

The Potential Impacts of Climate Variability and Change on Health Impacts of Extreme Weather Events in the United States

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Extreme weather events such as precipitation extremes and severe storms cause hundreds of deaths and injuries annually in the United States. Climate change may alter the frequency, timing, intensity, and duration of these events. Increases in heavy precipitation have occurred over the past century. Future climate scenarios show likely increases in the frequency of extreme precipitation events, including precipitation during hurricanes, raising the risk of floods. Frequencies of tornadoes and hurricanes cannot reliably be projected. Injury and death are the direct health impacts most often associated with natural disasters. Secondary effects, mediated by changes in ecologic systems and public health infrastructure, also occur. The health impacts of extreme weather events hinge on the vulnerabilities and recovery capacities of the natural environment and the local population. Relevant variables include building codes, warning systems, disaster policies, evacuation plans, and relief efforts. There are many federal, state, and local government agencies and nongovernmental organizations involved in planning for and responding to natural disasters in the United States. Future research on health impacts of extreme weather events should focus on improving climate models to project any trends in regional extreme events and as a result improve public health preparedness and mitigation. Epidemiologic studies of health effects beyond the direct impacts of disaster will provide a more accurate measure of the full health impacts and will assist in planning and resource allocation. *Key words:* climate change, extreme weather events, flooding, global warming, natural disasters, storms. — *Environ Health Perspect* 109(suppl 2):191–198 (2001). <http://ehpnet1.niehs.nih.gov/docs/2001/suppl-2/191-198greenough/abstract.html>

By definition, the term “extreme” refers to a departure from what is considered the norm. The extreme weather events considered here are meteorologic events that have a significant impact upon a local community or ecosystem. Included in this definition are temperature and precipitation extremes and severe tropical storms. Every year these events cause hundreds of deaths in the United States (1) and many more injuries, along with disruption of local environments and communities.

Climate change may alter the frequency, timing, intensity, and duration of extreme weather events (2–4). Increases in heavy precipitation have occurred over the past century (3,5). Future climate scenarios show likely increases in the frequency of extreme precipitation events, including precipitation during hurricanes (6). This poses an increased risk of floods (7). Frequencies of tornadoes and hurricanes cannot reliably be projected.

The potential health impacts of extreme weather events include both direct impacts, such as traumatic deaths and injuries, and indirect impacts, such as illnesses associated with ecologic or social disruption. In the United States, we have been fortunate in recent years not to have been severely affected by such indirect impacts, which include waterborne disease, dehydration due to unavailable safe potable water, and infection due to increased exposure to mosquitoes or

other disease vectors. Emergency relief and public health infrastructures are able to provide temporary shelter and safe food and water, albeit at significant private and taxpayer cost. Compliance with evacuation orders has been an issue in the past. A current focus of research is to learn more about the variables involved in natural disasters in order to better prepare for and/or mitigate their impacts in the future. These variables range from weather and climate conditions favorable for storm formation, which are being investigated with advanced satellite and other new technologies, to land use patterns such as coastal and floodplain development that may increase population risk.

This article discusses in general the pathways and health effects associated with extreme weather events and also provide specific examples of recent extreme weather-related disasters in the United States that had significant public health consequences (8). In August 1992, Hurricane Andrew devastated Dade County, Florida, causing 61 deaths and an estimated \$25 billion in damages (over 125,000 homes were destroyed or damaged). During the summer of 1993, widespread flooding in the Midwest caused 48 deaths and approximately \$21 billion in damages. In 1997, a winter of numerous, heavy snowstorms caused the Red River in North Dakota to break its 100-year flood crest record during

the spring snowmelt. Over 60,000 residents were forced to evacuate Grand Forks and the cleanup costs were estimated in the \$1 million to \$2 billion range. In September 1998, Hurricane Georges ripped through the Caribbean and across the southern U.S. Gulf Coast, causing 600 deaths and \$5.9 billion in damages. In Puerto Rico alone, over 80,000 homes were damaged or destroyed, and the storm caused severe damage to the island's crops. The most deadly hurricane to strike the Western Hemisphere in the last two centuries was Hurricane Mitch, occurring from October 26 to November 4, 1998, with 11,000 deaths and thousands of others missing in Central America. The remnants of Mitch drifted northward and pounded Key West with tropical storm force winds and heavy rains. On May 3, 1999, devastating tornadoes hit portions of Oklahoma, Kansas, Texas, and Tennessee, causing an estimated 54 deaths. These events demonstrate the human and property losses associated with extreme weather.

Figure 1 illustrates the complexity of the possible relationships among the various factors of global climate change, extreme events, and human health effects. The left side of the figure represents how global climate change might effect the intensity, duration, or occurrence of severe events. Although the right side of the illustration depicts the obviously

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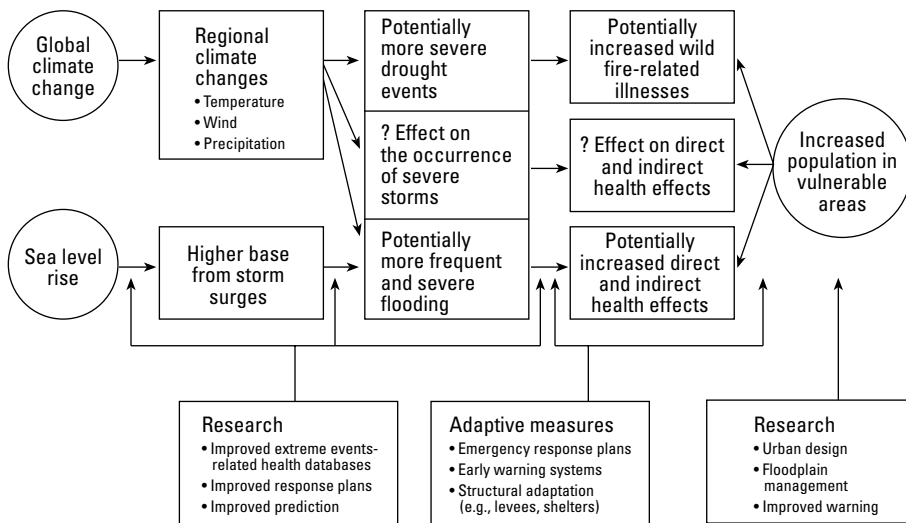


Figure 1. Extreme weather events-related health effects of global climate change. ?, uncertainty. Data from National Clinical Data Center (86).

increased risk from combining a higher number of extreme events with an increasing vulnerable population, it is not known how implementing adaptive measures might reduce that risk. Important areas for future research are also presented.

El Niño–Southern Oscillation

An example of how climate can vary because of alterations in the internal dynamics of the climate system is the El Niño–Southern Oscillation (ENSO). ENSO events arise from natural coupled interactions between the ocean and atmosphere in the tropical Pacific; these interactions prompt changes in rainfall and temperature patterns around the world (9,10). As such, ENSO is the most prominent global climate system associated with year-to-year weather variability. Although ENSO itself is not an extreme event, the related perturbations in the climate system alter the probability of extreme events, such as drought, floods, hurricane activity, or severe storms. The interannual variability worldwide in rates of persons affected by these events has been linked to ENSO (11). The sequence and pattern of ENSO-related changes in rainfall and temperature also have a role in determining health consequences, such as vector-borne disease transmission (12).

The winter of 1997–1998 was marked by a record-breaking El Niño event and unusual weather extremes in several parts of the country. More than 20% of the country experienced extremely heavy monthly precipitation totals during January, February, and March (8). California was struck by a series of storms due in part to the effects of El Niño. While the West Coast experiences winter flooding during non-El Niño years, precipitation amounts in several California counties set all-time high records during February 1998 (8),

causing several deaths and widespread property damage. ENSO-related drought exacerbated forest fires in Florida, Canada, Mexico, Central America, and several other parts of the world.

In the spring and summer of 1998, despite domestic and international relief efforts, the extended duration of biomass burn (i.e., burning of peat and soil) affected air quality over areas far greater than the immediate burn area. Health alerts were issued and respiratory effects were reported in Florida and Texas. These events provide one model for assessing the ecologic and health impacts of climate variability and change.

Health Effects of Extreme Weather Events

Direct and Indirect Pathways

The pathways through which extreme weather events can affect human health are often complex and interrelated. Direct morbidity and mortality are the health effects typically associated with disasters. In addition, secondary or indirect health impacts may be associated with changes in ecologic systems and human population displacement. Ecologic changes affecting land cover or the ability to sustain a level of biodiversity can alter the abundance and distribution of disease-carrying insects, rodents, and other vectors. In cases of prolonged or severe drought, human populations may migrate or move to urban areas in search of employment. Both the direct and indirect impacts of extreme weather events can lead to impaired public health infrastructure, reduced access to health care services, and psychological and social effects. Local population preparedness for extreme events is, therefore, an important determinant of a disaster's impacts. Factors

affecting community preparedness include exposure to natural elements (e.g., type of dwellings), socioeconomic status, early warning capability, and cultural practices (13); these factors are targets for local and state mitigation efforts.

Data Collection

Disaster data are scattered among various organizations (e.g., insurance companies, development firms, and state and federal agencies). The data are sought for different reasons (e.g., medical records, weather reporting, news and scientific interest broadcasting, accounting purposes, and evaluation and assessment of programs), and collected by different methods (e.g., quantitative and qualitative). Because the quality of these data varies widely, it is important to view reported numbers as estimates, not as concrete numbers. However, even with the disparate sources of information, trends can be discerned.

Direct Effects: Injuries and Deaths

From 1945 to 1989, 145 natural disasters caused 14,536 deaths in the United States, an average of 323 deaths per year (Table 1) (14). From 1986 to 1995, average annual deaths were 485 (15). In 1996, severe weather events caused 540 deaths and 2,711 injuries. In 1997, these events caused 600 deaths and 3,799 injuries (15). On September 8, 1900, a hurricane struck Galveston, Texas, and killed more than 6,000 people (16,17).

An increasing number of Americans live and work in areas associated with significant natural disaster risk (18,19). For instance, the last several decades have seen increased residential, commercial, and industrial development in floodplains. The heightened pace of coastal development has placed millions at risk from the storm surges and high winds that accompany hurricanes (18,19). In some of these areas, emergency management systems may be overburdened during extreme events.

Indirect Effects: Infectious Diseases and Mental Disorders

Epidemics of specific communicable diseases will occur only if those pathogens are endemic to the disaster-affected area (20) and if the public health infrastructure is insufficient to respond to increased exposure. In other parts of the world, secondary effects of extreme weather events have included massive population displacement, destruction of existing safe water supplies and health and sanitation facilities, and disruption of immunization and vector control programs. Such disease outbreaks and other secondary impacts have not occurred in recent history in the United States. For example, data following Hurricane Andrew and the 1993 Midwest floods did not document any increases in mosquito populations or

vector-borne diseases (21,22), although lack of shelter from damaged housing caused mosquito-biting rates to increase (23). In Louisiana, mosquito control was implemented for large nuisance populations that hampered disaster-recovery efforts after Hurricane Andrew (21). The largest outbreak of vector-borne disease in humans in the United States following a natural disaster was an outbreak of western equine encephalitis following the Red River flood of 1975 (24).

The occurrence of extreme events may also impact affected individuals' emotional or mental health. Depending on the severity and nature of the weather event, people may experience disabling fear or extreme aversion (25). There is controversy about the incidence and continuation of significant mental problems, such as post-traumatic stress disorder (PTSD), following disasters (26). However, an increase in the number of mental disorders has been observed following several natural disasters in the United States. Increased mental problems were described during the 5-year period after Hurricane Agnes caused widespread flooding in Pennsylvania in 1972 (27). More recently, a longitudinal study of local residents who lived through Hurricane Andrew showed that 20–30% of adults in the area met criteria for PTSD at 6 months and at 2 years after the event (28).

Disaster-Specific Health Outcomes

Floods and storm surges. Floods are the most frequent natural disaster and the leading cause of death from natural disasters in the United States, accounting for 40% of all natural disaster damage and injury (17). Future climate scenarios project increases in the frequency of extreme precipitation events and, consequently, an increased risk of floods (6,7). The severity of a flood is largely determined by topography, the surrounding infrastructure of the flooded area, a variety of human-generated factors, and the potential of floodwater to spread over a wide area. Flood-controlling infrastructure such as levees, embankments, retention walls, and drainage channels can affect the severity of flooding and contribute, if they fail, to resultant

injuries and deaths. For example, during flooding in one Georgia county in July 1994, the collapse of an earthen dam caused about half of the 15 deaths reported (29). Drainage ditches can be sources of injuries and deaths to individuals trying to escape flooded areas, as occurred in the Puerto Rico floods of 1992 when rapidly rising waters swept away people and cars and made escape more difficult by causing damage to roads and bridges (30).

With urbanization, more individuals live in higher risk areas, especially coasts and floodplains. Urbanization creates areas of land incapable of absorbing precipitation, placing greater numbers of people at risk for flash floods. To accommodate runoff, extensive systems of drainage channels must be built, adding an additional risk for injuries and deaths from rapidly rising water. Finally, environmentally destructive land use patterns contribute to higher morbidity and mortality. Overgrazing and general deforestation in upland areas with marginal foliage increase the potential for a higher volume of runoff that can accumulate in the populated floodplain downstream (31).

The degree to which flooding can cause injuries and deaths largely depends on the type of flood. Flash floods from heavy rainfalls in short periods are the most deadly, simply because of increased overall water volume, high water flow rates, and a limited warning period in which to seek safety. Increased rainfall in a catchment area can lead to a sudden increase in water release from a dam or a dam failure. According to National Weather Service (NWS) data, of flash flood-related deaths in the United States from 1969 to 1981, 1,185 deaths were attributed to 32 flash floods, with an average of 37 deaths occurring per flash flood. Drownings were thought to be responsible for over 90% of the fatalities (32). From 1995 to 1997, an average of 80 deaths per year occurred as a result of flash floods (15). More than 20,000 U.S. cities and communities are currently at risk for flash floods (33).

Although slow-rising, riverine floods do not have the potential for high mortality, they can cause significant morbidity (33) primarily due to lacerations, puncture wounds, and occasionally electrocution. Displacement of large groups of people into crowded shelters has the potential for triggering respiratory and gastrointestinal infectious disease outbreaks, especially when water and sewage systems are disrupted. Although the possibility that flooding in the Midwest in 1993 caused dispersal of microorganisms and chemicals from agricultural lands and industrial sites has been suggested (13), the Centers for Disease Control and Prevention (CDC) was not able to demonstrate dispersal of chemicals at that time.

In the aftermath of flooding, molds and fungi grow on interior surfaces, providing an added risk to allergic persons, and aggravating or triggering airways reactivity among susceptible persons. For example, the recently reported outbreak of pulmonary hemosiderosis attributed to *Stachybotris* spp. occurred in homes with high fungal levels following flooding (34,35).

Tornadoes. Because of their violent nature and frequent occurrence, tornadoes are the weather events most likely to result in a disaster (36). The United States has more severe tornadic storms than any other industrialized region in the middle latitudes (36), resulting in the most significant tornado disasters in the world (37). An average of 800 tornadoes is reported each year in the United States (38). The region of the United States with the highest frequency of severe tornadoes, known as "Tornado Alley," includes parts of Oklahoma, Indiana, Nebraska, Iowa, and Kansas (Figure 2). Texas has the greatest total number of tornadoes and the greatest number of tornado deaths per area (39). All 50 states can be affected by tornadic storms (40). The effect of climate change on the frequency and intensity of tornadoes cannot be reliably projected.

Injury and death result from tornadoes because these storms arise quickly, leaving little time for warning and for seeking appropriate shelter. A tornado's destructiveness is based on vortex wind speed and path width and length. Although the most powerful storms constitute 1–2% of all tornadoes, they cause more than half of all deaths, because they tend to have the longest paths (41). From 1950 to 1995, 4,236 deaths and 70,063 injuries were associated with tornadic storms in the United States (39). Soft tissue wounds are the most frequently reported injury, resulting from debris accelerated to high speeds by the winds (40). Other injuries commonly reported are fractures, head injuries, and blunt trauma (Table 2). Head injuries from highly energized flying debris are the most common causes of death (42). Nocturnal tornadoes are more deadly because victims are less likely to hear warnings. Other tornadoes that pose an increased threat are those that cause power outages, thus disabling warning systems, and those with accompanying heavy rain, wind, and hail that obscure paths to safety. As with floods, risk can result from natural and human factors. Heavily populated areas pose the greatest risk for injuries and deaths. For example, the Oklahoma and Kansas tornadoes in May 1999 left 54 dead and over 9,000 homes and businesses damaged or destroyed (8). Several studies delineated a variety of human risk factors, including: living in a mobile home (41,43,44); age > 60 years (44); remaining

Table 1. Natural disasters in the United States by type of disaster, 1945–1989.

Type	Number of disasters	Number of deaths	Deaths per disaster
Storms	58	3,968	68
Tornadoes	39	3,033	78
Hurricanes	15	3,075	205
Other weather	24	3,745	156
Geological	6	551	92
All other	3	164	55
Total	145	14,536	100

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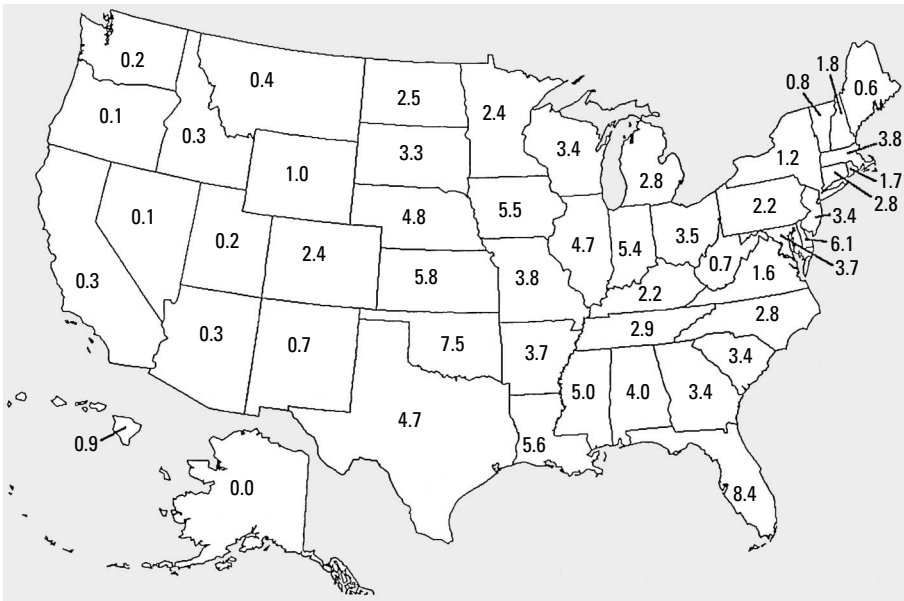


Figure 2. U. S. tornadoes, highlighting the region with the highest frequency of severe tornadoes.

Table 2. Specified injuries from tornado storm reports from 1962 to 1994. Type of injury with number of cases reported.

Literature report (first author)	Soft tissue laceration (n = 749)	Fracture (n = 406)	Head injury (n = 99)	Blunt trauma (n = 102)	Minor strains (n = 31)	Medical diagnoses ^a (n = 6)
Beelman (87)	193	129		3	9	
Mandelbaum (88)	24	13	14	3		
Ivy (89)	78	69	16	2		
Glass (43)	42	39	8	12		3
Leibovich (90)	17	3 ^b	1	5	7	1
Morris (91)	113	10	16	16		
Duclos (92)	31	24 ^b	6	11		
Harris (93)	25	40 ^b	9	5		2
Rosenfield (94)	160	50	19	21		
CDC (95)	66	29	10	24	15	
Frequency	53.6%	29.1%	7.1%	7.3%	2.2%	0.4%

^aIncluded in this category are patients having a heart attack, psychogenic shock, or other medical or psychiatric illness or disorder related to the storm. ^bIncludes 2, 2, and 6 rib fractures, respectively. Reprinted from Bohonos and Hogan (40) with permission from Elsevier Science.

outdoors (42); lacking protective covering (44); remaining in a vehicle while trying to outrun a tornado or guessing its course (43); and not understanding tornado warning terminology (42,45). This latter risk was tragically illustrated by the Saragosa, Texas, tornado of 1987 in which a largely rural Hispanic population did not understand the warnings communicated in English; the disaster killed 30 and injured 131 (45).

Hurricanes. There is no consensus among climatologists on whether projected changes in climate will result in an increase in either the frequency or the intensity of hurricanes striking the United States. However, they have been included in this article because of the tremendous impact to public health when these storms make landfall. The impact from hurricanes generally extends over a wide area, with damage resulting from strong winds and heavy rains. Worldwide, approximately

900,000 people were killed by these storms from 1967 to 1991 (alternatively called cyclones or typhoons in the western Pacific and Indian Ocean) (46). In the United States, hurricanes this century have caused more than 14,600 deaths (47). Approximately 70 million people are at risk in the United States and 50–100 people, on average, are killed per event. Although improved warning systems prevent or reduce deaths, increased population growth and development along vulnerable coastal areas increase the risk associated with hurricane-related injuries, deaths, and property damage (18,19).

Hurricanes classically trigger secondary weather effects, such as tornadoes, landslides, and flooding that, together with winds and storm surges, can cause extraordinarily high rates of injury and death. During tropical storm Isabel in Puerto Rico in 1985, 127 deaths (78% of all storm-related deaths)

occurred in one landslide (48). The majority of hurricane fatalities usually are due to drowning associated with storm surges (17,31,49); these surges often create difficult rescue problems in locating and evacuating individuals stranded by rising waters. Other causes of injuries and deaths include burial beneath houses and penetrating or blunt trauma due to wind-strewn debris (50). A confounding problem in flooded areas is soil or fecal matter in rising waters contaminating open wounds (51,52). The deaths of several people after Hurricane Andrew were associated with being in mobile homes during the storm (50).

Injuries and deaths associated with hurricanes can occur during the impact phase of a hurricane or the period of response and recovery immediately following the storm. Deaths from falling trees, trauma related to use of chain saws, and burns from unattended flames and generators were reported after Hurricane Hugo (53). Electrocutions from loose or wet wiring have been reported during the postdisaster cleanup (54). Although serious infectious disease outbreaks have not been documented on the United States mainland after a hurricane, enteric and respiratory agents could contribute to the overall morbidity observed. The need for food, shelter, clothing, and sanitation may create public health problems in the post-disaster phase. Crowding people into storm shelters may increase the probability of disease spread via aerosol or fecal–oral routes (55). Finally, access to health care may require the use of mobile hospitals when health care facilities have been damaged or destroyed, as was the case in St. Croix after Hurricane Hugo (56) and in South Florida after Hurricane Andrew (57).

Drought and fires. Severe drought conditions have been associated with widespread crop failure and food shortages, resulting in famine in developing countries (58,59). In the United States, malnutrition and starvation have not been public health concerns associated with extreme weather events because of an advanced capacity for food production and distribution. However, drought has been associated with crop failure, economic losses and, in some cases, increased potential for wildfires and infectious diseases. In addition, forest fires causing public health hazards have been related to dry conditions associated with El Niño events.

Drought-generated wildfires have less impact on mortality but cause an increased incidence of functional limitations and respiratory symptoms (60). Fire smoke carries a large amount of fine particles that exacerbate cardiac and respiratory problems, including asthma and other chronic obstructive lung disease (61,62). Individuals with preexisting respiratory disease are most at risk. Sinusitis,

upper respiratory infections, laryngitis, and eye irritation have been reported following exposure to smoke from wildfires (63,64).

As the circumference of cities grows outward, suburbs encroach on wilderness areas, resulting in more people at risk from wildfire injury. For example, a 1991 grass wildfire that swept through parts of Alameda County, California, thought to have been fueled by dry vegetation resulting from drought conditions, resulted in 25 fatalities and 241 fire-related hospital emergency visits (65). Twice as many people sought treatment for smoke-related injuries as for burns or traumatic injuries, and the majority (61%) of people with smoke-related disorders had documented bronchospasm.

Drought in association with extreme climate variability has been associated with infectious diseases. For example, a pattern of above average rainfall followed by drought has been associated by some studies with an increased incidence of hantavirus pulmonary syndrome (12,66) and possibly fungal infections such as coccidioidomycosis (67,68).

Other extreme weather events. Winter severe storms are associated with mortality other than low temperature mortality. [Low temperature mortality is discussed in McGeehin and Mirabelli (69).] Deaths from ischemic heart disease were reported to rise during and in the week immediately following blizzards (70). In a retrospective study of deaths in Pennsylvania that occurred during the months of January from 1991 to 1996, total mortality increased on days when snowfall was greater than 3 cm and when temperatures were below -7°C (71).

A number of other extreme weather events cause morbidity and mortality of considerable public health importance. For example, there were 1,916 fatalities due to lightning strikes in the United States from 1968 through 1985 (63) and 1,318 such fatalities from 1980 through 1995 (72). Lightning is directly dangerous because of its high voltage, secondary heat production, and explosive force. Indirectly, lightning may cause injury by kindling forest fires or by dropping objects such as trees on occupied homes and cars (73). Dust storms are a risk factor for asthma (74). A recent study of mortality rates in Spokane, Washington, showed that the 24-hr mean concentration of inhalable particles [particulate matter with an aerodynamic diameter less than $10\ \mu\text{m}$ (PM_{10})] during duststorms was higher than the concentration on days with no storm. However, there was no apparent increased risk of nonaccidental deaths on the dust storm days (75).

Population Susceptibility

More intense rainfall events may result in more floods, and a higher sea level provides a

higher base for storm surges that might overtop protective levees and seawalls and make flooding more likely (16). Increasing development in areas of high risk for extreme weather events, such as floodplains and coastal areas, is expected to continue (76). One study estimates that a rise in sea level of 30 cm would increase the size of the 100-year floodplain (area expected to flood on average once every 100 years) in the United States from 51,000 to 60,000 km^2 (77). Although there is disagreement regarding future projection of the occurrence of hurricanes and tornadoes in North America (78), there has been an increase in the number of people living in low-lying areas vulnerable to hurricanes on the Atlantic and Gulf coasts.

Adaptive Capacity

The impact of disasters on individuals and communities depends on the likelihood of the event, whether it can be predicted or controlled, the type of agent (natural or technological), the speed of onset, the scope of impact (focused or diffused), and the destructive potential of the event (79). Many practitioners and researchers separate disaster preventive measures into the following categories: structural and unstructural mitigation (e.g., building code regulations, warning response systems, disaster policies, retrofitted buildings); preparedness (e.g., individual evacuation); response (e.g., quick and adequate relief efforts); and recovery (e.g., both short- and long-term efforts such as rebuilding correctly or helping individuals and businesses survive). These categories are not mutually exclusive; for example, mitigation often takes place during the recovery phase.

State of Current Disaster Mitigation/Planning

Several federal agencies play major roles in mitigating and planning for disasters. National Oceanic and Atmospheric Administration (NOAA) organizations, such as the NWS and the National Environmental Satellite, Data, and Information Service (NESDIS), update weather observation and forecast systems. The Office of Emergency Preparedness (OEP), within the Department of Health and Human Services, works in partnership with the Federal Emergency Management Agency (FEMA), the Department of Defense (DOD), and the Department of Veterans Affairs to manage federal health, medical and social services for federally declared natural disasters within the Federal Response Plan. The OEP coordinates the National Disaster Medical System (NDMS), FEMA, local and state governments, and private and civilian volunteer efforts during an emergency, including the American Red Cross, military, and nongovernmental relief agencies. To

reduce the burden of fire, the National Fire Protection Association (NFPA) establishes building codes and standards and promotes fire and related safety issues.

The NWS is the primary source of weather, hydrologic, and climate forecasts and is the official voice for issuing warnings in extreme weather situations. Data are gathered from weather radar, weather satellites, and data buoys for marine observations and surface observing systems. This information is disseminated by a telecommunications switching center to television weathercasters and private meteorology companies. In addition, information during hazardous situations is broadcast on the NOAA weather radio network and via the Internet.

NESDIS operates satellites and manages the multitude of data and images they produce. The primary use of data created by these satellites is weather forecasting by the NWS.

The NWS developed a Doppler weather surveillance radar system that, when fully deployed, will increase tornado warning lead time by detecting tornado formation miles above the earth before it touches the ground. The system is also expected to improve detection of damaging winds, turbulence, wind shear, and hail storms; improve the forecasting of the location and severity of thunderstorms; increase the accuracy of identifying threatened areas; reduce the number of incorrect forecasts and false alarms; increase the accuracy of rainfall estimates for flash flood warnings; and improve water resource management and river flood forecasts (80).

FEMA is an independent agency of the federal government with a mission to reduce loss of life and property and to protect the nation's infrastructure from all types of hazards through a comprehensive, risk-based emergency management program of mitigation, preparedness, response, and recovery (81). FEMA conducts disaster preparedness training programs for emergency management officials, primary responders, engineers, architects, and building code officials, among others, at its National Emergency Training Center in Emmitsburg, Maryland, USA. FEMA recently launched a National Mitigation Strategy designed to increase public awareness of natural hazard risk and to reduce the risk of injury, death, economic loss, community disruption, and natural and cultural resources loss from disasters (82). The strategy, used as a tool by federal, state, and local governments and by private partners, consists of a series of initiatives: hazard identification and risk assessment; transfer of applied research and technology through development of private-public partnerships; public awareness, training, and education; creating incentives and resources to redirect federal funding from a postdisaster phase emphasis to predisaster

planning; and providing leadership help integrate mitigation practices into state and local emergency management.

Specific extreme events have their own spheres of mitigation efforts. Floodplain management, especially in the form of controls and zoning that limit development, is a significant preventive measure for floods and storm surges from hurricanes and coastal tsunamis. Other ongoing flood prevention schemes include relocating structures away from flood plains, reconvertng floodplains to natural state/wetlands, and formulating a comprehensive coastline management framework.

The increasing sensitivity of early warning systems, as elaborated above, should improve lead time for those seeking safety. Such systems should target at-risk groups: the elderly, disabled, recent immigrants and foreign language speakers, and those who dwell in remote, rural settings. Early warning has gotten a boost with the proliferation of weather channels and increased cable access along with the improved radar and satellite systems. Research has shown that warning messages for disasters need to have the following components to be successful: the message needs to be clear; there needs to be a degree of certainty that the threat is real; the magnitude needs to be known (e.g., how large is the predicted impact); and the timing and location need to be conveyed (83).

The impact of an effective warning system can be seen in the improvement in tornado warnings in the NSW began broadcasting tornado warnings in 1952. With improvements in NEXRAD (Next Generation Weather Radar Doppler systems), the system is 30–60% more sensitive than conventional radar at distances of more than 200 miles. Tornadoes can be detected an average of 20 min before touchdown. However, not all communities are covered yet. Such was the case in 1990 in Plainfield, Illinois, where a tornado with windspeeds exceeding 260 miles per hour arose quickly and, before adequate detection, killed 28 and injured 274. NWS also maintains a network of weather spotters especially geared for sighting rapidly occurring funnels.

Because most deaths from tornadoes occur before the victim can reach the hospital, prevention is crucial. Mortality rates are higher when no effective storm warnings are issued and no adequate shelter is available. Communities vary as to the presence of warning sirens and weather scanners and whether tornado drills are actively taught and practiced. Such practical prevention methods depend on the resources of local emergency services and the health department. A 1991 survey found that only 40% of mobile home parks have shelters. Despite the arguably marginal preventive measures and despite the fact that the average number of tornadoes increased from 1921 to 1990, the average

number of deaths from tornadoes decreased from 322 deaths per year in the 1920s to 51 deaths per year in the 1980s (38).

Future Trends in Disaster Management

The fact that the field of disaster mitigation has come to the forefront is a positive development. Globally, the United Nations declared the 1990s as the International Decade for Natural Disaster Reduction. In the United States, a wide array of agencies, private insurance companies, governmental agencies (CDC, NOAA, FEMA, and the United States Geological Survey), and academic institutions (National Association of Medical Examiners, the American College of Emergency Physicians, and the UCLA Center for Public Health and Disaster Relief) have recognized the need for interagency research and communication. The goal is to instill a heightened awareness of disaster mitigation into the public consciousness. Others are working to develop disaster prevention and response curricula in schools of public health.

The future is promising for tornado early-warning mechanisms. Among these are the modernization of NWS to improve dissemination of weather warnings through the media, implementation of Doppler systems for all areas, automatic telephone warning alert systems, storm warnings that reach indoors and outdoors, and cable television overrides that warn of immediate tornadoes. The goal is to improve warnings with limited numbers of false alarms. A survey conducted in 1986, after a tornado in the Carolinas, found that only 40% of the population knew the difference between commonly used weather warnings (84). Coupled with dissemination of warnings are public education programs describing the nomenclature of warnings, for example, tornado “watch,” which refers to conditions conducive to tornado formation, versus “warnings,” which refers to a tornado sighted by ground observers or radar system. Finally, continuity of satellite information is vital in weather forecasting and early warning operations.

Capacity to Adapt to Climate Change

As indicated above, technology can help refine our prevention efforts, minimize human and property loss once a disaster occurs, and help institute mitigation measures as part of the disaster recovery process. However, integrating technology must be coupled with a greater public understanding of individual roles in the mitigation process and of the need for specific disaster planning. For example, tornado-prone states should target money for more shelters, particularly in mobile home parks. Communities can ensure that those who are outdoors and in poorly anchored buildings, mobile homes, or portable

classrooms have access to adequately anchored buildings, preferably with basements.

Workable floodplain management, with mitigation incentives to reduce losses from floods, should take precedence over haphazard development. This action, coupled with restoring environmentally sensitive coastal land and critical estuarial and riverine habitats or converting other areas to recreational uses, should minimize death and injury from flooding and hurricane storm surges. Mitigation policies should be established in areas not yet developed. The roles of disaster response agencies and relief organizations need to be better defined, and coordination among local fire, public health, EMS, police, and relief agencies must be improved.

Public education is critical. Carter et al. surveyed tornado victims and found that only 21% of those in a building when a tornado hit chose the recommended safe location (42). As the Puerto Rico flood study revealed (30), educating people not to cross floodwaters by car or bike is a priority. FEMA recommends the establishment of a National Hurricane Program, commissioned to minimize loss from hurricanes through training and education, especially in the areas of warning, evacuation procedures and property protection.

Research Gaps

Improved climate models at temporal and spatial scales useful for projecting trends in regional extreme events will help mitigation and preparedness. In addition, national and regional health data collection beyond the direct impacts of a disaster will help in health program planning. Examples include information on the kind of response activity undertaken, the resources made available for relief and recovery, and long-term health effects such as PTSD. Databases should use standardized definitions and outputs. To fully understand climate-driven health impacts, we need long time-series of compatible data from integrated monitoring programs.

Research into climate-health connections must be interdisciplinary and must take into account factors such as the vulnerability of populations, water and sanitation systems, and quality of and access to health care infrastructure. For floods and hurricane storm surges, studies have been proposed that examine associations between morbidity/mortality and mitigation measures, as well as qualitative research that evaluates early warning systems, surveillance methods, and mitigation strategies. Insurance companies and departments of commerce are looking at risk analysis and predictors of mortality, such as geographical topography, stream flow velocities, and coastal/floodplain development. Flow studies are needed that delineate toxic releases into water supplies and their potential health

effects. The technology to map out the entire continent to determine risk areas—population densities in flood plains and coastal areas, areas of landslide risk, and areas of deforestation—could be used for that purpose.

Risk analysis and research studies are needed to develop effective preventive strategies for tornadoes. Studies are needed to investigate such things as shelter-seeking behavior, shelter access, adequacy of warning systems, and the usefulness of cable and satellite transmissions for warning systems. Studies examining the links between tornado characteristics and injury patterns, the risk factors for injury and death, and the comparisons of types of structures with injury pattern and death rates demand a multidisciplinary approach incorporating meteorologists, structural engineers, epidemiologists, disaster specialists, health care providers, and social scientists.

Comprehensive epidemiologic studies can better guide mitigation efforts. Future studies on floods, for instance, should elucidate the relationship of extreme events and morbidity and mortality rather than looking only at the individual event. To date, few epidemiologic studies have examined the public health effects of flooding or evaluated the benefits of effective mitigation strategies. More studies are needed on morbidity from woodland fires. An assessment of acute exacerbations of respiratory disease and the subsequent health care costs from the Florida wildfires of 1998, a consequence of El Niño, would be a significant step in developing this useful body of knowledge. There needs to be a formal risk assessment on human and economic losses from urban woodland fires.

The health effects resulting from economic losses and natural resource devastation from disasters remain an unexplored area. In 1999 CDC, along with the Institute for Business and Home Safety and the National Science and Technology Council, convened a forum on public health in natural disasters (85) as part of the Public Private Partnership 2000 Initiative; this represents an important step forward. A coordinated national database on injuries, deaths, and public health effects of extreme weather events should be kept and used for analysis and planning. Developing a national surveillance database would be useful for all types of extreme events.

Conclusion

It is not well understood how climate change may alter the frequency of extreme weather events in the United States. Even without an increase in magnitude or frequency, however, these events currently cause hundreds of deaths and injuries annually. Adaptive strategies such as improved warning systems, stronger building codes, and restricted development in flood plains should be implemented to reduce the

vulnerability of the U.S. population to the health impacts of severe events now and in the future.

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