weather variables, such as precipitation amount and high and low temperature, measured for a specified period of time and location. Others, such as tornados, tropical cyclones, and droughts, are phenomena that extend over an area in space and period of time (minutes to weeks or longer); these can generate extremes in weather variables as well as other hazards (2).

The impacts of a particular weather event depend on how the weather conditions interact with other components of physical and societal systems, mediated through vulnerability (see Section 4, below). Interactions between weather and impacts can be highly nonlinear, and the impacts of extreme weather can vary significantly across time, space, and populations. For example, hot temperatures affect crops differently depending on when they occur relative to the plants' stage of development (26). The temperature threshold for a heat wave is lower in a colder climate than a warmer one, and the human impacts of unusually high temperatures can be higher in colder climates because people tend to be more sensitive to heat and have less capacity to avoid harm (30–32). Yet even in very warm climates, unusually high temperatures do cause negative impacts, particularly for certain populations (31, 33, 34). Furthermore, extreme weather conditions can interact with the natural and built environment and social systems in complex ways that lead to very-high-impact extreme events, often referred to as disasters (11, 35–39).

Estimates of the magnitude of extreme weather impacts vary with the types of weather and impacts that are included, the data source, and the choice of temporal and spatial scale (4, 26, 40–44). Although data are often problematic or lacking, studies generally agree that the negative outcomes from extreme weather are significant and that economic losses have grown in recent years (2, 4, 8, 10, 14, 26, 45). The most frequently discussed extreme weather outcomes are deaths, injuries, and property damage (particularly insured losses). Yet these measures can underestimate or neglect other important impacts that are more difficult to quantify. For example, extreme weather can cause economic disruption; damage to infrastructure and agriculture; disruption of food and water supplies; and changes in species population, range, morphology, and behavior (2, 36, 38, 40, 46–49). It can also contribute to respiratory symptoms and other human health issues; stress, misery, and other mental health disorders; and land erosion, hazardous chemical pollution, and other environmental issues (18, 30, 36, 47). Furthermore, extreme weather can interact with societal, political, economic, and environmental systems in ways that lead to other types of impacts, such as hunger, food insecurity, and famine; stress on water resources; disease outbreaks; displaced populations; and disturbances in ecosystem structure and function (2, 18, 30, 38, 46, 47, 49). This can contribute to other long-term harm, such as poverty, malnutrition, loss of livelihood and culture, and desertification (18, 36, 38, 50).

These types of impacts demonstrate that extreme weather can have a huge human, social, and environmental cost that is poorly measured by direct economic impacts, especially for low-income populations (see Section 4, below). Extreme weather events can devastate lives and communities. In developing countries, they can also destroy the capital stock, infrastructure, and other resources needed by a country to achieve development goals, and they can divert resources away from development efforts (51, 52). For example, Hurricane Mitch in 1998 caused damage in Nicaragua and Honduras equivalent to the countries' combined Gross Domestic Product, setting development efforts back many years (36, 38, 53). The most vulnerable populations then become even more vulnerable to future extreme weather, as well as to other political and economic shocks.

Extreme weather can redistribute losses and gains among regions and individuals; for example, property losses create a need for materials and construction that can generate economic gains for others (40). Extreme weather can also be beneficial. For example, tropical cyclones and thunderstorms are an important source of precipitation in some areas (3, 26). Floods can replenish soil fertility, and wildfires and other weather extremes can play important roles in species breeding and ecosystem dynamics (3, 46). And, disastrous extreme weather events can provide "windows of opportunity" that help motivate people to make changes that reduce vulnerability and build longer-term resilience (although they often do not) (e.g., 54).

Extreme weather can affect anyone and everyone. Because one cannot predict or prepare for every possibility, no one is immune. Yet some countries, communities, and individuals are more vulnerable and thus tend to suffer more (see Section 4, below). The political and economic institutions required to prepare for, respond to, and recover from extreme weather often function less effectively in developing countries (53). Thus, although wealthy countries tend to have the highest (insured) property losses, it is in developing countries that extreme weather events most frequently have long-term devastating impacts on large numbers of people (43, 45, 51–53). However, events such as Hurricane Katrina in 2005 in the United States and the 2003 European heat waves illustrate that, even in wealthy countries, certain groups can experience devastating impacts from extreme weather (31, 39). As we discuss further in Section 4, vulnerability and risk can be distributed very unevenly at the national, regional, and community levels (33, 34, 55–57).

For scientific study of weather extremes and policy design, it is often useful to identify thresholds above which weather causes significant negative impacts (Section 3, below). Yet doing so can be challenging because of the multiple, nonlinear interactions that lead to harm (26, 58). As discussed above, social vulnerability is complex, and extreme weather impacts are often embedded in the unique geographic, political, historical, social, and cultural context of the affected area and population. Thus, thresholds for negative outcomes can vary significantly among countries, geographic regions, and population segments, as well as with the specific circumstances of the event (Section 4, below) (31, 32, 59). Consequently, although linking physical measures of extremes with those relevant to decision making is important (26), physical thresholds are only a first-order approximation of what weather conditions are likely to have significant impacts.

Natural modes of climate variability, such as the El Niño–Southern Oscillation, the Madden Julian Oscillation, and the North Atlantic Oscillation, can affect the probability and intensity of weather extremes, as can weather regimes and anomalies such as atmospheric blocks (e.g., 60–64, 64a). Other dynamical phenomena, such as Rossby wave trains, can generate spatial/temporal coherence and propagation in weather extremes (65, 66). Weather extremes can also create hydrological, environmental, and societal conditions that interact or influence subsequent events. For example, antecedent wet conditions contributed to the 1993 Mississippi Basin flood (67). During the 2010 heat wave in Russia, smoke from fires associated with the ongoing drought led to poor air quality, exacerbating adverse urban health conditions. And the impacts of Hurricane Katrina strongly influenced people's protective decisions when Hurricane Rita threatened the U.S. Gulf Coast one month later (68). Thus, although specific extreme weather events are frequently treated as distinct phenomena, they occur within a larger physical and societal context and are often interconnected in space and time.

3. CLIMATE CHANGE AND WEATHER EXTREMES

Changes in extreme weather are of significant interest because some of the most severe impacts of anthropogenic climate change may be experienced through changes in extremes (2, 12, 69). Anthropogenic climate change by itself does not cause extreme conditions, but it can make naturally occurring rare conditions more common or even more extreme. Climate change can affect weather extremes in several ways. From a statistical viewpoint, climate warming shifts the distribution of a quantity such as surface temperature to the right (**Figure 1**); this significantly increases the probability of extreme warm temperatures and decreases the probability of extreme cold temperatures. Thus, seemingly small increases of globally averaged surface temperatures are accompanied by relatively large increases in temperature extremes (3, 15, 25). The far ends of the distribution in **Figure 1** show that such a shift also generates more record-setting (unprecedented) daily maximum temperatures and fewer record-setting daily minimum temperatures. Climate change can also affect weather extremes by altering other aspects of the distribution, e.g., by increasing the variance (broadening the distribution, **Figure 1**) (3, 27, 69). Furthermore, changes in the base state circulation produced by increased greenhouse gases may alter teleconnection patterns associated with modes of climate variability such as the El Niño–Southern Oscillation, changing spatial and temporal patterns in weather extremes (Section 2) (e.g., 62, 64a).

The remainder of this section reviews selected recent research on projected changes in extreme weather with anthropogenic climate change, including examples of climate modeling results for the major types of extreme weather discussed in Section 2: temperature extremes, precipitation extremes, and storms. (For a more comprehensive review, see References 6 and 15.) As discussed in Section 2, above, one challenge of diagnosing and projecting changes in weather extremes is selecting measures, often defined using climatological or societal thresholds. To build credibility that a climate model can provide information about possible future changes, output from model simulations of the recent past can be compared with analyses of observed trends in weather extremes. To generate climate projections, the model is run into the future, using one or more scenarios of future increased greenhouse gases and other forcings, sometimes for an ensemble of initial conditions. The resulting model output is then analyzed for changes in future weather extremes using the selected measures. The dynamical processes underlying these changes can be examined to enhance credibility from a physical perspective. Results can also be compared across multiple models to provide further information about projected changes.

For cold temperatures, a common measure is a *frost day*, when the nighttime minimum temperature drops below freezing. Frost days are a threshold of interest because of their impacts on, e.g., growing season length, ranges of species and ecosystems, insect infestations, and snowmelt timing (important for water resources). Analyses of observations document a decrease in frost days in the United States over the second half of the twentieth century, with greater decreases over the western United States (70). Meehl et al. (71) found a similar trend and spatial pattern in a climate model simulation of the twentieth century that includes both natural and anthropogenic forcings, providing some credibility to the climate model. The same model run forward to 2100 with a scenario of increasing greenhouse gases projects this twentieth century pattern continuing, with decreased frost days in most locations but greater decreases over the western parts of the United States and other continents (71). In the model, the pattern can be attributed to changes in atmospheric circulation in the warmer climate, with an anomalous ridge of high pressure over western North American that leads to more warming in the west than the east (71).

Extremely hot temperatures are often discussed in terms of heat waves, which can be defined in many ways. Meehl & Tebaldi (27) studied possible future changes in heat waves using two definitions. The first definition, heat wave intensity, is measured as the hottest three-night average in a year, on the basis of human mortality in the 1995 Chicago heat wave (72). National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalyses indicate that, in the twentieth century, heat waves in the United States were most intense in the southeast and southwest and least intense in the northwest. Over Europe, heat waves were most intense in the Mediterranean region (27). A climate model simulation of the twentieth century that included natural and anthropogenic forcing shows a similar pattern (27), again building credibility for the model. In a scenario with increasing greenhouse gases, the climate model projects significant increases in heat wave intensity over most areas of the United States and Europe that already experience extreme heat events, as well as increases in regions that are currently less susceptible, such as the northwest United States (27). The second definition of heat waves includes measures of duration and number. Using this definition, the climate model also projects longer lasting and more frequent heat waves (27).

Analysis of the model output indicates that these projected changes in heat waves are related to changes in the atmospheric circulation in summer. On average in a future warmer climate, the model produces increased high pressure over most of the United States. When a naturally occurring high-pressure system that produces a heat wave occurs, it is superimposed on this average higher pressure. Together, this produces even more intense high pressure and more severe heat waves, which are attributable to increasing greenhouse gases (27, 73). These and other related results indicate a much greater probability in the future of record heat waves, such as the one that devastated western Europe in 2003 (74). Even if governments manage to achieve one of the currently proposed climate change mitigation targets, such as constraining average global warming to below 2°C, heat extremes could still increase significantly, causing substantial negative impacts (75).

As discussed above, anthropogenic climate change is expected to lead to more record high temperatures and fewer record low temperatures. An analysis of daily temperature observations over the United States shows that the ratio of record high to record low temperatures has increased over the past several decades (76). For every two record high temperatures, only one record low temperature is now set. A similar current observed two-to-one ratio of record highs to lows has been documented in Australia (77). Meehl et al. (76) found that a model simulation of twentieth century climate shows a trend similar to the observations. When the model is run into the future with a scenario of increasing greenhouse gases, this trend continues, projecting a ratio of record highs to lows of about 20 to 1 by midcentury, and 50 to 1 by the end of the twenty-first century (76). The climate model also projects an average warming of several degrees by the end of the century. However, even in this warmer world, record-setting extreme cold temperatures are still experienced, although far less frequently than record highs.

Measures of precipitation extremes include precipitation intensity (average precipitation amount per event) and dry days (days between precipitation events). Analyses of observations indicate that precipitation intensity has increased over the United States and several other regions in recent decades (6, 16). Physically, this occurs because warmer air can hold more moisture that is evaporated from the warming oceans. This moisture-laden air provides a greater moisture source for precipitation in storms, increasing precipitation amount when precipitation occurs. Climate models represent a similar process, and they project an increase in precipitation intensity almost everywhere in the world in a future warmer climate (**Figure 2**) (23). However, models also project a change in the character of daily precipitation, with an increase of consecutive dry days in the subtropics and lower midlatitudes, as well as a decrease of consecutive dry days in the higher midlatitudes (**Figure 2**). Combined, these precipitation changes produce decreased season-averaged precipitation in the subtropics and increased season-averaged precipitation at higher latitudes (78). This pattern of changes can be interpreted as an increased risk of drought in areas already prone to dry conditions, such as the southwest United States (79). The increased precipitation intensity can be interpreted as a greater risk of heavy precipitation events and, perhaps, of associated flooding (16).

Projecting changes in tropical cyclones, thunderstorms, and associated severe weather is difficult because, with current computing resources, it is not feasible to run the appropriate climate models at the high spatial resolution required to adequately simulate the storms' dynamics and their interactions with the larger-scale environment. Thus, modeling studies to date have had to rely either on relatively high-resolution global atmospheric models run with specified sea surface temperatures (i.e., not dynamically coupled to an interactive ocean model) (80) or on embedded high-resolution regional models (81). Detecting and attributing past changes in tropical cyclone activity also raise challenges (82). In spite of these limitations, current projections generally indicate that greenhouse warming will likely lead to fewer tropical cyclones overall, but the storms that do form will likely be more intense and produce higher rainfall rates (15, 16, 82). A few studies have also projected an increase in the frequency of meteorological conditions favorable for severe thunderstorm development (16, 83). These results should be interpreted, however, with the modeling limitations in mind.

Projections of changes in the frequency, intensity, and patterns of weather extremes, as in the examples just presented, suggest that anthropogenic climate change will only worsen many types of extreme weather conditions. As we discuss further in Section 5, below, this has raised concerns about reducing greenhouse gas emissions as well as adapting to reduce future extreme weather impacts. To aid decisions about mitigation options, new Earth System Model efforts are under way to provide improved projections of climate change, including information about extremes, beyond the mid-twenty-first century. For many adaptation decisions, information about regional- and local-scale changes in extremes is needed. To help meet this need, new work in decadal climate prediction is focusing on producing time-evolving statistics of regional climate change with better-quantified uncertainties to inform applications in various sectors and regions. Model outputs with finer spatial and temporal scales provide opportunities for integrated analysis of impacts and vulnerabilities at scales more relevant for adaptation decision making. However, because the impacts of extreme weather result from interactions among physical and human systems, it is important to consider social vulnerability with the same degree of importance that is devoted to understanding the physical aspects of weather and climate.

4. SOCIAL VULNERABILITY TO WEATHER EXTREMES: EXPOSURE, SENSITIVITY, AND ADAPTIVE CAPACITY

As discussed in Section 2, above, extreme weather events disproportionately affect certain people, and different people experience impacts from extreme weather at different thresholds. A growing body of recent research has elucidated how these differential impacts can largely be attributed to differences in social vulnerability. In this section, we describe key aspects of vulnerability to extreme weather and review recent literature on interactions between weather extremes and vulnerability. We also discuss current themes in vulnerability research, spanning across perspectives from natural hazard and disaster risk reduction to climate adaptation.

Vulnerability has been studied from multiple theoretical and disciplinary perspectives (20, 56, 58, 84–87). Although the specific nomenclature varies, the concept is fairly consistent: In general terms, vulnerability is the susceptibility of people or systems to damage or harm (88). Societal outcomes (or risk) are a product of natural phenomena (weather hazards or extreme weather conditions) interacting with social vulnerability. Vulnerability is complex, dynamic, and spatially and temporally variable. Over the last few decades, social vulnerability has evolved from a concept based primarily on response to the severity of a hazard to a much more comprehensive notion involving social capital, poverty, inequity, access to resources, and other social and political factors (11, 34, 56, 58, 85, 86, 89).

Following related recent work, we characterize vulnerability of human systems (e.g., households, communities, countries) to extreme weather as a function of three interrelated components: exposure (conditions of the natural and built environment that position a system to be affected by extreme weather conditions), sensitivity (the degree to which a system is affected by extreme weather conditions), and adaptive capacity (the ability or potential of a system to modify its features and behaviors to better cope with or adapt to existing and anticipated extreme weather conditions) (28, 29, 34, 58, 85, 86, 90). In the terminology we use here, adaptive capacity influences both coping (the adjustments people make to deal with existing weather extremes) and adaptation (the long-term or fundamental changes people make to systematically reduce potential harm or take advantage of opportunities from changing weather extremes; see Section 5, below). Coping and adaptation both influence vulnerability to and outcomes of weather extremes, as well as longer-term resilience. Specific use of the terms coping and adaptation varies, and the two concepts overlap; here, we use both terms to incorporate the perspectives of multiple literatures on how people do or could manage weather extremes. Vulnerability is also influenced by drivers, which are factors that shape the characteristics of the system; examples include climate change, public policies, and other macroscale environmental, socioeconomic, and political stressors. Although several frameworks defining these concepts and their interrelationships have been proposed (e.g., 28, 29, 34, 85, 87, 91), definitions vary, and the concepts' detailed attributes and the dynamics among them are not yet well understood (29, 58). In this review, we use the general framework presented in **Figure 3**; the framework was adapted from previous work on urban vulnerability to extreme heat (34).

Exposure to weather extremes is related to the physical characteristics of a location, including climate, features of the landscape and the built environment (including structural hazard mitigation programs), land use, and urbanization patterns. Along with variation in these characteristics, exposure to weather extremes varies spatially on global to local scales. For extreme heat, for example, people living in large cities have greater exposure than others living in similar climate zones, owing to urban heat island effects (33, 92). Heat exposure also varies significantly within cities because of variations in land surface characteristics (33, 93, 94). Tropical cyclones provide another example: Certain areas of the U.S. Atlantic and Gulf coasts are more likely to experience hurricanes (95), and exposure to associated hazards, such as coastal flooding caused by storm surge, varies with the local coastline, topography, and hazard mitigation measures. Exposure to weather extremes at a location also varies with time, seasonally, and with weather regimes and modes of climate variability (Section 2, above).

Sensitivity to weather extremes is influenced by demographic and socioeconomic factors, including age, material constraints, and health conditions (34). A number of empirical studies

Hazard mitigation: actions taken prior to hazardous weather events to reduce long-term risks to people and property have identified sensitivities of affected populations by investigating the relationships between extreme weather conditions and adverse outcomes. For example, studies of extreme heat indicate that individuals who are elderly, very young, obese, poor, mentally ill, and socially isolated as well as those who have certain health conditions, lack air-conditioning, and work outdoors are disproportionately affected (34, 96, 97). More generally, characteristics such as age, race or ethnicity, socioeconomic status, housing, and gender have been found to significantly influence individuals' outcomes from a variety of weather extremes (57, 98).

Adaptive capacity reflects a population's potential to reduce harm from current and future extreme weather, in a changing environment. Adaptive capacity is context specific and dynamic; it is influenced by factors such as availability of information and technology; access to material, economic, and human resources; institutional capabilities; and knowledge, attitudes, practices, and beliefs. Also important are social capital, including safety nets and social networks that connect individuals to community resources, and social learning (28, 29, 34, 99–101). For example, several recent studies have found that community-based programs strengthen social resilience of communities and thus should be integrated into efforts to reduce risk from weather extremes and to adapt to climate change (53, 90, 101–103). This highlights the importance of understanding what determines adaptive capacity and how to enhance it, especially at household and community levels, where coping and adaptive behavior is most prominent.

Because of the spatially variable and dynamic nature of its components, projecting changes in vulnerability is difficult. However, here we summarize some general expected trends. Human exposure to weather extremes is expected to increase over the next few decades owing to the influence of several macroscale drivers, including climate change (Section 3), population growth, urbanization, coastal development, and migration (12). Demographic projections indicate that the numbers of certain sensitive populations are also expected to increase, including the elderly, especially those living alone (104), and children living in vulnerable urban settlements (105). Trends in gender and poverty may also influence future sensitivity. Adaptive capacity will also be influenced by trends in macroscale drivers, such as governance, civil and political rights, inequality, and literacy (28, 29, 106). However, it is the realization of these macroscale drivers of adaptive capacity at the local level that is most important for characterizing vulnerability (28).

Because of the many interrelated factors that contribute to vulnerability and the variability across spatial and temporal scales, measuring vulnerability and its components can be challenging (29, 55, 58, 91, 107). Some studies use adverse outcomes (i.e., number of people killed or affected or economic losses) from historic extreme weather events as indicators of risk or measures of vulnerability (e.g., 43, 45, 58, 106). Doing so facilitates broad comparisons, but it has several limitations. Using economic losses as a measure places significantly less weight on losses in low-income communities and countries (43, 57). Higher-income individuals and groups also have greater access to material resources and insurance that helps them rebuild livelihoods, property, and infrastructure; thus, greater economic losses do not always equate to greater long-term impacts or vulnerability (56). Another broad measure of outcomes is weather-related human mortality (106), but deaths can be underreported and attributing them raises challenges (31, 32, 41). In addition, existing databases on impacts of weather extremes include only certain types of events and losses and have other limitations and biases (40, 42, 44, 45). More generally, economic losses, mortality, and other readily available measures often do not adequately account for many of the other important impacts discussed in Section 2, above (26). Other studies use risk or vulnerability indices constructed from proxies or contributing factors (e.g., 43, 45, 56–58, 107, 108). Although such indices are useful, it is important not to neglect contributors to vulnerability that are more difficult to quantify (55). Most of these studies have also been conducted using aggregated population-statistics measures or census-level demographic data that do not fully represent the attitudes and behaviors underlying how individuals and communities cope and adapt. Lack of data at the individual and local levels makes it challenging to reliably link context-specific attributes of human systems to the outcomes of extreme weather events, and thus to better understand social vulnerability (58, 107).

Although people's attitudes and behaviors toward extreme weather events have been studied empirically in a variety of situations (e.g., 109–113; M. Hayden, H. Brenkert-Smith, O. Wilhelmi, submitted to *Weather*, *Climate*, *and Society*), how these influence vulnerability across contexts is not well understood. Thus, an important area of research is improving our understanding of how individual and collective attitudes and decisions interact with vulnerability. For example, experience with past events, at the individual and community levels, can reduce vulnerability by enhancing hazard mitigation and preparedness, or it can increase vulnerability when consecutive events lower coping ability. Experience and hazard mitigation also affect risk perception, which influences individuals' preparedness and response decisions (90, 109, 112, 114–116) and thus is an important element of adaptive capacity. A related need is improving understanding of interactions among individual and community adaptive capacity, larger-scale attitudes and policies, and social learning. Building an understanding of adaptive capacity is a key gap because exposure and sensitivity are easier to measure at an aggregated level, whereas adaptive capacity is often nuanced and best examined qualitatively or at the individual level. To fill these gaps, indicators of individual-level attitudes and behaviors and local-level adaptive capacity must be incorporated into work on vulnerability to weather extremes (34, 117). Another important issue in vulnerability research is understanding and assessing vulnerability to multiple interacting stressors, including extreme weather (56, 58, 118).

Work on social vulnerability to weather extremes also raises environmental justice and equity issues (11, 58, 86, 119). Certain populations experience a disproportionately large burden of impacts from weather extremes. For example, poorer and minority populations are more likely both to live in urban neighborhoods that are more exposed to heat extremes and to have lower coping capacity (33). Low-lying areas in coastal cities have high exposure to multiple types of extreme weather events; within these areas, poor populations living in substandard housing are particularly vulnerable, especially in developing countries (120). Some socioeconomically disadvantaged populations are more vulnerable not only to weather extremes, but also to other environmental hazards, such as toxic waste or air pollution (121). Because of the greater long-term harm these populations generally experience (Section 2), addressing their vulnerability to weather extremes and other hazards is particularly important. Yet because different people have different definitions of harm and acceptable risk, it is important for researchers and practitioners not to impose definitions of vulnerability on populations, especially groups that have a history of being disempowered or marginalized (58, 84, 122). Consequently, assessing and reducing vulnerability to weather extremes require empirical studies and participatory efforts (see Section 5) (20, 29, 58, 122a).

5. COPING AND ADAPTATION: STRATEGIES AND OPPORTUNITIES FOR IMPROVING SOCIETAL OUTCOMES OF EXTREME WEATHER

As civilizations have evolved, humans have developed a variety of strategies for managing the risks associated with extreme weather events, at scales ranging from individuals and households to communities to international organizations. This section first reviews strategies for reducing risk and harm from extreme weather. Despite considerable knowledge about these interventions, they are currently often underused (123, 124), and societal and climatic change create additional challenges. Given this context, we argue that such interventions are necessary but not sufficient to improve outcomes; attention must also be paid to understanding and addressing the root causes of vulnerability and harm. We then present key recommendations for improving outcomes from weather extremes, including improving the societal and policy conditions that contribute to vulnerability and harm; enhancing local flexibility and adaptive capacity; and implementing participatory, community-based programs and case studies.

From a natural hazards perspective, one way that people cope with extreme weather is hazard mitigation, i.e., actions taken prior to events to reduce long-term risks to people and property (98, 125). Structural mitigation includes protective engineering measures (such as levees, seawalls, dams, and flood control) and construction or modification of buildings and critical infrastructure to better withstand weather hazards. Building codes, if well enforced, and retrofitting programs can help motivate weather-resistant construction. A related technological measure is adoption of air-conditioning to mitigate extreme heat. Nonstructural mitigation includes land-use planning, which can reduce risks by, e.g., regulating property development in at-risk areas, conserving or restoring features of the natural environment that provide protection from storms and floods, or modifying urban areas to reduce urban heat island effects. People have also attempted to reduce the likelihood of extreme weather conditions through weather modification (e.g., cloud seeding, storm modification), but so far most of such efforts are infeasible, controversial, or not yet scientifically proven successful (126).

Because it is not possible to prevent all extreme weather events or their impacts, strategies are also needed to reduce harm when events occur. Warning systems can help notify people when an event threatens, so they can take protective action. To be effective, warning systems involve more than timely detection or prediction of events and alert and notification technology; they must also communicate warning messages in ways that promote effective responses from intended audiences (35). Once an event is in progress, emergency response activities help meet the immediate safety, security, and health needs of affected populations. Postevent recovery includes activities to replace or repair damaged property and infrastructure and to reestablish household and community functions; recovery is often a long-term process during which damaged systems evolve to a revised state (35, 98). In this way, recovery also provides an opportunity to mitigate and prepare for future events (or not), affecting future vulnerability and ability to cope and adapt. People's capacity to take protective action, respond, and recover can be improved through preparedness activities to address anticipated problems, such as evacuation and emergency planning and hazard education (35, 98). Insurance (when available and purchased) and postdisaster financial aid can help people recoup losses and rebuild. Traditional coping strategies, such as adjusting agricultural cropping practices to manage drought and flood risk, are also important in many communities, as are related strategies such as water storage and irrigation (84, 127). Another resource that people often use to help prepare for and recover from extreme weather is family and community support networks (90, 99, 101).

Observed and projected changes in weather extremes (Section 3, above) have generated substantial discussion about ways to mitigate climate change by reducing emissions and concentrations of carbon dioxide and other greenhouse gases. Despite these concerns, levels of greenhouse gases continue to rise. Moreover, because of inertia in the climate system, society has likely already committed to a certain level of anthropogenic climate change: Even if greenhouse gas emissions were drastically reduced in the near future—a challenging proposition—impacts on the climate system and extreme weather would be expected to continue through the twenty-first century and beyond (128, 129). Consequently, adaptation to climate change is rising in importance. Space limitations preclude us from discussing climate change adaptation in depth, so here we focus on the interactions between extreme weather and climate change adaptation (for more comprehensive discussion of adaptation, see, e.g., References 12, 99, and the references therein).

As discussed in Section 3 above, some of the most significant impacts of anthropogenic climate change may result from changes in extremes. Moreover, people typically experience and respond to shorter-term hazards rather than long-term trends (55). Thus, as noted by Burton (10) in his discussion of adjustments to current climate variability and to climate change: "From the perspective of the person on the ground, these distinctions are not so important. . .it is both the risk of extreme events now and the possible longer run change in their frequency that is of concern" (p. 195; see also Reference 51). Stated another way, from a practical perspective, coping and adaptation overlap significantly. In many cases, adaptation to reduce harm from changes in weather extremes will occur through similar adjustments to those for coping with weather hazards more generally, which are discussed above (124). Because these strategies are already underutilized, improving management of current extreme weather risks is one important strategy for adapting to climate change (10, 51).

Yet adaptation to anthropogenic climate changes in extreme weather does raise special challenges beyond those experienced in coping with current extremes. Some areas are projected to experience new types of weather extremes or extremes of much greater magnitude than current coping strategies can manage (Section 3, above). For example, improving management of water resources or modifying crops may not allow a system to maintain its current state in the face of significant precipitation decreases and severe, long-term drought (10, 29). Thus, adaptation to climate change may require system transformations as well as incremental adjustments (119). Some populations may need to permanently migrate or change their livelihoods or way of life. Planned adaptation also requires looking far into an uncertain future. As difficult as it is for people to attend to current risks of weather extremes, it is even more difficult for them to respond to potential future changes in risk. Furthermore, adjustments to try to reduce harm, even if they appear successful in the short term, can increase vulnerability over the longer term or for other populations and thus lead to what is sometimes referred to as maladaptation, as discussed further below (10, 119). Thus, effective long-term coping and adaptation will involve not only making adjustments for specific extreme weather risks, but also applying a broader system resilience framework (119).

Many coping and adaptation strategies use scientific information about weather extremes, including climate projections, estimates of long-term event risk, seasonal-to-interannual climate forecasts, and weather forecasts. Such scientific information is valuable; without it, many of these strategies would be much less effective (or even impossible). Yet this scientific information is unavoidably uncertain because of fundamental challenges in estimating long-term risk and projecting future weather and climate, exacerbated by the difficulties associated with rare events (15, 16, 19, 130–132). In addition, as one moves from physical aspects of weather extremes to interactions with human systems, uncertainty cascades and grows (32). This uncertainty can create challenges for decisions about management of extreme weather risks (130), and in some cases, it can contribute to decisions that increase rather than reduce harm (131–133).

Moreover, structural measures and regulation of development in at-risk areas are designed to provide protection only up to a certain level of event; worse events can and do occur (134, 135). Structural measures can also transfer risk in the long term by limiting damage from small events but increasing population and property at risk when a larger event occurs (114, 136, 137). Choosing a higher level of protection involves trade-offs between benefits and costs; for example, restricting land development limits some types of beneficial use. Furthermore, structural measures are imperfect: They sometimes fail below design levels, as the levee failures after Hurricane Katrina and many other floods have illustrated (39, 136, 137).

The challenges of scientific uncertainty, combined with the fact that structural mitigation and other interventions cannot eliminate all risk of harm, highlight the importance of hedging by adopting multiple strategies for managing extreme weather risks. The growing emphasis on advance hazard mitigation and preparedness along with postevent management, and on adaptation along with climate change mitigation, has been an important step in this direction. But current efforts still often emphasize engineering and technological interventions, such as flood protection, infrastructure modifications, and access to air-conditioning (34, 136, 138). Not only do such interventions have limitations, but they also are often expensive and require technological and human resources unavailable in certain areas (99). Harm from extreme weather events results from interactions between hydrometeorological conditions and human systems. Thus, it is critical to focus not only on understanding, predicting, and reducing the risk of extreme weather conditions, but also on addressing the societal conditions that contribute to vulnerability and harm.

Reducing vulnerability to extreme weather can be framed as a human rights issue, according to Hooke as cited in Reference 139 (see also Reference 119). Consequently, it is important to employ not only interventions focused specifically on extreme weather risks, but also on what are sometimes referred to as no regrets, win-win, or pro-poor interventions, such as asset enhancement and protection, empowerment, and livelihood support (38, 51, 55, 138). Such interventions reduce sensitivity to and improve capacity to cope with and adapt to weather extremes while promoting other sustainable development goals, such as reducing poverty, inequality, extreme hunger, and environmental degradation and enhancing health and sustainable livelihoods (51). Furthermore, proactive management of extreme weather and climate risks must be integrated into development programs and planning, so that extreme weather does not nullify development investments and so that development interventions reduce rather than contribute to extreme weather risks (38, 51, 53).

Another recommendation is facilitating flexibility and creativity in coping and adaptation at the local level, so that decision makers can revise strategies as specific events and the physical and societal environment in which they occur evolves. This is important because extreme weather events are rare for a population and often involve complex interactions between natural and human systems specific to a location (Section 2, above). Consequently, events can evolve in ways that are difficult to anticipate, leading to surprises that can create challenges for decision making (119, 135, 140). The likelihood for surprises is further exacerbated by climatic and societal changes, as well as by the complexities of interactions among multiple stressors. A key strategy for promoting flexibility is enhancing adaptive capacity. Enhancing adaptive capacity includes addressing contributing factors, such as risk perceptions, access to resources, social learning, and social networks, as well as attending to the interactions among them (Section 4, above) (29, 90). Building adaptive capacity for vulnerable populations in developing countries is especially important because they generally suffer the most long-term harm (Section 2). However, extreme weather also continues to cause substantial harm for certain populations in developed countries, despite significant overall availability of resources, knowledge, and technology (Section 2) (99). In these situations, there may be a "weakest link" in adaptive capacity (141), such as institutional factors, attitudes toward risk, or social safety nets, that is most important to identify and address. More generally, enhancing flexibility and adaptive capacity is needed not only so that specific actors can cope and adapt to specific extreme weather risks, but also so that populations and systems can build long-term resilience to extreme weather and other stressors in an ever-changing environment (119).

Our recommendations are consistent with the growing body of work focusing on the importance of adaptive capacity, especially in the context of global environmental change (28, 29, 90, 99, 101, 119). Yet because of the dynamic, interactive, context-specific nature of adaptive capacity, many knowledge gaps remain. The causes of harm from weather extremes typically depend on the specific physical-human system interactions at a local level, which is also where many hazard risk management and climate adaptation measures are undertaken. Furthermore, views of harm and acceptable risk vary among and within populations (99, 109, 142). Thus, bottom-up efforts are needed that use participatory, community-based mechanisms to understand and address local vulnerability and enhance local adaptive capacity (20, 29, 34, 53, 58, 122, 122a). From a research perspective, these in-depth, place- and people-based case studies are needed to assess vulnerability and link impacts to causality at the household and community levels, using comparable research frameworks where possible (55, 85, 107, 143). Such studies typically involve stakeholders and apply a flexible research framework, often integrating quantitative and qualitative approaches and data (e.g., 20, 33, 34, 55, 122a, 144). From a practical perspective, such efforts allow individuals, households, community organizations, and others to define what harm and risk means for them and what coping and adaptation strategies are most appropriate in the context of the multiple stresses they face; doing so empowers them and obtains their participation in and commitment to proposed solutions. Bottom-up efforts also include incorporating local knowledge and traditional coping and adaptation practices, which can provide valuable approaches grounded in the local context (84, 122, 127). Such efforts further facilitate the strong, fluid social networks and community programs that help reduce harm from weather extremes and build flexible, adaptive, resilient populations (101, 114, 119, 145).

Over time, building understanding in a number of comparable case studies can help build broader lessons across contexts. Top-down (regional, national, and international) efforts are also important to fill gaps left by community-based efforts and help bottom-up efforts succeed (53, 137, 138, 146). Larger-scale conditions and programs have important influences on local adaptive capacity, coping, and adaptation (Section 4, above). Furthermore, people tend to underestimate the likelihood of low-probability events, to be myopic when making protective decisions, and to be overly optimistic that a disaster will not happen to them (10, 146, 147). Hazard mitigation can lead people to perceive less risk from extreme weather, lowering their adoption of other coping and adaptation measures and thus increasing their vulnerability in other ways (90, 114). Local governments and public officials also have difficulties in adopting and enforcing policies to manage risk owing to these same attitudes as well as political factors (35, 137, 148). To overcome these limitations, facilitation and sound policies are needed from larger-scale governmental and nongovernmental organizations that have a broader public-good perspective (135, 137, 146).

6. CONCLUSIONS

Over the past few decades, humans have expended substantial effort on understanding extreme weather, predicting it, and preventing its negative outcomes. Yet losses continue to mount; our knowledge and investments do not appear to be reducing harm as efficiently as they might (123). This is in part because the societal impacts of extreme weather are created through complex interactions among the natural and built environment and social systems, across spatial scales and timescales. The unique dynamics in any given context make it challenging to project risk, to anticipate how specific events will unfold, and to learn and apply lessons across contexts. These challenges are exacerbated by climatic and societal change. In addition, efforts to manage extreme weather risks face many barriers, including limitations in resources, institutional capabilities, and human attitudes and behaviors toward risk.

But the situation is not all bleak. Economic growth and development increase population and property at risk, but they also enhance the resources, knowledge, and technology available for improving outcomes. Furthermore, the threat of climate change has brought a global focus to the suffering from extreme weather that is often experienced locally and disappears quickly from news headlines. This focus provides new opportunities for scientists and decision makers to learn how to improve societal outcomes from weather extremes and new motivation to apply that knowledge. Climate change has also helped bring issues such as inequality, differential social vulnerability, and adaptive capacity forward on research and policy agendas. Addressing these issues is critical not only for reducing harm from extreme weather and climate change, but also for alleviating other pressing societal concerns, such as extreme poverty, food security, and sustainable livelihoods.

How extreme weather events are framed influences scientific studies and policy solutions. In this article, we review key aspects of physical and human system contributions to harm from extreme weather along with their interactions. We emphasize causality and solutions at the local scale, where weather extremes and social vulnerability typically interact and many coping and adaptation actions are taken, within the larger-scale climate and policy context that shapes them. Because extreme weather interconnects with a broad set of issues, the relevant literature is rapidly growing and diverse. A range of expertise is needed to synthesize information from the large quantity of domain-specific literature. Scientists interested in building understanding and practitioners interested in implementing solutions must identify a piece of the problem to address. By providing an integrated perspective, we seek to help scientists and practitioners understand and place their work in a larger context.

Humans have always had to cope with and adapt to the environment, including weather extremes. But the strategies people have developed for managing extreme weather risk have limitations, especially given scientific uncertainty, and humans have multiple priorities to balance. Thus, it is neither practical nor possible to eliminate all suffering from weather extremes. But it is also not permissible, from an ethical or human rights perspective, to accept the current situation. Moreover, climate change and societal trends are expected to worsen the impacts of extreme weather. Adaptation to climate change that seeks to maintain the status quo is insufficient because it leaves many people highly vulnerable and at growing risk. What, then, are the key opportunities and critical knowledge gaps for improving outcomes from weather extremes, both in general and in the face of anticipated climatic and societal changes?

One recommendation is to adopt multiple strategies for coping with and adapting to extreme weather risk, developing and selecting strategies that are most appropriate for the specific situation. This includes a mix of technological and nontechnological interventions as well as traditional measures. At the same time, we must also emphasize broad reduction of baseline vulnerability, especially the societal conditions that contribute to the disproportionate harm experienced by some people. Another recommendation is enhancing adaptive capacity to facilitate flexibility and creativity in coping and adaptation. Scientists and decision makers often consider improved knowledge and information as a tool for narrowing decision spaces. However, current knowledge about the risks of anthropogenic climate change brings even greater uncertainty for future extreme weather, meaning that even more flexibility and innovative capacity are needed to provide a buffer against risk and to build system resilience. Enhancing adaptive capacity includes addressing larger-scale determinants and drivers as well as context-specific contributors, such as social networks and social learning.

Predictions of extreme weather and projections of changes in extreme weather can help people anticipate, prepare for, and reduce risk associated with future extreme weather events. However, to help these predictions and projections be usable, the scientific information must be linked to decision-making needs (21). This includes connecting physical science measures of extremes to information that can be used by decision makers (26). One way to do so is to predict weather extremes and project changes in terms of thresholds that have societal impacts. This requires research to identify the thresholds above which extreme weather causes harm, across locations and populations. Given the complex nature of vulnerability, however, different thresholds may be needed for different populations. Linking science to decisions also involves providing information at temporal and spatial scales appropriate for the decision context, often at the regional or local level. For climate change mitigation and long-term adaptation decisions, this means improved global and regional projections, including meaningful error bars to provide measures of reliability. For shorter-term adaptation decisions, a current priority is decadal climate modeling. For protective decisions when hazardous weather threatens, a priority is integrating socioeconomic considerations into weather prediction efforts, including developing systems that explicitly predict weather impacts along with weather conditions (149). Across these areas, it is important to improve estimates of predictive uncertainty and to learn to communicate uncertainty in ways that provide value for decision making (6, 131, 150). More generally, creating ongoing, iterative relationships among users and producers of knowledge aids in producing usable science (19, 21).

Extremes, risk, vulnerability, and harm are relative terms. To assess vulnerability and risk across populations, metrics for measuring societal outcomes from weather extreme must go beyond economic losses. When one includes societal considerations, it becomes difficult to systematically analyze weather extremes across contexts because views of harm and acceptable risk vary widely. Until we have a clear, detailed understanding of causality, it is difficult to know how to reduce vulnerability and harm. Thus, improving outcomes requires understanding the specific interactions contributing to the risk of harm in specific situations, now and in the future, and the most appropriate coping and adaptation strategies for each situation given local values, resources, barriers, and constraints. To do so, participatory, community-based programs are needed along with locally oriented empirical case studies, using similar research frameworks when possible. Although each context is unique, a large body of locally oriented work allows synthesis of larger lessons, learning from successes, failures, similarities, and differences across contexts. These local programs must be complemented by work at the regional, national, and international scales to facilitate household and community efforts, fill gaps, and change the larger-scale conditions that contribute to harm. The long-term goal is not to become disaster resistant or to eliminate risk but to become disaster resilient and to work toward sustainability given a population's other needs, goals, and stresses. This includes expanding our focus from trying to prevent, control, or resist extreme weather events to a broader systems resilience framing in which we learn how to live with an ever-changing, sometimes risky environment.

SUMMARY POINTS

1. Extreme weather events and their societal impacts occur through complex interactions between physical and human systems.
2. The societal impacts of extreme weather and the interactions that cause them are often focused at the local level, as are many coping and adaptation strategies.

3. Despite the local nature of many of their impacts, extreme weather events are interconnected in space and time and occur within a larger physical, societal, and policy context.
4. Anthropogenic climate change is projected to increase the likelihood and/or magnitude of several types of damaging weather extremes, and some of the most severe impacts of anthropogenic climate change may be experienced through changes in extremes.
5. Susceptibility to harm from weather extremes is denoted by social vulnerability, which is dynamic, varies widely across and within populations, and can be conceptualized in terms of three interrelated components: exposure, sensitivity, and adaptive capacity.
6. Because of the substantial losses from extreme weather events and the anticipated continued growth in losses, especially among more vulnerable populations, it is important to reduce baseline vulnerability to extreme weather as well as vulnerability in the context of climate change.
7. Given the limitations of specific interventions to reduce harm, improving societal outcomes of weather extremes requires adopting multiple coping and adaptation strategies. Especially important is enhancing adaptive capacity and flexibility in the face of uncertainty.
8. Community-based, participatory programs and empirical case studies are needed to identify root causes of vulnerability, risk, and harm at the household and community levels and to understand how to best target vulnerability reduction efforts in specific contexts, given local views, capabilities, and barriers. These must be complemented by larger-scale efforts to fill gaps in local programs and help them succeed.

FUTURE ISSUES

1. What are the key barriers to coping with and adapting to extreme weather in different contexts, and how can those barriers best be overcome to improve societal outcomes and build resilience in the face of societal and environmental changes?
2. What are the most important contributors to adaptive capacity in specific contexts, and how can local adaptive capacity and flexibility in decision making be enhanced?
3. What are the thresholds above which different types of extreme weather cause harm across locations and populations? When can thresholds be generalized across contexts, and when must different thresholds be used for different locations or populations?
4. How do individual attitudes and behaviors, community and larger-scale policies, and influences on adaptive capacity (such as social networks and social learning) interact to contribute to social vulnerability?
5. How can knowledge across empirical case studies of vulnerability and extreme weather be linked to build more generalizable knowledge across contexts?
6. How can new Earth System Model projections, decadal climate predictions, and weather impact predictions be designed to provide information (including uncertainty estimates) that is more usable by decision makers in strategies for mitigating and adapting to climate change and coping with extreme weather?

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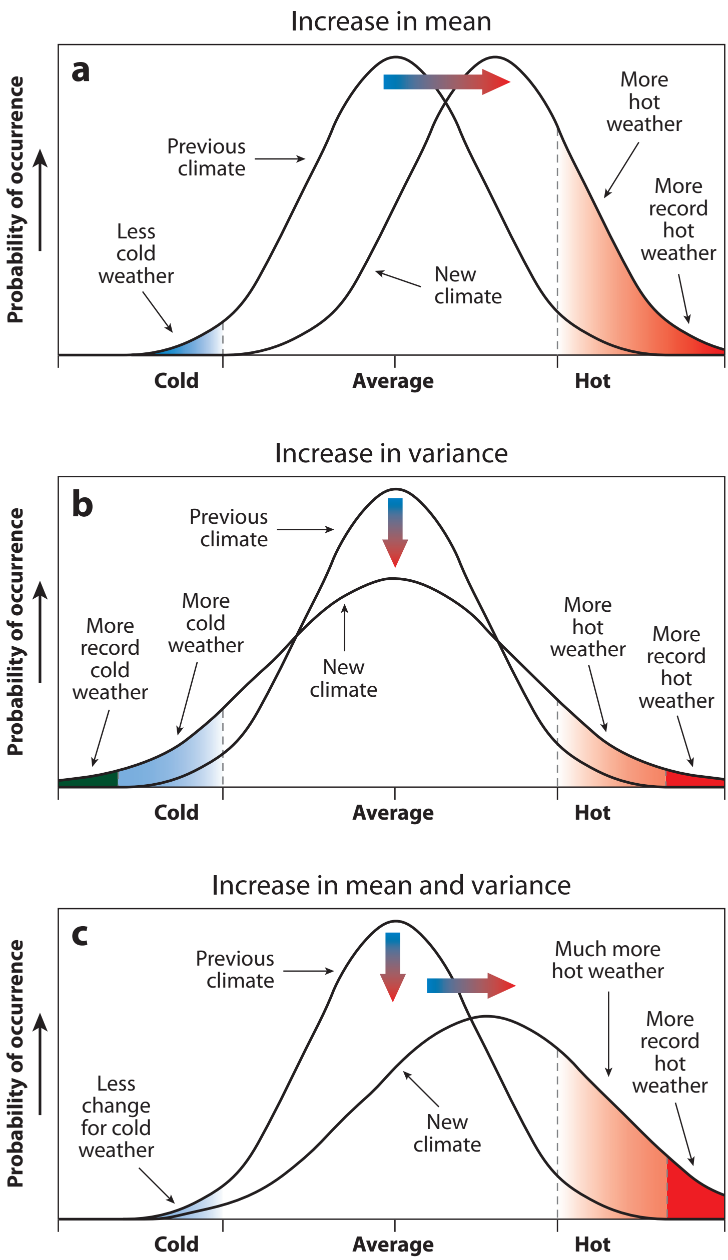

Figure 1

Schematic depicting different ways that changes in climatological probability distributions can influence weather extremes. Figure modified from Reference 3; see also Reference 10.

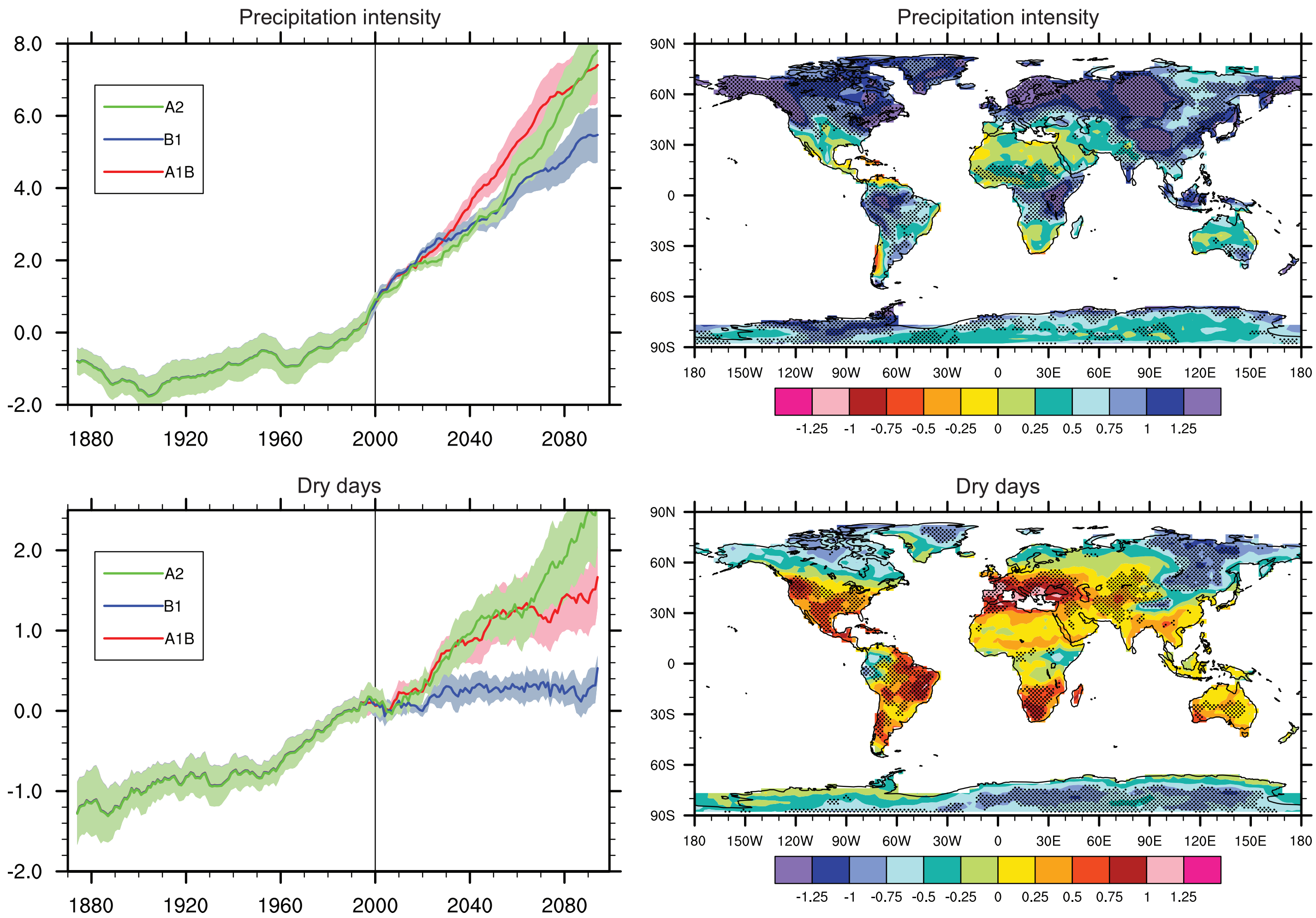

Figure 2

Projected changes in precipitation intensity (*top panels*), index = annual total precipitation (mm) divided by the number of wet days, and dry days (*bottom panels*), index = maximum number of consecutive dry days, averaged over a multimodel ensemble, as described in detail in Reference 23. (*Left panels*) Time series, smoothed by a 10-year running mean, with shading representing intermodel variability (measured by one standard deviation of the ensemble mean). For the twenty-first century, projections are depicted for three Special Report on Emissions Scenarios (A2, B1, A1B). (*Right panels*) Spatial patterns of changes under the A1B scenario, depicted as differences for the end of the twenty-first century compared to the end of the twentieth century, as described in detail in Reference 23. Figure modified from figures 2 and 3 in Tebaldi C, Arblaster JM, Hayhoe K, Meehl GA, 2006. Going to the extremes: an intercomparison of model-simulated historical and future changes in extreme events. *Clim. Change* 79:185–211 with kind permission from Springer Science + Business Media B.V. (copyright Springer 2006).

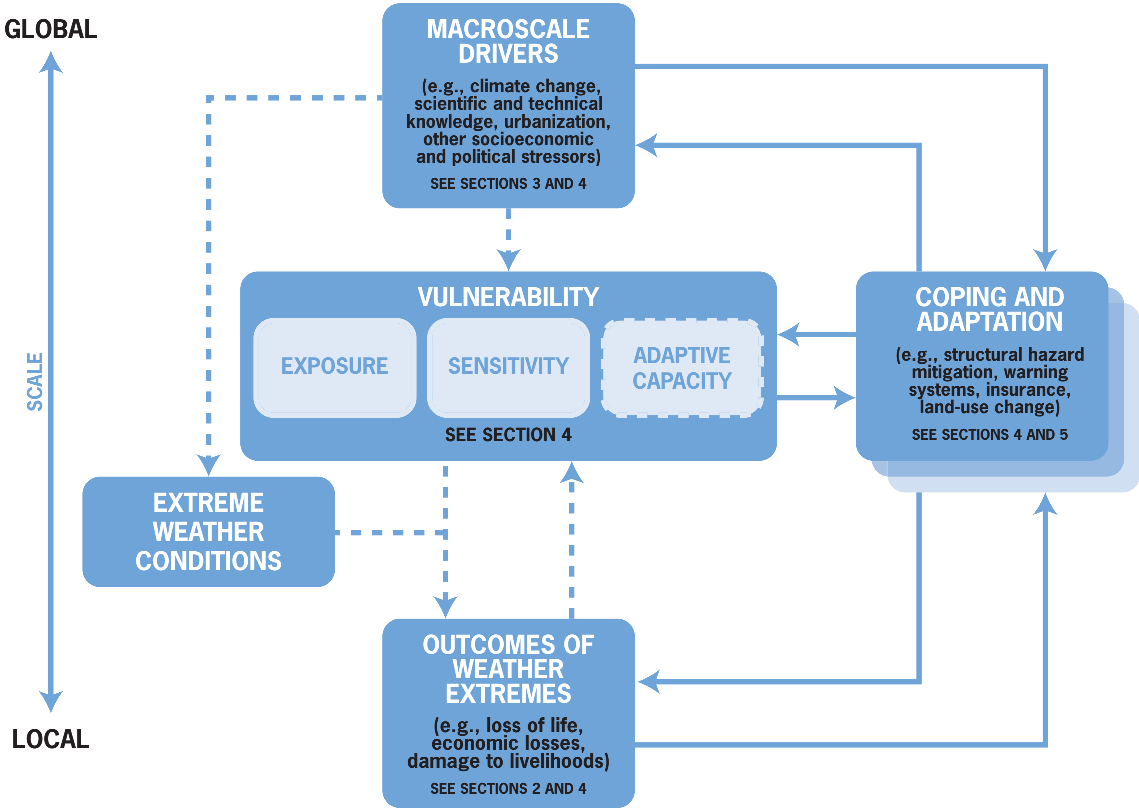

Figure 3

Schematic representing the general interactions and feedbacks among factors affecting the outcomes from weather extremes. The factors are defined and discussed in the sections noted in the figure. The primary relationships are discussed in the beginning of Section 4. Over the long term, vulnerability is also influenced by the outcomes from previous weather extremes, and coping and adaptation can influence macroscale drivers. Scientific information, including weather and climate predictions and projections, is influenced by macroscale drivers, influences coping and adaptation measures, and interacts with the other factors. The dotted arrows and boxes indicate relationships or concepts for which knowledge or data are lacking, uncertainty is high, or key issues need to be addressed. The multiple boxes in coping and adaptation represent the need for diverse strategies, flexibility, and possible mid-course adjustments given uncertainty. The scale axis, although simplified, represents the typical spatial scales at which macroscale drivers, extreme weather conditions, and outcomes occur. Although one can consider vulnerability and implement coping and adaptation measures across a range of scales, in this article we emphasize them at the local scale.