CHAPTER 1

Why Weather and Climate Extremes Matter

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KEY FINDINGS

- Climate extremes expose existing human and natural system vulnerabilities.

- Changes in extreme events are one of the most significant ways socioeconomic and natural systems are likely to experience climate change.
    - Systems have adapted to their historical range of extreme events.
    - The impacts of extremes in the future, some of which are expected to be outside the historical range of experience, will depend on both climate change and future vulnerability. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, the sensitivity of the system, and its adaptive capacity. The adaptive capacity of socioeconomic systems is determined largely by such factors as poverty and resource availability.

- Changes in extreme events are already observed to be having impacts on socioeconomic and natural systems.
    - Two or more extreme events that occur over a short period reduce the time available for recovery.
    - The cumulative effect of back-to-back extremes has been found to be greater than if the same events are spread over a longer period.

- Extremes can have positive or negative effects. However, on balance, because systems have adapted to their historical range of extremes, the majority of the impacts of events outside this range are expected to be negative.

- Actions that lessen the risk from small or moderate events in the short-term, such as construction of levees, can lead to increases in vulnerability to larger extremes in the long-term, because perceived safety induces increased development.

1.1 WEATHER AND CLIMATE EXTREMES IMPACT PEOPLE, PLANTS, AND ANIMALS

Extreme events cause property damage, injury, loss of life, and threaten the existence of some species. Observed and projected warming of North America has direct implications for the occurrence of extreme weather and climate events. It is very unlikely that the average climate could change without extremes changing as well. Extreme events drive changes in natural and human systems much more than average climate (Parmesan *et al*., 2000; Parmesan and Martens, 2008).

Society recognizes the need to plan for the protection of communities and infrastructure from extreme events of various kinds, and engages in risk management. More broadly, responding to the threat of climate change is quintessentially a risk management problem. Structural measures (such as engineering works), governance measures (such as zoning and building codes), financial instruments (such as insurance and contingency funds), and emergency practices are all risk management measures that have been used to lessen the impacts of extremes. To the extent that changes in extremes can be anticipated, society can engage in additional risk management practices that would encourage proactive adaptation to limit future impacts.

Extreme events drive changes in natural and human systems much more than average climate.

Global and regional climate patterns have changed throughout the history of our planet. Prior to the Industrial Revolution, these changes occurred due to natural causes, including variations in the Earth's orbit around the Sun, volcanic eruptions, and fluctuations in the Sun's energy. Since the late 1800s, the changes have been due more to increases in the atmospheric concentrations of carbon dioxide and other trace greenhouse gases (GHG) as a result of human activities, such as fossil-fuel combustion and land-use change. On average, the world has warmed by 0.74°C (1.33°F) over the last century with most of that occurring in the last three decades, as documented by instrument-based observations of air temperature over land and ocean surface temperature (IPCC, 2007a; Arguez, 2007; Lanzante *et al*., 2006). These observations are corroborated by, among many examples, the shrinking of mountain glaciers (Barry, 2006), later lake and river freeze dates and earlier thaw dates (Magnuson *et al*., 2000), earlier blooming of flowering plants (Cayan *et al.*, 2001), earlier spring bird migrations (Sokolov, 2006), thawing permafrost and associated shifts in ecosystem functioning, shrinking sea ice (Arctic Climate Impact Assessment, 2004), and shifts of plant and animal ranges both poleward and up mountainsides, both within the U.S. (Parmesan and Galbraith, 2004) and globally (Walther *et al.*, 2002; Parmesan and Yohe, 2003; Root *et al.*, 2003; Parmesan, 2006). Most of the recent warming observed around the world very likely has been due to observed changes in GHG concentrations (IPCC, 2007a). The continuing increase in GHG concentration is projected to result in additional warming of the global climate by 1.1 to 6.4°C (2.0 to 11.5°F) by the end of this century (IPCC, 2007a).

Extremes are already having significant impacts on North America. Examination of Figure 1.1 reveals that it is an unusual year when the United States does not have any billion dollar weather- and climate-related disasters. Furthermore, the costs of weather-related disasters in the U.S. have been increasing since 1960, as shown in Figure 1.2. For the world as a whole, "weather-related [insured] losses in recent years have been trending upward much faster than population, inflation, or insurance penetration, and faster than non-weather-related events" (Mills, 2005a). Numerous studies indicate that both the climate and the socioeconomic vulnerability to weather and climate extremes are changing (Brooks and Doswell, 2001; Pielke *et al.*, 2008; Downton *et al.*, 2005), although these factors' relative contributions to observed increases in disaster costs are subject to debate. For example, it is not easy to quantify the extent to which increases in coastal building damage is due to increasing wealth and population growth[1] in vulnerable locations versus an increase in storm intensity. Some authors (*e.g.*, Pielke *et al.*, 2008) divide damage costs by a wealth factor in order to "normalize" the damage costs. However, other factors such as changes in building codes, emergency response, warning systems, *etc*. also need to be taken into account. At this time, there is no universally

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[1] Since 1980, the U.S. coastal population growth has generally reflected the same rate of growth as the entire nation (Crossett *et al*., 2004).

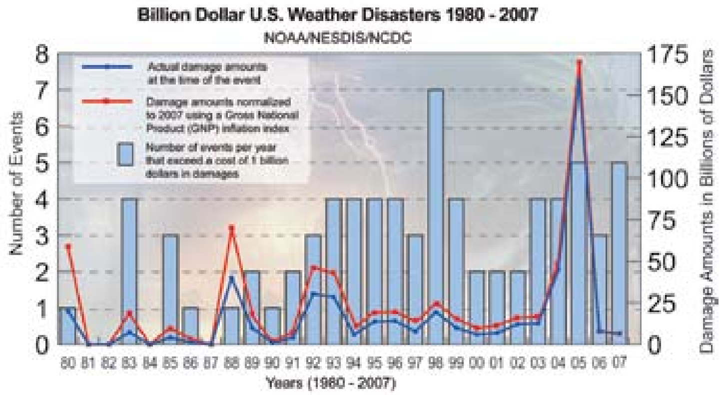


Figure 1.1 U.S. Billion Dollar Weather Disasters. The blue bars show number of events per year that exceed a cost of one billion dollars (these are scaled to the left side of the graph). The red line (costs adjusted for wealth/inflation) is scaled to the right side of the graph, and depicts the annual damage amounts in billions of dollars. This graphic does not include losses that are non-monetary, such as loss of life (Lott and Ross, 2006).

accepted approach to normalizing damage costs (Guha-Sapir *et al.*, 2004). Though the causes of the current damage increases are difficult to quantitatively assess, it is clear that any change in extremes will have a significant impact.

The relative costs of the different weather phenomena are presented in Figure 1.3 with tropical cyclones (hurricanes) being the most costly (Box 1.1). About 50% of the total tropical cyclone damages since 1960 occurred in 2005. Partitioning losses into the different categories is often not clear-cut. For example, tropical storms also contribute to damages that were categorized as flooding and coastal erosion. Based on data from 1940 to 1995, the annual mean loss of life from weather extremes in the U.S. exceeded 1,500 per year (Kunkel *et al.*, 1999), not including such factors as fog-related traffic fatalities. Approximately half of these deaths were related to hypothermia due to extreme cold, with extreme heat responsible for another one-fourth of the fatalities. For the period 1999 through 2003, the Centers for Disease Control reported an annual average of 688 deaths in the U.S. due to exposure to extreme heat (Luber *et al.*, 2006). From 1979 to 1997, there appears to be no trend in the number of deaths from extreme weather (Goklany and Straja, 2000). However, these statistics were compiled before the 1,400 hurricane-related fatalities in 2004-2005 (Chowdhury and Leatherman, 2007).

Natural systems display complex vulnerabilities to climate change that sometimes are not evident until after the event. According to van Vliet and Leemans (2006), "the unexpected rapid appearance of ecological responses throughout the world" can be explained largely by the observed changes in extremes over the last few decades. Insects in particular have the ability to respond quickly to climate warming by increasing in abundances and/or increasing numbers of generations per year, which has resulted in widespread mortality of previously healthy trees (Logan *et al.*, 2003) (Box 1.2). The observed warming-related biological changes may have direct adverse effects on biodiversity, which in turn have been shown to impact ecosystem stability, resilience, and ability to provide societal goods and services (Parmesan and Galbraith, 2004; Arctic Climate Impact Assessment, 2004). The greater the change in global mean temperature, the greater will be the change in extremes and their consequent impacts on species and systems.

The costs of weather-related disasters in the U.S. have been increasing since 1960.

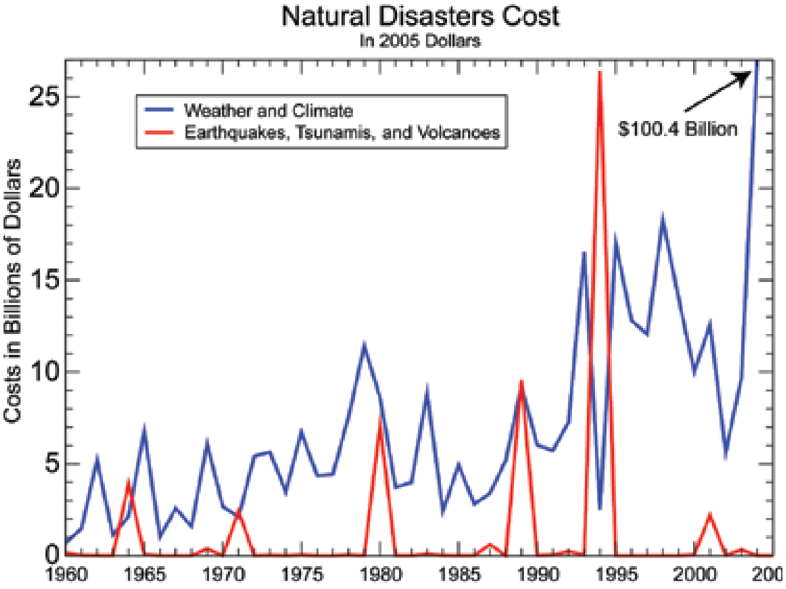


Figure 1.2 Costs from the SHELDUS database (Hazards and Vulnerability Research Institute, 2007) for weather and climate disasters and non-weather-related natural disasters in the U.S. The value for weather and climate damages in 2005 is off the graph at $100.4 billion. Weather and climate related damages have been increasing since 1960.

BOX 1.1: Damage Due to Hurricanes

There are substantial vulnerabilities to hurricanes along the Atlantic and Gulf Coasts of the United States. Four major urban areas represent concentrations of economic vulnerability (with capital stock greater than $100 billion)—the Miami coastal area, New Orleans, Houston, and Tampa. Three of these four areas have been hit by major storms in the last fifteen years (Nordhaus, 2006). A simple extrapolation of the current trend of doubling losses every ten years suggests that a storm like the 1926 Great Miami Hurricane could result in perhaps $500 billion in damages as early as the 2020s (Pielke *et al.*, 2008; Collins and Lowe, 2001).

Property damages are well-correlated with hurricane intensity (ISRTC, 2007). Kinetic energy increases with the square of its speed. So, in the case of hurricanes, faster winds have much more energy, dramatically increasing damages, as shown in Figure Box 1.1. Only 21% of the hurricanes making landfall in the United States are in Saffir-Simpson categories 3, 4, or 5, yet they cause 83% of the damage (Pielke and Landsea, 1998). Nordhaus (2006) argues that hurricane damage does not increase with the square of the wind speed, as kinetic energy does, but rather, damage appears to rise faster, with the eighth power of maximum wind speed. The 2005 total hurricane economic damage of $159 billion was primarily due to the cost of Katrina ($125 billion) (updated from Lott and Ross, 2006). As Nordhaus (2006) notes, 2005 was an economic outlier not because of extraordinarily strong storms but because the cost as a function of hurricane strength was high.

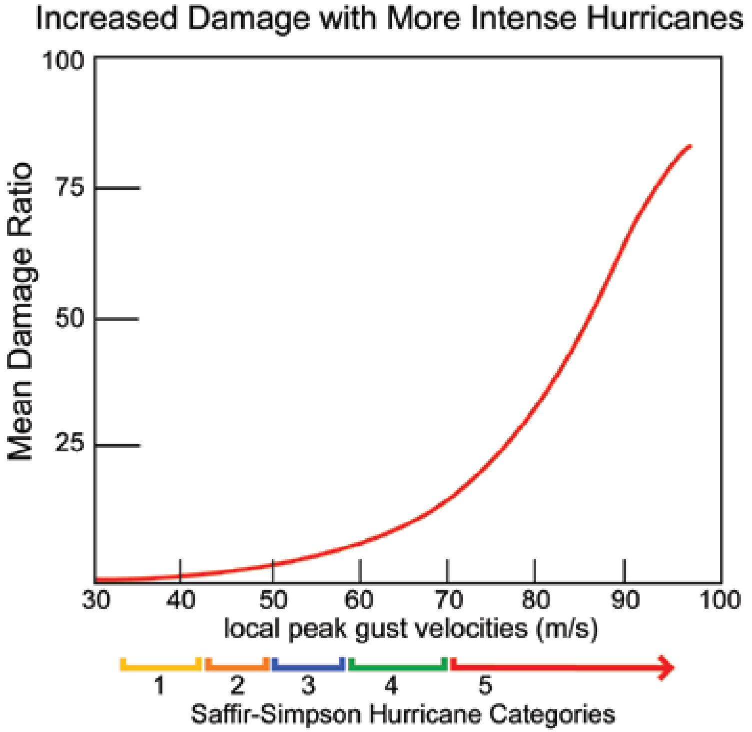
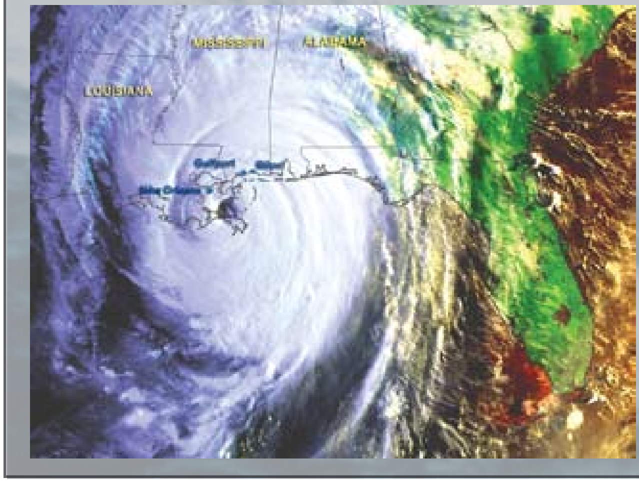


Figure Box 1.1 More intense hurricanes cause much greater losses. Mean damage ratio is the average expected loss as a percent of the total insured value. Adapted from Meyer *et al.* (1997).

A fundamental problem within many economic impact studies lies in the unlikely assumption that there are no other influences on the macro-economy during the period analyzed for each disaster (Pulwarty *et al.*, 2008). More is at work than aggregate indicators of population and wealth. It has long been known that different social groups, even within the same community, can experience the same climate event quite differently. In addition, economic analysis of capital stocks and densities does not capture the fact that many cities, such as New Orleans, represent unique corners of American culture and history (Kates *et al.*, 2006). Importantly, the implementation of past adaptations (such as levees) affects the degree of present and future impacts (Pulwarty *et al.*, 2003). At least since 1979, the reduction of mortality over time has been noted, including mortality due to floods and hurricanes in the United States. On the other hand, the effectiveness of past adaptations in reducing property damage is less clear because aggregate property damages have risen along with increases in the population, material wealth, and development in hazardous areas.



BOX 1.2: Cold Temperature Extremes and Forest Beetles

Forest beetles in western North America have been responding to climate change in ways that are destroying large areas of forests (Figure Box 1.2). The area affected is 50 times larger than the area affected by forest fire with an economic impact nearly five times as great (Logan *et al.*, 2003). Two separate responses are contributing to the problem. The first is a response to warmer summers, which enable the mountain pine beetle (*Dendroctonus ponderosae*), in the contiguous United States, to produce two generations in a year, when previously it had only one (Logan *et al.*, 2003). In south-central Alaska, the spruce beetle (*Dendroctonus rufipennis*) is maturing in one year, where previously it took two years (Berg *et al.*, 2006).

The second response is to changes in winter temperatures, specifically the lack of extremely cold winter temperatures, which strongly regulate over-winter survival of the spruce beetle in the Yukon (Berg *et al.*, 2006) and the mountain pine beetle in British Columbia, Canada. The supercooling threshold (about -40°C/F), is the temperature at which the insect freezes and dies (Werner *et al.*, 2006). Recent warming has limited the frequency of sub -40°C (-40°F) occurrences, reducing winter mortality of mountain pine beetle larvae in British Columbia. This has led to an explosion of the beetle population, killing trees covering an area of 8.7 million hectares (21.5 million acres) in 2005, a doubling since 2003, and a 50-fold increase since 1999 (British Columbia Ministry of Forests and Range, 2006a). It is estimated that at the current rate of spread, 80% of British Columbia's mature lodgepole pine trees, the province's most abundant commercial tree species, will be dead by 2013 (Natural Resources Canada, 2007). Similarly in Alaska, approximately 847,000 hectares (2.1 million acres) of south-central Alaska spruce forests were infested by spruce beetles from 1920 to 1989 while from 1990 to 2000, an extensive outbreak of spruce beetles caused mortality of spruce across 1.19 million hectares (2.9 million acres), approximately 40% more forest area than had been infested in the state during the previous 70 years (Werner *et al.*, 2006). The economic loss goes well beyond the lumber value (millions of board-feet) of the trees, as tourism revenue is highly dependent on having healthy, attractive forests. Hundreds of millions of dollars are being spent to mitigate the impacts of beetle infestation in British Columbia alone (British Columbia Ministry of Forests and Range, 2006b).

Figure Box 1.2 Photograph of a pine forest showing pine trees dying (red) from beetle infestation in the Quesnel-Prince George British Columbia area. Fewer instances of extreme cold winter temperatures that winterkill beetle larvae have contributed a greater likelihood of beetle infestations. Copyright © Province of British Columbia. All rights reserved. Reprinted with permission of the Province of British Columbia. www.ipp.gov.bc.ca

Adding further complexity to the climate-beetle-forest relationship in the contiguous United States, increased beetle populations have increased incidences of a fungus they transmit (pine blister rust, *Cronartium ribicola*) (Logan *et al.*, 2003). Further, in British Columbia and Alaska, long-term fire suppression activities have allowed the area of older forests to double. Older trees are more susceptible to beetle infestation. The increased forest litter from infected trees has, in turn, exacerbated the forest fire risk. Forest managers are struggling to keep up with changing conditions brought about by changing climate extremes.

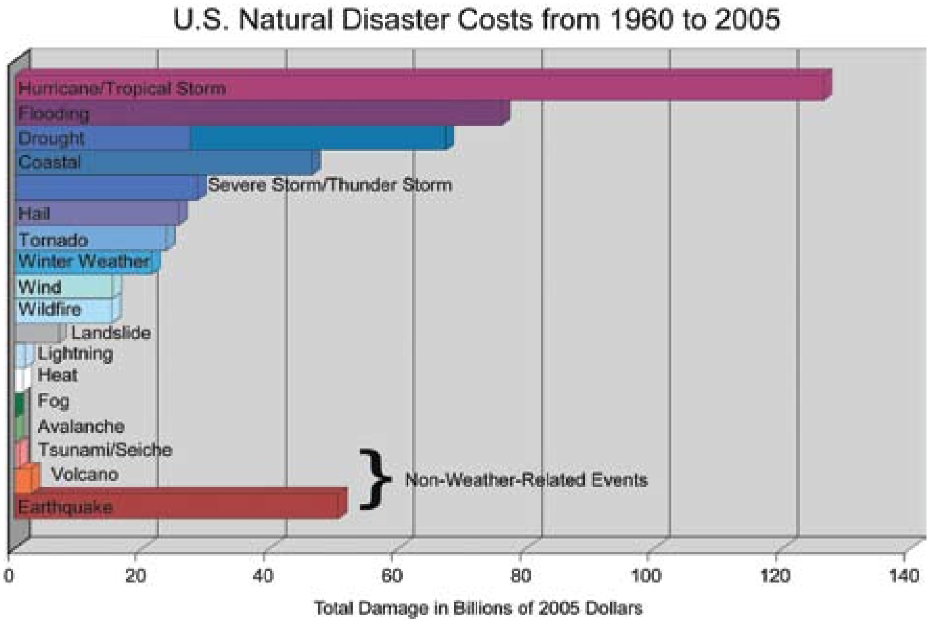


Figure 1.3 The magnitude of total U.S. damage costs from natural disasters over the period 1960 to 2005, in 2005 dollars. The data are from the SHELDUS data base (Hazards and Vulnerability Research Institute, 2007). SHELDUS is an event-based data set that does not capture drought well. Therefore, the drought bar was extended beyond the SHELDUS value to a more realistic estimate for drought costs. This estimate was calculated by multiplying the SHELDUS hurricane/tropical storm damage value by the fraction of hurricane/tropical storm damages (52%) relative to drought that occurs in the Billion Dollar Weather Disasters assessment (Lott and Ross, 2006). The damages are direct damage costs only. Note that weather- and climate-related disaster costs are 7.5 times those of non-weather natural disasters. Approximately 50% of the total hurricane losses were from the 2005 season. All damages are difficult to classify given that every classification is artificial and user- and database-specific. For example, SHELDUS' coastal classification includes damages from storm surge, coastal erosion, rip tide, tidal flooding, coastal floods, high seas, and tidal surges. Therefore, some of the coastal damages were caused by hurricanes just as some landslide damages are spawned by earthquakes.

This introductory chapter addresses various questions that are relevant to the complex relationships just described. Section 1.2 focuses on defining characteristics of extremes. Section 1.3 discusses the sensitivities of socioeconomic and natural systems to changes in extremes. Factors that influence the vulnerability of systems to changes in extremes are described in Section 1.4. As systems are already adapted to particular morphologies (forms) of extremes, Section 1.5 explains why changes in extremes usually pose challenges. Section 1.6 describes how actions taken in response to those challenges can either increase or decrease future impacts of extremes. Lastly, in Section 1.7, the difficulties in assessing extremes are discussed. The chapter also includes several boxes that highlight a number of topics related to particular extremes and their impacts, as well as analysis tools for assessing impacts.

The greater the change in global mean temperature, the greater will be the change in extremes and their consequent impacts on species and systems.

1.2 EXTREMES ARE CHANGING

When most people think of extreme weather or climate events, they focus on short-term intense episodes. However, this perspective ignores longer-term, more cumulative events, such as droughts. Thus, rather than defining extreme events solely in terms of how long they last, it is useful to look at them from a statistical point of view. If one plots all values of a particular variable, such as temperature, the values most likely will fall within a typical bell-curve with many values near average and fewer occurrences far away from the average. Extreme temperatures are in the tails of such distributions, as shown in the top panel of Figure 1.4.

According to the Glossary of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007a), "an extreme weather event is an event that is rare at a particular place and time of year." Here, as in the IPCC, we define rare as at least less common than the lowest or highest 10% of occurrences. For example, the heavy downpours that make up the top 5% of daily rainfall observations in a region would be classified as extreme precipitation events. By definition, the characteristics of extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (*e.g.*, drought or heavy rainfall over a season). Extreme climate events, such as drought, can often be viewed as occurring in the tails of a distribution similar to the temperature distribution.

Daily precipitation, however, has a distribution that is very different from the temperature distribution. For most locations in North America, the majority of days have no precipitation at all. Of the days where some rain or snow does fall, many have very light precipitation, while only

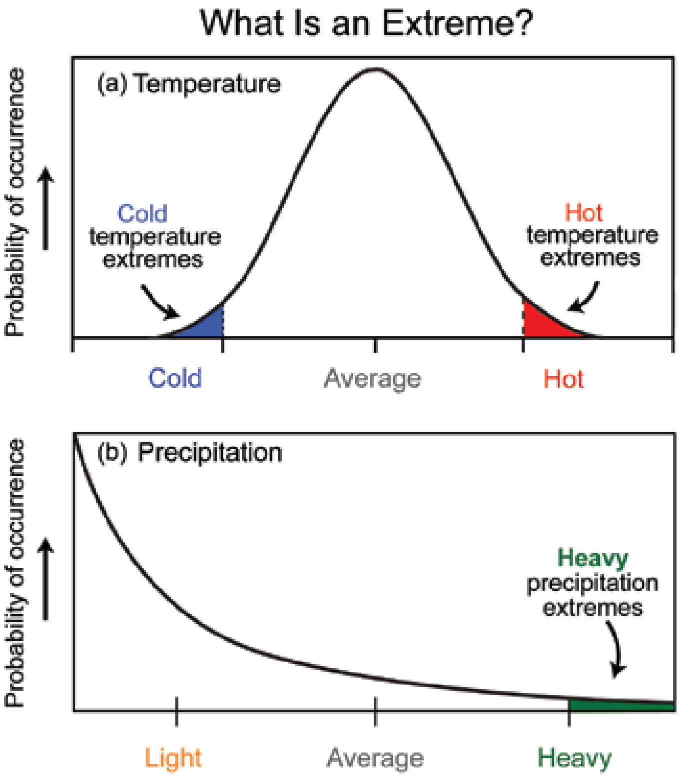


Figure 1.4 Probability distributions of daily temperature and precipitation. The higher the black line, the more often weather with those characteristics occurs.

a few have heavy precipitation, as illustrated by the bottom panel of Figure 1.4. Extreme value theory is a branch of statistics that fits a probability distribution to historical observations. The tail of the distribution can be used to estimate the probability of very rare events. This is the way the 100-year flood level can be estimated using 50 years of data. One problem with relying on historical data is that some extremes are far outside the observational record. For example, the heat wave that struck Europe in 2003 was so far outside historical variability (Figure 1.5) that public health services were unprepared for the excess mortality. Climate change is likely to increase the severity and frequency of extreme events for both statistical and physical reasons.

Wind is one parameter where statistics derived from all observations are not generally used to define what an extreme is. This is because most extreme wind events are generated by special meteorological conditions that are well known. All tornadoes and hurricanes are considered extreme events. Extreme wind events associated with other phenomena, such as blizzards or nor'easters, tend to be defined by thresholds based on impacts, rather than statistics, or the wind is just one aspect of the measure of intensity of these storms.

An extreme weather event is an event that is rare at a particular place and time of year.

Most considerations of extreme weather and climate events are limited to discrete occurrences. However, in some cases, events that occur in rapid succession can have impacts greater than the simple sum of the individual events. For example, the ice storms that occurred in eastern Ontario and southern Quebec in 1998 were the most destructive and disruptive in Canada in recent memory. This was a series of three storms that deposited record amounts of freezing rain (more than 80 mm/3 in) over a record number of hours during January 5-10, 1998. Further, the storm brutalized an area extending nearly 1000 km^2 (380 mi^2), which included one of the largest urban areas of Canada, leaving more than four million people freezing in the dark for hours and

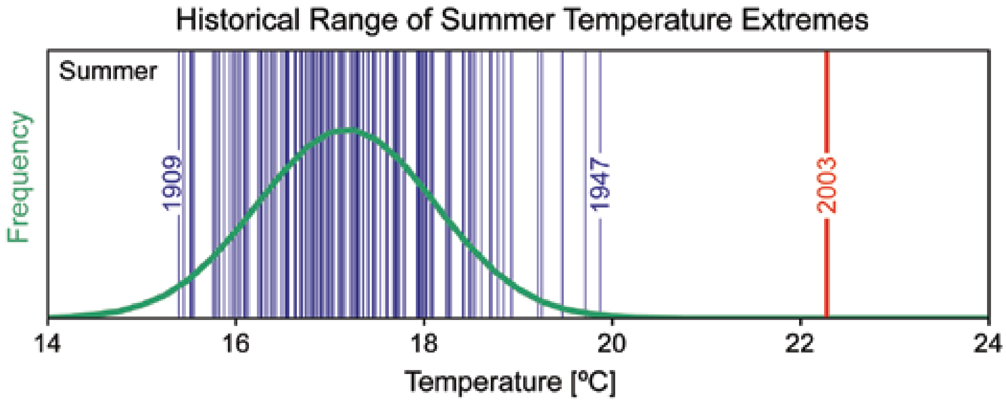


Figure 1.5 Like the European summer temperature of 2003, some extremes that are more likely to be experienced in the future will be far outside the range of historical observations. Each vertical line represents the mean summer temperature for a single year from the average of four stations in Switzerland over the period 1864 through 2003. Extreme values from the years 1909, 1947, and 2003 identified. [From Schär *et al.*, 2004.]

Events that occur in rapid succession can have impacts greater than the simple sum of the individual events.

even days. The conditions were so severe that no clean-up action could be taken between storms. The ice built up, stranding even more people at airports, bringing down high-tension transmission towers, and straining food supplies. Damage was estimated to exceed $4 billion, including losses to electricity transmission infrastructure, agriculture, and various electricity customers (Lecomte *et al*., 1998; Kerry *et al.*, 1999). Such cumulative events need special consideration.

Also, compound extremes are events that depend on two or more elements. For example, heat waves have greater impacts on human health when they are accompanied by high humidity. Additionally, serious impacts due to one extreme may only occur if it is preceded by a different extreme. For example, if a wind storm is preceeded by drought, it would result in far more wind-blown dust than the storm would generate without the drought.

As the global climate continues to adjust to increasing concentrations of greenhouse gases in the atmosphere, many different aspects of extremes have the potential to change as well (Easterling *et al.*, 2000a,b). The most commonly considered aspect is frequency. Is the extreme occurring more frequently? Will currently rare events become commonplace in 50 years? Changes in intensity are as important as changes in frequency. For example, are hurricanes becoming more intense? This is important because, as explained in Box 1.1, hurricane damage increases exponentially with the speed of the wind, so an intense hurricane causes much more destruction than a weak hurricane.

Frequency and intensity are only two parts of the puzzle. There are also temporal considerations, such as time of occurrence and duration. For example, the timing of peak snowmelt in the western mountains has shifted to earlier in the spring (Johnson *et al.*, 1999; Cayan *et al.*, 2001). Earlier snowmelt in western mountains means a longer dry season with far-reaching impacts on the ecologies of plant and animal communities, fire threat, and human water resources. Indeed, in the American West, wildfires are strongly associated with increased spring and summer temperatures and correspondingly earlier spring snowmelt in the mountains (Westerling *et al.*, 2006). In Canada, anthropogenic (human-induced) warming of summer temperatures has increased the area burned by forest fires in recent decades (Gillett *et al.*, 2004). Changing the timing and/or number of wildfires might pose threats to certain species by overlapping with their active seasons (causing increased deaths) rather than occurring during a species' dormant phase (when they are less vulnerable). Further, early snowmelt reduces summer water resources, particularly in California where summer rains are rare. Also of critical importance to Southern California wildfires are the timing and intensity of Santa Ana winds, which may be sensitive to future global warming (Miller and Schlegel, 2006). The duration of extreme events (such as heat waves, flood-inducing rains, and droughts) is also potentially subject to change. Spatial characteristics need to be considered. Is the size of the impact area changing? In addition to the size of the individual events, the location is subject to change. For example, is the region susceptible to freezing rain moving farther north?

Therefore, the focus of this assessment is not only the meteorology of extreme events, but how climate change might alter the characteristics of extremes. Figure 1.6 illustrates how the tails of the distribution of temperature and precipitation are anticipated to change in a warming world.

For temperature, both the average (mean) and the tails of the distributions are expected to warm. While the change in the number of average days may be small, the percentage change in the number of very warm and very cold days can be quite large. For precipitation, model and observational evidence points to increases in the number of heavy rain events and decreases in the number of light precipitation events.

1.3 NATURE AND SOCIETY ARE SENSITIVE TO CHANGES IN EXTREMES

Sensitivity to climate is defined as the degree to which a system is affected by climate-related stimuli. The effect may be direct, such as crop yield changing due to variations in temperature or precipitation, or indirect, such as the decision to build a house in a location based on insurance rates, which can change due to flood risk caused by sea level rise (IPCC, 2007b). Indicators of sensitivity to climate can include changes in the timing of life events (such as the date a plant flowers) or distributions of individual species, or alteration of whole ecosystem functioning (Parmesan and Yohe, 2003; Parmesan and Galbraith, 2004).

Sensitivity to climate directly impacts the vulnerability of a system or place. As a result, managed systems, both rural and urban, are constantly adjusting to changing perceptions of risks and opportunities (OFCM, 2005). For example, hurricane destruction can lead to the adoption of new building codes (or enforcement of existing codes) and the implementation of new construction technology, which alter the future sensitivity of the community to climate. Further, artificial selection and genetic engineering of crop plants can adjust agricultural varieties to changing temperature and drought conditions. Warrick (1980) suggested that the impacts of extreme events would gradually decline because of improved planning and early warning systems. Ausubel (1991) went further, suggesting that irrigation, air conditioning, artificial snow making, and other technological improvements, were enabling society to become more climate-proof. While North American society is not as sensitive to extremes as it was 400 years ago – for example, a megadrought in Mexico in the mid-to-late 1500s created conditions that may have altered rodent-human interactions and thereby contributed to tremendous population declines as illustrated by Figure 1.7 – socioeconomic systems are still far from being climate-proof.

Society is clearly altering relationships between climate and society and thereby sensitivities to climate. However, this is not a unidirectional change. Societies make decisions that alter regional-scale landscapes (urban expansion, pollution, land-use change, water withdrawals) which can increase or decrease both societal and ecosystem sensitivities (*e.g.*, Mileti, 1999; Glantz, 2003). Contrary to the possible gradual decline in impacts mentioned above, recent droughts have resulted in increased economic losses and conflicts (Riebsame *et al.*, 1991; Wilhite, 2005). The increased concern about El Niño's impacts reflect a heightened awareness of its effects on extreme events worldwide, and growing concerns about the gap between scientific information and adaptive responses by communities and governments (Glantz, 1996). In the U.S. Disaster Mitigation Act of 2000, Congress specifically wrote that a "greater emphasis needs to be placed on . . . implementing adequate mea-

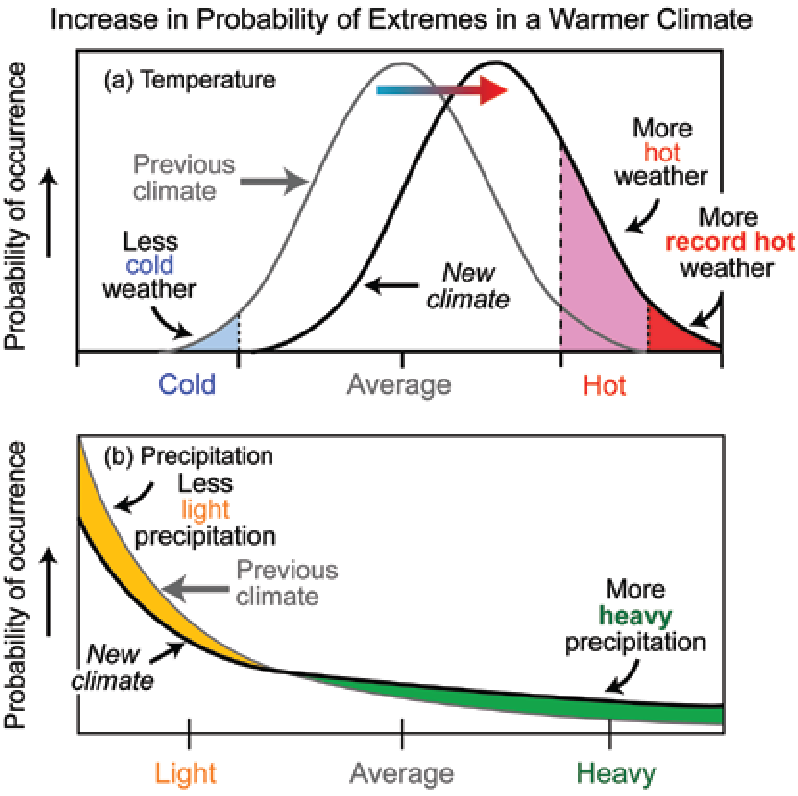


Figure 1.6 Simplified depiction of the changes in temperature and precipitation in a warming world.

While North American society is not as sensitive to extremes as it was 400 years ago, socioeconomic systems are still far from being climate-proof.

Drought and Population Collapse in Mexico

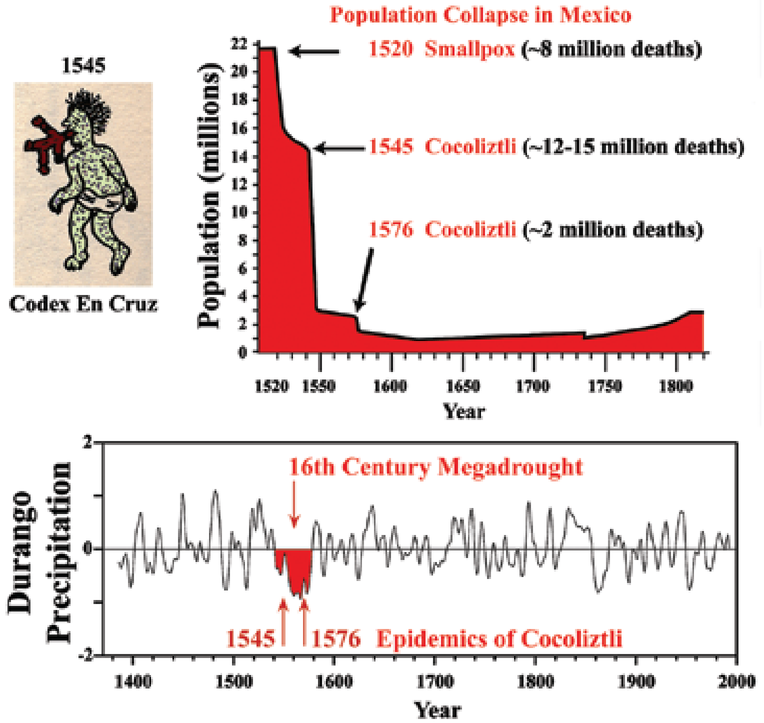


Figure 1.7 Megadrought and megadeath in 16th century Mexico. Four hundred years ago, the Mexican socioeconomic and natural systems were so sensitive to extremes that a megadrought in Mexico led to massive population declines (Acuna-Soto *et al.*, 2002). The 1545 Codex En Cruz depicts the effects of the cocoliztli epidemic, which has symptoms similar to rodent-borne hantavirus hemorrhagic fever.

Many biological processes undergo sudden shifts at particular thresholds of temperature or precipitation.

sures to reduce losses from natural disasters." Many biological processes undergo sudden shifts at particular thresholds of temperature or precipitation (Precht *et al.*, 1973; Weiser, 1973; Hoffman and Parsons, 1997). The adult male/female sex ratios of certain reptile species such as turtles and snakes are determined by the extreme maximum temperature experienced by the growing embryo (Bull, 1980; Bull and Vogt, 1979; Janzen, 1994). A single drought year has been shown to affect population dynamics of many insects, causing drastic crashes in some species (Singer and Ehrlich, 1979; Ehrlich *et al.*, 1980; Hawkins and Holyoak, 1998) and population booms in others (Mattson and Haack, 1987); see Box 1.3 on drought for more information. The nine-banded armadillo (*Dasypus novemcinctus*) cannot tolerate more than nine consecutive days below freezing (Taulman and Robbins, 1996). The high sea surface temperature event associated with El Niño in 1997-98 ultimately resulted in the death of 16% of the world's corals (Hoegh-Guldberg, 1999, 2005; Wilkinson, 2000); see Box 1.4 on coral bleaching for more information. Further, ecosystem structure and function are impacted by major disturbance events, such as tornadoes, floods, and hurricanes (Pickett and White, 1985; Walker, 1999). Warming winters, with a sparse snow cover at lower elevations, have led to false springs (an early warming followed by a return to normal colder winter temperatures) and subsequent population declines and extirpation (local extinction) in certain butterfly species (Parmesan, 1996, 2005).

By far, most of the documented impacts of global warming on natural systems have been ecological in nature. While ecological trends are summarized in terms of changes in mean biological and climatological traits, many detailed studies have implicated extreme weather events as the mechanistic drivers of these broad ecological responses to long-term climatic trends (Inouye, 2000; Parmesan *et al.*, 2000). Observed ecological responses to local, regional, and continental warming include changes in species' distributions, changes in species' phenologies (the timing of the different phases of life events), and alterations of ecosystem functioning (Walther *et al.*, 2002; Parmesan and Yohe, 2003; Root *et al.*, 2003; Parmesan and Galbraith, 2004; Parmesan, 2006; IPCC, 2007b). Changes in species' distributions include a northward and upward shift in the mean location of populations of the Edith's checkerspot butterfly in western North America consistent with expectations from the observed 0.7°C (1.3°F) warming—about 100 kilometers (60 mi) northward and 100 meters (330 ft) upslope (Parmesan, 1996; Karl *et al.*, 1996). Phenological (*e.g.*, timing) changes include lilac blooming 1.5 days earlier per decade and honeysuckle blooming 3.5 days earlier per decade since the 1960s in the western U.S. (Cayan *et al.*, 2001). In another example, tree swallows across the U.S. and southern Canada bred about 9 days earlier from 1959 to 1991, mirroring a gradual increase in mean May temperatures (Dunn and Winkler, 1999). One example of the impacts of warming on the functioning of a whole ecosystem comes from the Arctic tundra, where warming trends have been considerably stronger than in the contiguous U.S. Thawing of the permafrost layer has caused an increase in decomposition rates of dead organic matter during winter, which in some areas has already resulted in a shift from the tundra being a carbon sink to being a carbon source (Oechel *et al.*, 1993; Oechel *et al.*, 2000).

While many changes in timing have been observed (*e.g.*, change in when species breed or migrate), very few changes in other types of behaviors have been seen. One of these rare examples of behavioral changes is that some sooty shearwaters, a type of seabird, have shifted their migration pathway from the coastal California current to a more central Pacific pathway, apparently in response to a warming-induced shift in regions of high fish abundance during their summer flight (Spear and Ainley, 1999; Oedekoven *et al.*, 2001). Evolutionary studies of climate change impacts are also few (largely due to dearth of data), but it is clear that genetic responses have already occurred (Parmesan, 2006). Genetic changes in local populations have taken place resulting in much higher frequencies of individuals who are warm-adapted (*e.g.*, for fruit flies; Rodriguez-Trelles and Rodriguez, 1998; Levitan, 2003; Balanya *et al.*, 2006), or can disperse better (*e.g.*, for the bush cricket; Thomas *et al.*, 2001). For species-level evolution to occur, either appropriate novel mutations or novel genetic architecture (*i.e.*, new gene complexes) would have to emerge to allow a response to selection for increased tolerance to more extreme climate than the species is currently adapted to (Parmesan *et al.*, 2000; Parmesan *et al.*, 2005). However, so far there is no evidence for change in the absolute climate tolerances of a species, and, hence, no indication that evolution at the species level is occurring, nor that it might occur in the near future (Parmesan, 2006).

Ecological impacts of climate change on natural systems are beginning to have carry-over impacts on human health (Parmesan and Martens, 2008). The best example comes from bacteria which live in brackish rivers and sea water and use a diversity of marine life as reservoirs, including many shellfish, some fish, and even water hyacinth. Weather influences the transport and dissemination of these microbial agents via rainfall and runoff, and the survival and/or growth through factors such as temperature (Rose *et al,*. 2001). Two-hundred years of observational records reveal strong repeated patterns in which extreme high water temperatures cause algae blooms, which then promote rapid increases in zooplankton abundances and, hence, also in their associated bacteria (Colwell, 1996). Additionally, dengue is currently endemic in several cities in Texas and the mosquito vector (carrier) species is distributed across the Gulf Coast states (Brunkard *et al.*, 2007; Parmesan and Martens, 2008). Thus, climate related changes in ecosystems can also affect human health.

Ecological impacts of climate change on natural systems are beginning to have carry-over impacts on human health.

1.4 FUTURE IMPACTS OF CHANGING EXTREMES ALSO DEPEND ON VULNERABILITY

Climate change presents a significant risk management challenge, and dealing with weather and climate extremes is one of its more demanding aspects. In human terms, the importance of extreme events is demonstrated when they expose the vulnerabilities of communities and the infrastructure on which they rely. Extreme weather and climate events are not simply hydrometeorological occurrences. They impact socioeconomic systems and are often exacerbated by other stresses, such as social inequalities, disease, and conflict. Extreme events can threaten our very well-being. Understanding vulnerabilities from weather and climate extremes is a key first step in managing the risks of climate change.

According to IPCC (2007b), "vulnerability to climate change is the degree to which…systems are susceptible to, and unable to cope with, adverse impacts." Vulnerability is a function of the character, magnitude, and rate of climate change to which a system is exposed, its sensitivity, and its adaptive capacity. A system can be sensitive to change but not be vulnerable, such as some aspects of agriculture in North America, because of the rich adaptive capacity; or relatively insensitive but highly vulnerable. An example of the latter is incidence of diarrhea (caused by a variety of water-borne organisms) in less developed countries. Diarrhea is not correlated with temperatures in the U.S. because of highly-developed sanitation facilities. However, it does show a strong correlation with high temperatures in Lima, Peru (Checkley *et al.*, 2000; WHO, 2003, 2004). Thus, vulnerability is highly dependent on the robustness of societal infrastructures. For example, water-borne diseases have been shown to significantly increase following extreme precipitation events in the U.S. (Curriero *et al.*, 2001) and Canada (O'Connor, 2002) because water management systems failed (Box 1.5). Systems that normally survive are

BOX 1.3: Drought

Drought should not be viewed as merely a physical phenomenon. Its impacts on society result from the interplay between a physical event (*e.g.*, less precipitation than expected) and the demands people place on water supply. Human beings often exacerbate the impact of drought. Recent droughts in both developing and developed countries and the resulting economic and environmental impacts and personal hardships have underscored the vulnerability of all societies to this natural hazard (National Drought Mitigation Center, 2006).

Over the past century, the area affected by severe and extreme drought in the United States each year averages around 14% with the affected area as high as 65% in 1934. In recent years, the drought-affected area ranged between 35 and 40% as shown in Figure Box 1.3. FEMA (1995) estimates average annual drought-related losses at $6-8 billion (based on relief payments alone). Losses were as high as $40 billion in 1988 (Riebsame *et al.*, 1991). Available economic estimates of the impacts of drought are difficult to reproduce. This problem has to do with the unique nature of drought relative to other extremes, such as hurricanes. The onset of drought is slow. Further, the secondary impacts may be larger than the immediately visible impacts and often occur past the lifetime of the event (Wilhite and Pulwarty, 2005).

In recent years, the western United States has experienced considerable drought impacts, with 30% of the region under severe drought since 1995. Widespread declines in springtime snow water equivalent in the U.S. West have occurred over the period 1925–2000, especially since mid-century. While non-climatic factors, such as the growth of forest canopy, might be partly responsible, the primary cause is likely the changing climate because the patterns of climatic trends are spatially consistent and the trends are dependent on elevation (Mote *et al.*, 2005). Increased temperature appears to have led to increasing drought (Andreadis and Lettenmaier, 2006). In the Colorado River Basin, the 2000-2004 period had an average flow of 9.9 million acre feet[1] (maf) per year, lower than the driest period during the Dust Bowl years of 1931-1935 (with 11.4 maf), and the 1950s (with 10.2 maf) (Pulwarty *et al.*, 2005). For the winter of 2004-2005, average precipitation in the Basin was around 100% of normal. However, the combination of low antecedent soil moisture (absorption into soil), depleted high mountain aquifers, and the warmest January-July period on record (driving evaporation) resulted in a reduced flow of 75% of average.

At the same time, states in the U.S. Southwest experienced some of the most rapid economic and population growth in the country, with attendant demands on water resources and associated conflicts. It is estimated that as a result of the 1999-2004 drought and increased water resources extraction, Lake Mead and Lake Powell[2] will take 13 to 15 years of average flow conditions to refill. In the Colorado River Basin, high-elevation snow pack contributes approximately 70% of the annual runoff. Because the Colorado River Compact[3] prioritizes the delivery of water to the Lower Basin states of Arizona,

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[1] One acre foot is equal to 325,853 U.S. gallons or 1,233.5 cubic meters. It is the amount of water needed to cover one acre with a foot of water.

[2] Lake Mead and Lake Powell are reservoirs on the Colorado River. Lake Mead is the largest man-made lake in the United States.

[3] The Colorado River Compact is a 1922 agreement among seven U.S. states in the basin of the Colorado River which governs the allocation of the river's water.

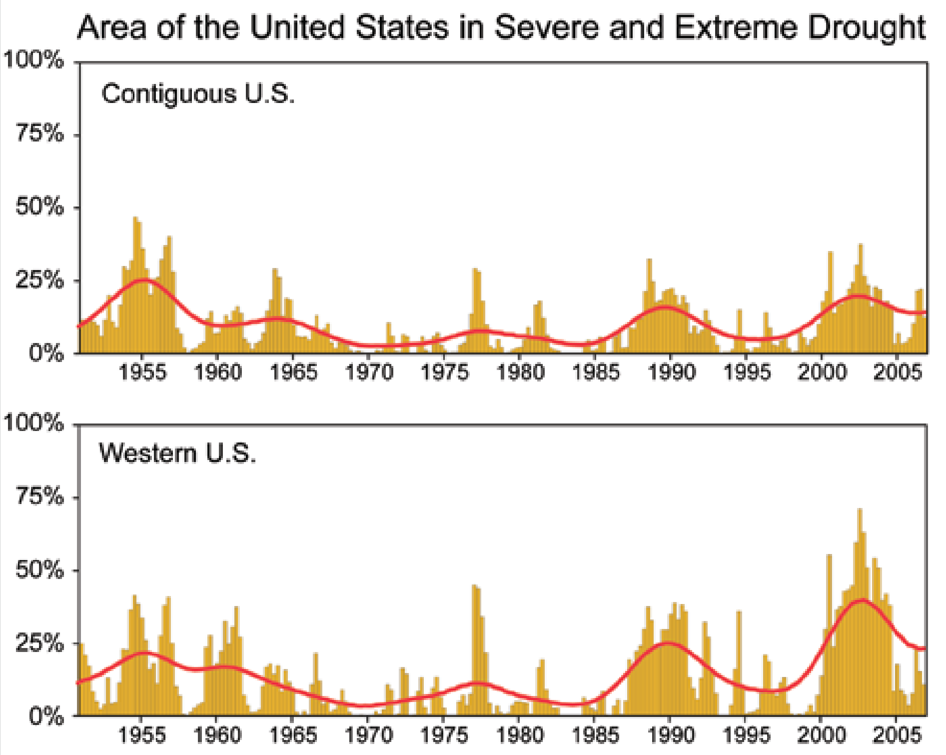
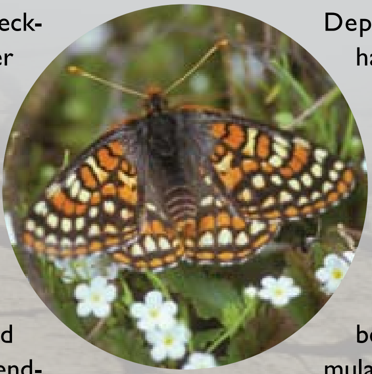


Figure Box 1.3 Percent of area in the contiguous U.S. and western U.S. affected by severe and extreme drought as indicated by Palmer Drought Severity Index (PDSI) values of less than or equal to -3. Data from NOAA's National Climatic Data Center.

California, and Nevada, the largest impacts may be felt in the Upper Basin states of Wyoming, Utah, Colorado, and New Mexico. With increased global warming, the compact requirements may only be met 59% to 75% of the time (Christensen *et al.*, 2004).



Severe droughts in the western U.S. have had multiple impacts on wild plants and animals. The 1975-1977 severe drought over California caused the extinction of 5 out of 21 surveyed populations of Edith's checkerspot butterfly (Ehrlich *et al.*, 1980; Singer and Ehrlich, 1979). A widespread drought in 1987-1988 caused simultaneous crashes of insect populations across the U.S., affecting diverse taxa from butterflies to sawflies to grasshoppers (Hawkins and Holyoak, 1998). Conversely, drought can be related to population booms in other insects (*e.g.*, certain beetles, aphids, and moths) (Mattson and Haack, 1987). An extended drought in New Mexico in the 1950s caused mass mortality in semiarid ponderosa pine forests, causing an overall upslope shift in the boundary between pine forests and piñon/juniper woodland of as much as 2,000 meters (6,500 feet) (Allen and Breshears, 1998). The ecosystem response was complex, "forest patches within the shift zone became much more fragmented, and soil erosion greatly accelerated," which may be the underlying reason why this boundary shift persisted over the next 40 years.

In the Sierra Nevada Mountains of California, increased frequency of fires has been shown to be an important element in local forest dynamics (Swetnam, 1993; Stephenson and Parsons, 1993; Westerling *et al.*, 2006). Fire frequency is correlated with temperature, fuel loads (related to tree species composition and age structure), and fuel moisture. Periods of drought followed by weeks of extreme heat and low humidity provide ideal conditions for fire, which are, ironically, often sparked by lightning associated with thunderstorms at the drought's end.

While there are multi-billion dollar estimates for annual agricultural losses (averaging about $4 billion a year over the last ten years), it is unclear whether these losses are directly related to crop production alone or other factors. Wildfire suppression costs to the United States Department of Agriculture (USDA) alone have surpassed $1 billion each of the last four years, though it is unclear how much of this is attributable to dry conditions. Little or no official loss estimates exist for the energy, recreation/tourism, timber, livestock, or environmental sectors, although the drought impacts within these sectors in recent years is known to be large. Better methods to quantify the cumulative direct and indirect impacts associated with drought need to be developed. The recurrence of a drought today of equal or similar magnitude to major droughts experienced in the past will likely result in far greater economic, social, and environmental losses and conflicts between water users.

BOX 1.4: High Temperature Extremes and Coral Bleaching

Corals are marine animals that obtain much of their nutrients from symbiotic[1] single-celled algae that live protected within the coral's calcium carbonate skeleton. Sea surface temperatures (SST), 1°C above long-term summer averages lead to the loss of symbiotic algae resulting in bleaching of tropical corals (Hoegh-Guldberg, 1999) (Figure Box 1.4). While global SST has risen an average of 0.13°C (0.23°F) per decade from 1979 to 2005 (IPCC, 2007a), a more acute problem for coral reefs is the increase in episodic warming events such as El Niño. High SSTs associated with the strong El Niño event in 1997-98 caused bleaching in every ocean basin (up to 95% of corals bleached in the Indian Ocean), ultimately resulting in 16% of corals dying globally (Hoegh-Guldberg, 1999, 2005; Wilkinson, 2000).

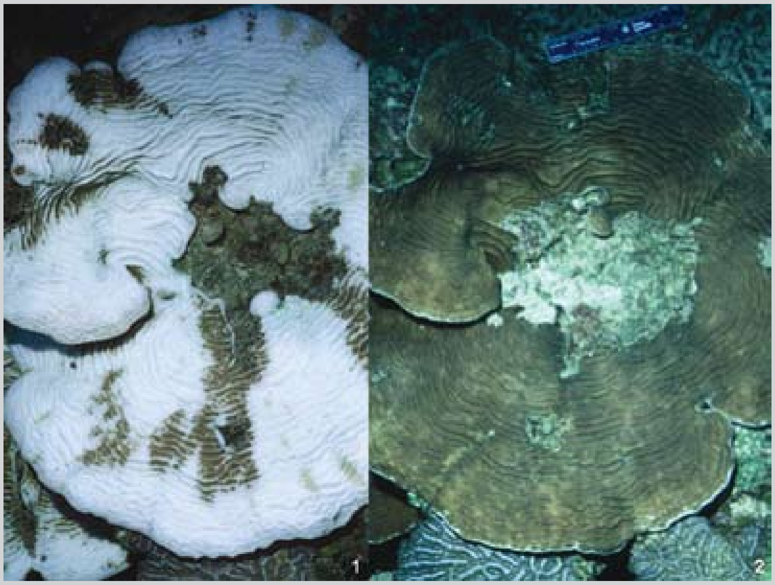


Figure Box 1.4 An Agaricia coral colony shown: 1) bleached, and 2) almost fully recovered, from a bleaching event. Photos courtesy of Andy Bruckner, NOAA's National Marine Fisheries Service.

Recent evidence for genetic variation in temperature thresholds among the relevant symbiotic algae suggests that some evolutionary response to higher water temperatures may be possible (Baker, 2001; Rowan, 2004). Increased frequency of high temperature-tolerant symbiotic algae appear to have occurred within some coral populations between the mass bleaching events of 1997/1998 and 2000/2001 (Baker *et al.*, 2004). However, other studies indicate that many entire reefs are already at their thermal tolerance limits (Hoegh-Guldberg, 1999). Coupled with poor dispersal of symbiotic algae between reefs, this has led several researchers to conclude that local evolutionary responses are unlikely to mitigate the negative impacts of future temperature rises (Donner *et al.*, 2005; Hoegh-Guldberg *et al.*, 2002). Interestingly, though, hurricane-induced ocean cooling can temporarily alleviate thermal stress on coral reefs (Manzello *et al.*, 2007).

Examining coral bleaching in the Caribbean, Donner *et al.* (2007) concluded that "the observed warming trend in the region of the 2005 bleaching event is unlikely to be due to natural climate variability alone." Indeed, "simulation of background climate variability suggests that human-caused warming may have increased the probability of occurrence of significant thermal stress events for corals in this region by an order of magnitude. Under scenarios of future greenhouse gas emissions, mass coral bleaching in the eastern Caribbean may become a biannual event in 20–30 years." As coral reefs make significant contributions to attracting tourists to the Caribbean, coral bleaching has adverse socioeconomic impacts as well as ecological impacts.

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[1] A symbiotic relationship between two living things is one that benefits both.

those well adapted to the more frequent forms of low-damage events. On the other hand, the less frequent high-damage events can overwhelm the ability of any system to recover quickly.

The adaptive capacity of socioeconomic systems is determined largely by characteristics such as poverty and resource availability, which often can be managed. Communities with little adaptive capacities are those with limited economic resources, low levels of technology, weak information systems, poor infrastructure, unstable or weak institutions, and uneven access to resources. Enhancement of social capacity, effectively addressing some of the exacerbating stresses, represents a practical means of coping with changes and uncertainties in climate. However, despite advances in knowledge and technologies, costs appear to be a major factor in limiting the adoption of adaptation measures (White *et al.*, 2001).

Communities can often achieve significant reductions in losses from natural disasters by adopting land-use plans that avoid the hazards, *e.g.*, by not allowing building in a floodplain. Building codes are also effective for reducing disaster losses, but they need to be enforced. For example, more than 25% of the damage from Hurricane Andrew could have been prevented if the existing building codes had been enforced (Board on Natural Disasters, 1999). One of the first major industry sectors to publicly show its concern about the threats posed by climate change was the insurance industry, in 1990 (Peara and Mills, 1999). Since then, the industry has recognized the steady increase in claims paralleling an increase in the number and severity of extreme weather and climate events—a trend that is expected to continue. The insurance industry, in fact, has an array of instruments/levers that can stimulate policyholders to take actions to adapt to future extremes. These possibilities are increasingly being recognized by governments. When such measures take effect, the same magnitude event can have less impact, as illustrated by the top panel of Figure 1.8.

Extreme events themselves can alter vulnerability and expose underlying stresses. There are various response times for recovery from the effects of any extreme weather or climate event—ranging from several decades in cases of significant loss of life, to years for the salinization of agricultural land following a tropical storm, to several months for stores to restock after a hurricane. A series of extreme events that occurs in a shorter period than the time needed for recovery can exacerbate the impacts, as illustrated in the bottom panel of Figure 1.8. For example, in 2004, a series of hurricanes made landfall in Florida; these occurred close enough in time and space that it often proved impossible to recover from one hurricane before the next arrived (Pielke *et al.*, 2008). Hardware stores and lumberyards were not able to restock quickly enough for residents to complete repairs to their homes which then led to further damage in the next storm. A multitude or sequence of extreme events can also strain the abilities of insurance and reinsurance companies to compensate victims.

Extremes can also initiate adaptive responses. For example, droughts in the 1930s triggered waves of human migration that altered the population distribution of the United States. After the 1998 eastern Canadian ice storm, the design criteria for freezing rain on high-voltage power and transmission lines were changed to accommodate radial ice accretion of 25 mm (1 inch) in the Great Lakes region to 50 mm (2 inches) for Newfoundland and Labrador (Canadian Standards Association, 2001).

Extreme events themselves can alter vulnerability and expose underlying stresses.

Factors such as societal exposure, adaptive capacity, and sensitivity to weather and climate can play a significant role in determining whether an event is considered extreme. In fact, an extreme weather or climate event, defined solely using statistical properties, may not be perceived to be an extreme if it affects something (*e.g.*, a building, city, *etc.*) that is designed to withstand that extreme. Conversely, a weather or climate event that is not extreme in a statistical sense might still be considered an extreme event because of the resultant impacts. Case in point, faced with an extended dry spell,

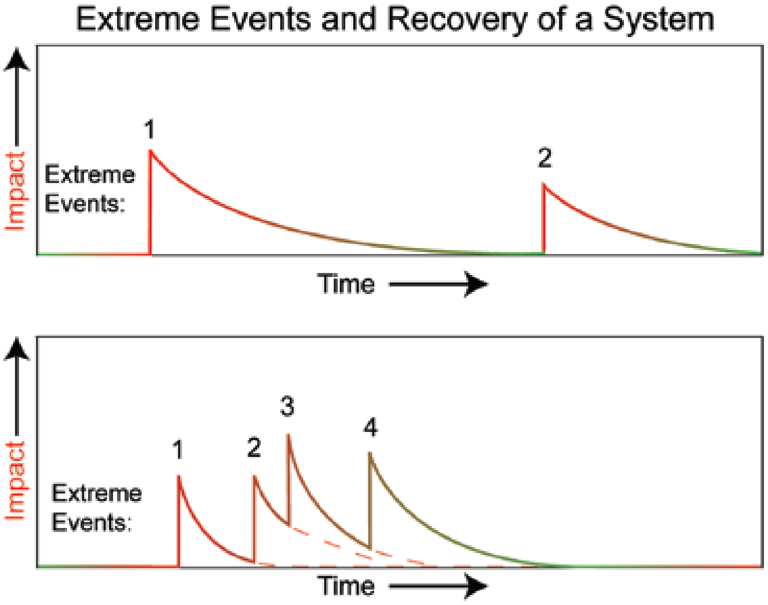

Figure 1.8 Extreme events such as hurricanes can have significant sudden impacts that take some time to recover from. Top: Two similar magnitude events take place but after the first one, new adaptation measures are undertaken, such as changes in building codes, so the second event doesn't have as great an impact. Bottom: An extreme that occurs before an area has completely recovered from the previous extreme can have a total impact in excess of what would have occurred in isolation.

consider the different effects and responses in a city with a well-developed water supply infrastructure and a village in an underdeveloped region with no access to reservoirs. These differences also highlight the role of adaptive capacity in a society's response to an extreme event. Wealthy societies will be able to devote the resources needed to construct a water supply system that can withstand an extended drought.

Given the relationship between extreme events and their resultant socioeconomic impacts, it would seem that the impacts alone would provide a good way to assess changes in extremes. Unfortunately, attempts to quantify trends in the impacts caused by extreme events are hindered by the difficulty in obtaining loss-damage records. As a result, there have been many calls for improvements in how socioeconomic data are collected (Changnon, 2003; Cutter and Emrich, 2005; National Research Council, 1999). However, there is no government-level coordinated mechanism for collecting data on all losses or damage caused by extreme events. A potentially valuable effort, led by the Hazards Research Lab at the University of South Carolina, is the assembly of the Spatial Hazard Events and Losses Database for the United States (SHELDUS) (Cutter *et al.*, 2008). If successful, this effort could provide standardized guidelines for loss estimation, data compilation, and metadata standards. Without these types of guidelines, a homogeneous national loss inventory will remain a vision and it will not be possible to precisely and accurately detect and assess trends in losses and quantify the value of mitigation (Figure 1.9).

There is no government-level coordinated mechanism for collecting data on all losses or damages caused by extreme events.

To date, most efforts at quantifying trends in losses caused by impacts are based on insured loss data or on total loss (insured plus non-insured losses) estimates developed by insurers. Unfortunately, the details behind most of the insured loss data are proprietary and only aggregated loss data are available. The relationship between insured losses and total losses will likely vary as a function of extreme event and societal factors such as building codes, the extent of insurance penetration, and more complex

BOX 1.5: Heavy Precipitation and Human Health

Human-caused climate change is already affecting human health (WHO 2002, 2003, 2004; McMichael *et al.*, 2004). For the year 2000, the World Health Organization (WHO) estimated that 6% of malaria infections, 7% of dengue fever cases and 2.4% of diarrhea could be attributed to climate change (Campbell-Lendrum *et al.*, 2003). Increases in these water-borne diseases has been attributed to increases in intensity and frequency of flood events, which in turn has been linked to greenhouse-gas driven climate change (Easterling *et al.*, 2000a,b; IPCC, 2007a). Floods directly promote transmission of water-borne diseases by causing mingling of untreated or partially treated sewage with freshwater sources, as well as indirectly from the breakdown of normal infrastructure causing post-flood loss of sanitation and fresh water supplies (Atherholt *et al.*, 1998; Rose *et al.*, 2000; Curriero *et al.*, 2001; Patz *et al.*, 2003; O'Connor, 2002). Precipitation extremes also cause increases in malnutrition due to drought and flood-related crop failure. For all impacts combined, WHO estimated the total deaths due to climate change at 150,000 people per year (WHO, 2002).

However, there is general agreement that the health sector in developed countries is strongly buffered against responses to climate change, and that a suite of more traditional factors is often responsible for both chronic and epidemic health problems. These include quality and accessibility of health care, sanitation infrastructure and practices, land-use change (particularly practices which alter timing and extent of standing water), pollution, population age structure, presence and effectiveness of vector control programs, and general socioeconomic status (Patz *et al.*, 2001; Gubler *et al.*, 2001; Campbell-Lendrum *et al.*, 2003; Wilkinson *et al.*, 2003; WHO, 2004, IPCC, 2007b). Indeed, it is generally assumed that diarrhea incidence in developed countries, which have much better sanitation infrastructure, has little or no association with climate (WHO, 2003, 2004). Yet, analyses of the U.S. indicate that the assumption that developed countries have low societal factors. The National Hurricane Center generally assumes that for the United States, total losses are twice insured loss estimates. However, this relationship will not hold for other countries or other weather phenomena.

Regardless of the uncertainties in estimating insured and total losses, it is clear that the absolute dollar value of losses from extreme events has increased dramatically over the past few decades, even after accounting for the effects of inflation (Figure 1.2). However, much of the increasing trend in losses, particularly from tropical cyclones, appears to be related to an increase in population and wealth (Pielke *et al.*, 2003; Pielke, 2005; Pielke and Landsea, 1998). The counter argument is that there is a climate change signal in recent damage trends. Damage trends have increased significantly despite ongoing adaptation efforts that have been taking place (Mills, 2005b; Stott *et al.*, 2004; Kunkel *et al.*, 1999). A number of other complicating factors also play a role in computing actual losses. For example, all other things being equal, the losses from Hurricane Katrina would have been dramatically lower if the dikes had not failed. Looking toward the future, the potential for an increase in storm intensity (*e.g.*, tropical cyclone wind speeds and precipitation) (Chapter 3, this report) and changes in the intensity of the hydrological cycle[2] (Trenberth *et al.*, 2003) raises the possibility that changes in climate extremes will contribute to an increase in loss.

Another confounding factor in assessing extremes through their impacts is that an extreme event that lasts for a few days, or even less, can have impacts that persist for decades. For example, it will take years for Honduras and Guatemala to recover from the damage caused by Hurricane Mitch in 1998 and it seems likely that New Orleans will need years to recover from Hurricane Katrina. Furthermore, extreme events not only produce “losers” but “winners”

In the U.S., 68% of water-borne disease outbreaks were preceded by downpours in the heaviest 20% of all precipitation events.

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[2] The hydrologic cycle is the continuous movement of water on, above, and below the surface of the Earth where it evaporates from the surface, condenses in clouds, falls to Earth as rain or snow, flows downhill in streams and rivers, and then evaporates again.

vulnerability may be premature, as independent studies have repeatedly concluded that water and food-borne pathogens (that cause diarrhea) will likely increase with projected increases in regional flooding events, primarily by contamination of main waterways (Rose *et al.*, 2000; Ebi *et al.*, 2006).

A U.S. study documented that 51% of water-borne disease outbreaks were preceded by precipitation events in the top 10% of occurrences, with 68% of outbreaks preceded by precipitation in the top 20% (Curriero *et al.*, 2001). These outbreaks comprised mainly intestinal disorders due to contaminated well water or water treatment facilities that allowed microbial pathogens, such as *E. coli*, to enter drinking water. In 1993, 54 people in Milwaukee, Wisconsin died in the largest reported flood-related disease outbreak (Curriero *et al.*, 2001). The costs associated with this one outbreak were $31.7 million in medical costs and $64.6 million in productivity losses (Corso *et al.*, 2003).

Another heavy precipitation-human health link comes from the southwestern desert of the United States. This area experienced extreme rainfalls during the intense 1992/1993 El Niño. Excess precipitation promoted lush vegetative growth, which led to population booms of deer mice (*Peromyscus maniculatus*). This wild rodent carries the hantavirus which is transmissible to humans and causes a hemorrhagic fever that is frequently lethal. The virus is normally present at moderate levels in wild mouse populations. In most years, humans in nearby settlements experienced little exposure. However, in 1993, local over-abundance of mice arising from the wet-year/population boom caused greater spill-over of rodent activity. Subsequent increased contact between mice and humans and resultant higher transmission rates led to a major regional epidemic of the virus (Engelthaler *et al.*, 1999; Glass *et al.*, 2000). Similar dynamics have been shown for plague in the western United States (Parmenter *et al.*, 1999).

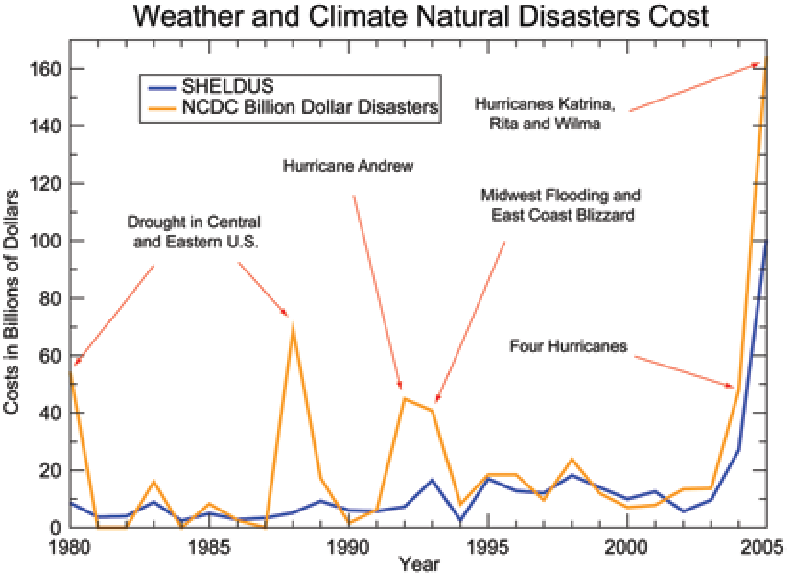

Figure 1.9 Different methodologies for collecting loss data can produce very different results. The NCDC Billion Dollar Weather Disasters loss data (Lott and Ross, 2006) assesses a subset of the largest events covered in the SHELDUS (Cutter and Emrich, 2005) loss data. SHELDUS is often less than the Billion Dollar Weather Disasters because (a) the SHELDUS event-based dataset does not fully capture drought costs and (b) SHELDUS assesses direct costs only while the Billion Dollar Weather Disasters estimates include both direct costs and indirect costs. Neither cost data set factors in the loss of life. Indeed, some extremes such as heat waves that can cause high loss of life may not show up at all in cost assessments because they cause very little property damage. Primary events contributing to peak values in the time series have been listed.

too. Examples of two extreme-event winners are the construction industry in response to rebuilding efforts and the tourism industry at locations that receive an unexpected influx of tourists who changed plans because their first-choice destination experienced an extreme event that crippled the local tourism facilities. Even in a natural ecosystem there are winners and losers. For example, the mountain pine beetle infestation that has decimated trees in British Columbia provided an increased food source for woodpeckers.

Different methodologies for collecting loss data can produce very different results.

1.5 SYSTEMS ARE ADAPTED TO THE HISTORICAL RANGE OF EXTREMES SO CHANGES IN EXTREMES POSE CHALLENGES

Over time, socioeconomic and natural systems adapt to their climate, including extremes. Snowstorms that bring traffic to a standstill in Atlanta are shrugged off in Minneapolis (WIST, 2002). Hurricane-force winds that topple tall, non-indigenous Florida trees like the Australian pine (*Casuarina equisetifolia*) may only break a few small branches from the native live oak (*Quercus virginiana*) or gumbo-limbo (*Bursera simaruba*) trees that evolved in areas frequented by strong winds. Some species even depend on major extremes. For example, the jack pine (*Pinus banksiana*) produces very durable resin-filled cones that remain dormant until wildfire flames melt the resin. Then, the cones pop open and spread their seeds (Herring, 1999).

Therefore, it is less a question of whether extremes are good or bad, but rather, what will be the impact of their changing characteristics? For certain species and biological systems, various processes may undergo sudden shifts at specific thresholds of temperature or precipitation (Precht *et al.*, 1973; Weiser, 1973; Hoffman and Parsons, 1997), as discussed in Section 1.3. Generally, managed systems are more buffered against extreme events than natural systems, but certainly are not immune to them. The heat waves of 1995 in Chicago and 2003 in Europe caused considerable loss of life in large part because building architecture and city design were adapted for more temperate climates and not adapted for dealing with such extreme and enduring heat (Patz *et al.*, 2005). As an illustration, mortality from a future heat wave analogous to the European heat wave of 2003 is estimated to be only 2% above that of the previous hottest historical summer for Washington, D.C., while New York, with its less heat-tolerant architecture, is estimated to have mortality 155% above its previous record hot summer (Kalkstein *et al.*, 2008). On balance, because systems have adapted to their historical range of extremes, the majority of the impacts of events outside this range are negative (IPCC, 2007b).

When considering how the statistics of extreme events have changed, and may change in the future, it is important to recognize how such changes may affect efforts to adapt to them. Adaptation is important because it can reduce the extent of damage caused by extremes (*e.g.*, Mileti, 1999; Wilhite, 2005). Currently, long-term

planning uses, where possible, the longest historical climate records, including consideration of extreme events. The combined probabilities of various parameters that can occur at any given location can be considered the cumulative hazard of a place. Past observations lead to expectations of their recurrence, and these form the basis of building codes, infrastructure design and operation, land-use zoning and planning, insurance rates, and emergency response plans.

However, what would happen if statistical attributes of extreme events were to change as the climate changes? Individuals, groups, and societies would seek to adjust to changing exposure. Yet the climate may be changing in ways that pose difficulties to the historical decision-making approaches (Burton *et al.*, 1993). The solution is not just a matter of utilizing projections of future climate (usually from computer simulations). It also involves translating the projected changes in climate extremes into changes in risk.

Smit *et al.* (2000) outline an "anatomy" of adaptation to climate change and variability, consisting of four elements: a) adapt to what, b) who or what adapts, c) how does adaptation occur, and d) how good is the adaptation. Changes in the statistics of climate extremes will influence the adaptation. As noted earlier, a change in the frequency of extreme events may be relatively large, even though the change in the average is small. Increased frequencies of extreme events could lead to reduced time available for recovery, altering the feasibility and effectiveness of adaptation measures. Changes to the timing and duration of extremes, as well as the occurrence of new extreme thresholds (*e.g.*, greater precipitation intensity, stronger wind speeds), would be a challenge to both managed and unmanaged systems.

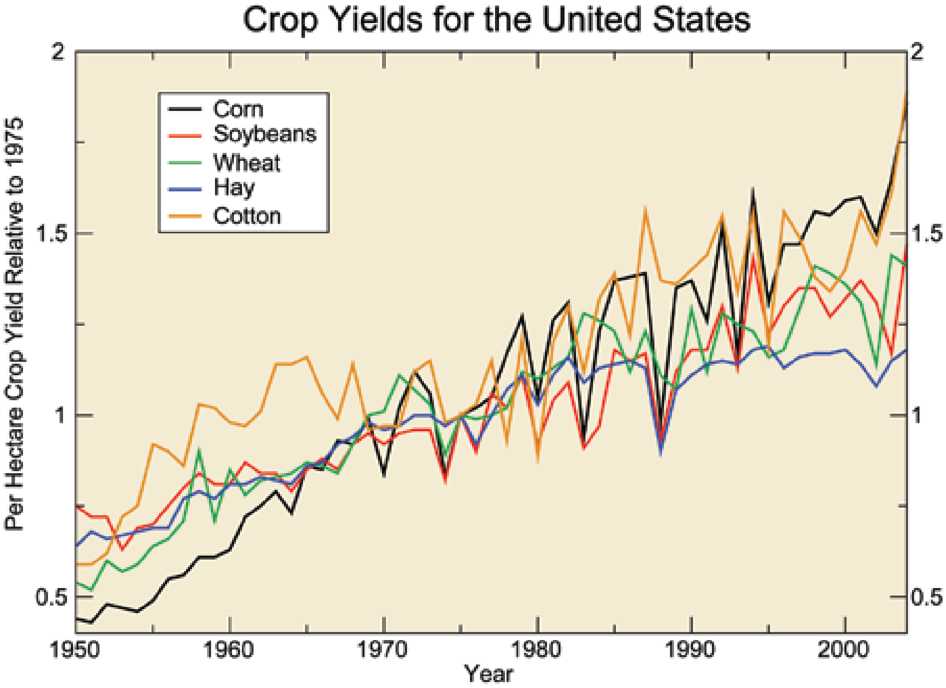

Figure 1.10 Climate variability may produce years with reduced crop yield, but because of technological improvements, a poor yield in the 1990s can still be higher than a good yield in the 1950s indicating a changing relationship between climate and agricultural yield. Data are in units of cubic meters or metric tons per unit area with the yield in 1975 assigned a value of 1. Data from USDA National Agricultural Statistics Service via update to Heinz Center (2002).

Trends in losses or productivity of climate-sensitive goods exhibit the influences of both climate variability/change and ongoing behavioral adjustments. For example, U.S. crop yields have generally increased with the introduction of new technologies. As illustrated by Figure 1.10, climatic variability still causes short-term fluctuations in crop production, but a poor year in the 1990s tends to have better yields than a poor year (and sometimes even a good year) in the 1960s. Across the world, property losses show a substantial increase in the last 50 years, but this trend is being influenced by both increasing property development and offsetting adaptive behavior. For example, economic growth has spurred additional construction in vulnerable areas but the new construction is often better able to withstand extremes than older construction. Future changes in extreme events will be accompanied by both autonomous and planned adaptation, which will further complicate calculating losses due to extremes.

It is less a question of whether extremes are good or bad, but rather, what will be the impact of their changing characteristics?

1.6 ACTIONS CAN INCREASE OR DECREASE THE IMPACT OF EXTREMES

It is important to note that most people do not use climate and weather data and forecasts directly. People who make decisions based

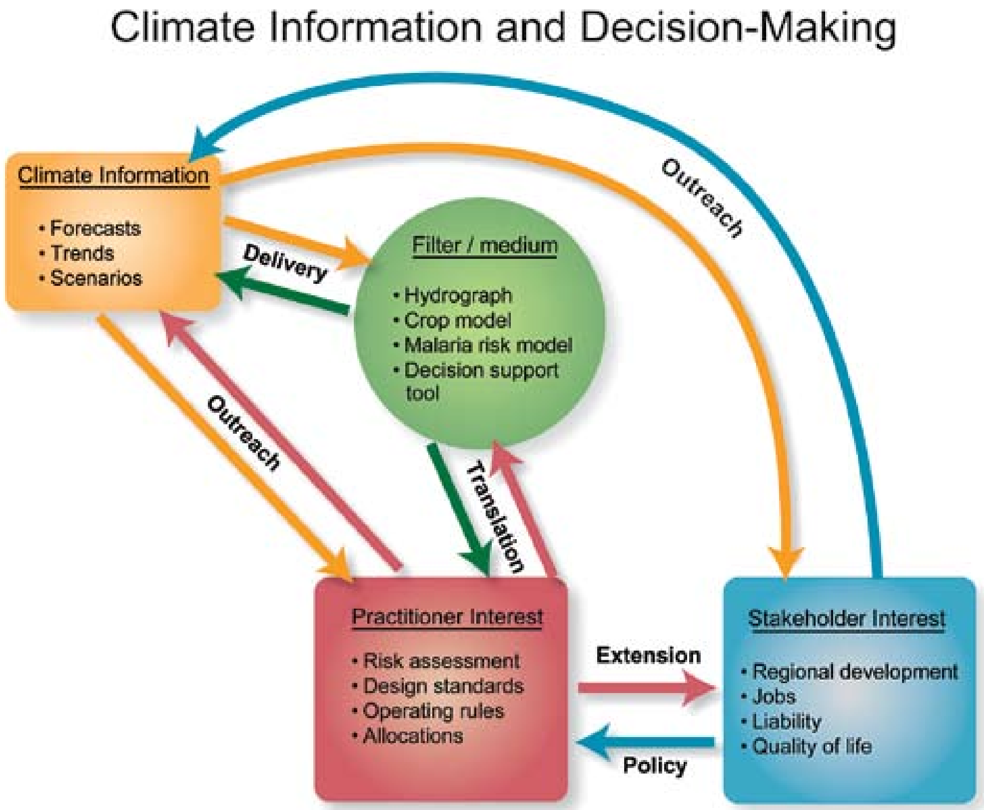

Figure 1.11 Illustration of how climate information is processed, filtered, and combined with other information in the decision process relevant to stakeholder interests (adapted from Cohen and Waddell, 2008).

Paradoxically, focusing on short-term risk reduction, such as building levees, can increase vulnerability to future large extreme events by stimulating development in unsafe locations.

on meteorological information typically base their decisions on the output of an intermediate model that translates the data into a form that is more relevant for their decision process (Figure 1.11). For example, a farmer will not use weather forecasts or climate data directly when making a decision on when to fertilize a crop or on how much pesticide to apply. Instead, the forecast is filtered through a model or mental construct that uses such information as one part of the decision process and includes other inputs such as crop type, previous pesticide application history, government regulations, market conditions, producer recommendations, and the prevalence and type of pest.

One useful decision tool is a plant hardiness zone map (Cathey, 1990). Plant hardiness zones are primarily dependent on extreme cold temperatures. Due to changing locations of plant hardiness zones, people are already planting fruit trees, such as cherries, farther north than they did 30 years ago as the probability of winterkill has diminished. This type of adaptation is common among farmers who continually strive to plant crop species and varieties well suited to their current local climate.

To a large extent, individual losses for hazard victims have been reduced as the larger society absorbs a portion of their losses through disaster relief and insurance. Clearly relevant for settings such as New Orleans is the so-called levee effect, first discussed by Burton (1962), in which construction of levees (as well as dams, revetments, and artificially-nourished beaches) induces additional development, leading to much larger losses when the levee is eventually overtopped. A more general statement of this proposition is found in the safe development paradox in which increased perceived safety (*e.g.*, due to flood control measures), induces increased development (such as in areas considered safe due to the protection provided by levees or dams), leading to increased losses when a major event hits. The notion that cumulative reduction of smaller scale risks might increase vulnerability to large events has been referred to as the levee effect, even when the concern has nothing to do with levees (Bowden *et al.*, 1981).

After particularly severe or visible catastrophes, policy windows have been identified as windows of opportunity for creating long-term risk reduction plans that can include adaptation for climate change. A policy window opens when the opportunity arises to change policy direction and is thus an important part of agenda setting (Kingdon, 1995). Policy windows can be created by triggering or focusing events, such as disasters, as well as by changes in government and shifts in public opinion. Immediately following a disaster, the social climate may be conducive to much needed legal, economic, and social change, which can begin to reduce structural vulnerabilities. Indeed, an extreme event that is far outside normal experience can alert society to the realization that extremes are changing and that society must adapt to these changes.

The assumptions behind the utility of policy windows are that (1) new awareness of risks after a disaster leads to broad consensus, (2) agencies are reminded of disaster risks, and (3) enhanced community will and resources become available. However, during the post-emergency phase, reconstruction requires weighing, prioritizing, and sequencing of policy programming, and there are usually many diverse public and private agendas for decision makers and operational actors to incorporate, with attendant requests for resources for various actions. Thus, there is pressure to quickly return to the "normal" conditions that existed prior to the event, rather than incorporate longer-term development strategies (Berube and Katz, 2005; Christoplos, 2006). In addition, while institutional capacity for adaptation clearly matters, it is often not there in the aftermath (or even before the occurrence) of a disaster.

In contrast to the actual reconstruction plans, the *de facto* decisions and rebuilding undertaken ten months after Katrina clearly demonstrate the rush to rebuild the familiar, as found after other major disasters in other parts of the world (Kates *et al.*, 2006). This perspective helps explain the evolution of vulnerability of settings such as New Orleans, where smaller events have been mitigated, but with attendant increases in long-term vulnerability. As in diverse contexts such as El Niño-Southern Oscillation (ENSO)-related impacts in Latin America, induced development below dams or levees in the United States, and flooding in the United Kingdom, the result is that focusing only on short-term risk reduction can actually produce greater vulnerability to future events (Pulwarty *et al.*, 2003). Thus, the evolution of responses in the short-term after each extreme event can appear logical, but might actually increase long-term risk to larger or more frequent events. Adaptation to climate change must be placed within the context of adaptation to climate across time scales (from extremes and year-to-year variability through long-term change) if it is to be embedded into effective response strategies.

Global losses from weather-related disasters amounted to a total of around $83 billion for the 1970s, increasing to a total of around $440 billion for the 1990s with the number of great natural catastrophe events increasing from 29 to 74 between those decades (MunichRe, 2004; Stern, 2006).

There is pressure to quickly return to the "normal" conditions that existed prior to the event, rather than incorporate longer-term development strategies.

1.7 ASSESSING IMPACTS OF CHANGES IN EXTREMES IS DIFFICULT

As has been mentioned, assessing consequences relevant to extreme weather and climate events is not simply a function of the weather and climate phenomena but depends critically on the vulnerability of the system being impacted. Thus, the context in which these extreme events take place is crucial. This means that while the changes in extreme events are consistent with a warming climate (IPCC, 2007a), any analysis of past events or projection of future events has to carefully weigh non-climatic factors. In particular, consideration must be given to changes

BOX 1.6: Tools for Assessing Impacts of Climate Extremes

There are a variety of impact tools that help translate climate information into an assessment of what the impacts will be and provide guidance on how to plan accordingly. These tools would be part of the filter/medium circle in Figure 1.11. However, as illustrated here, using the example of a catastrophe risk model, the tool has clear linkages to all the other boxes in Figure 1.11.

A catastrophe risk model can be divided into four main components, as shown in Figure Box 1.6. The hazard component provides information on the characteristics of a hazard. For probabilistic calculations, this component would include a catalog with a large number of simulated events with realistic characteristics and frequencies. Event information for each hazard would include the frequency, size, location, and other characteristics. The overall statistics should agree with an analysis of historical events.

The inventory component provides an inventory of structures that are exposed to a hazard and information on their construction. The vulnerability component simulates how structures respond to a hazard. This component requires detailed information on the statistical response of a structure to the forces produced by a hazard. This component would also account for secondary damage such as interior water damage after a structure's windows are breached. The fourth component in the risk model estimates losses produced by a hazard event and accounts for repair or replacement costs. In cases of insurance coverage, the loss component also accounts for business interruption costs and demand surge. If the model is used for emergency management purposes, the loss component also accounts for factors such as emergency supplies and shelters.

It should be noted, though, that how the loss component is treated impacts the vulnerability and inventory components, as indicated by the curved upward pointing arrows. Is a house destroyed in a flood rebuilt in the same location or on higher ground? Is a wind-damaged building repaired using materials that meet higher standards? These actions have profound effects on future catastrophe risk models for the area.

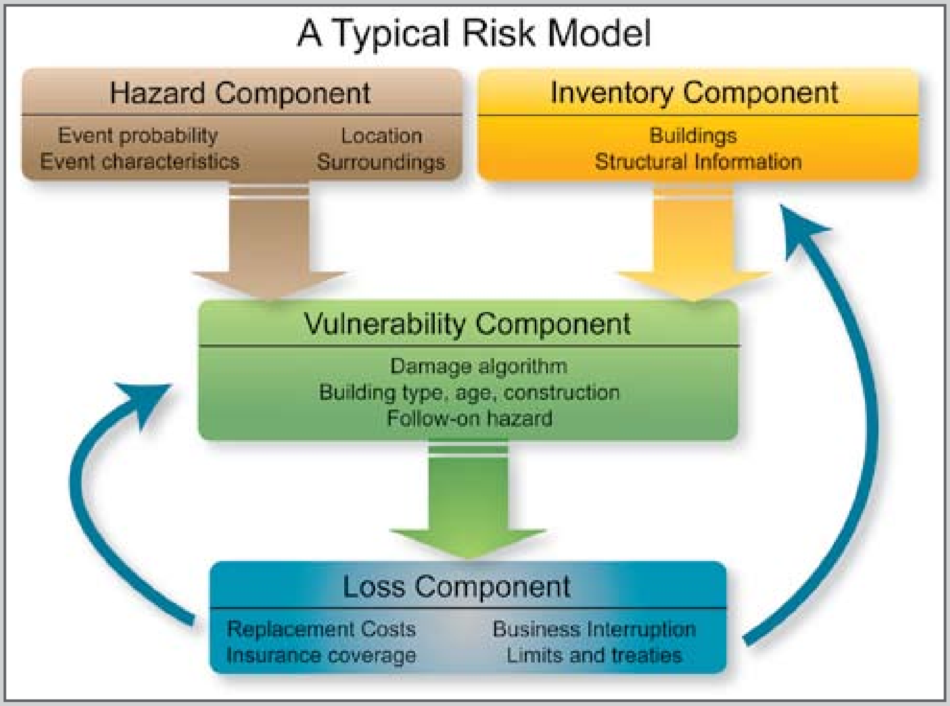

Figure Box 1.6 Schematic diagram of a typical risk model used by the insurance industry. The diagram highlights the three major components (hazard, damage, and loss) of a risk model. What happens to the loss component feeds back to the vulnerability and inventory components.

in demographic distributions and wealth, as well as the use of discount rates in assessments of future damage costs. The analysis presented by Stern (2006), regarding projected increased damage costs, has led to considerable debate on the methods for incorporating future climate and socioeconomic scenarios, including the role of adaptation, into such assessments (Pielke, 2007; Stern and Taylor, 2007; Tol and Yohe, 2006). Regarding recent trends in weather-related economic losses shown in Figure 1.2, it is likely that part of the increase in economic losses shown in Figure 1.2 has been due to increases in population in regions that are vulnerable, such as coastal communities affected by hurricanes, sea-level rise, and storm surges. In addition, property values have risen. These factors increase the sensitivity of our infrastructure to extreme events. Together with the expected increase in the frequency and severity of extreme events (IPCC, 2007a; Chapter 3 this report), our vulnerability to extreme events is very likely to increase. Unfortunately, because many extreme events occur at small temporal and spatial scales, where climate simulation skill is currently limited and local conditions are highly variable, projections of future impacts cannot always be made with a high level of confidence.

While anthropogenic climate change very likely will affect the distribution of extreme events (and is already observed to be having such effects – Chapter 2), it can be misleading to attribute any particular event solely to human causes. Nevertheless, scientifically valid statements regarding the increased risk can sometimes be made. A case in point is the 2003 heat wave in Europe, where it is very likely that human influence at least doubled the risk of such a heat wave occurring (Stott *et al.*, 2004). Furthermore, over time, there is expected to be some autonomous adaptation to experienced climate variability and other stresses. Farmers, for example, have traditionally altered their agricultural practices, such as planting different crop varieties based on experience, and water engineers have built dams and reservoirs to better manage resources during recurring floods or droughts. Such adaptation needs to be considered when assessing the importance of future extreme events.

Assessing historical extreme weather and climate events is more complicated than just the statistical analysis of available data. Intense rain storms are often of short duration and not always captured in standard meteorological records; however, they can often do considerable damage to urban communities, especially if the infrastructure has not been enhanced as the communities have grown. Similarly, intense wind events (hurricanes are a particular example), may occur in sparsely populated areas or over the oceans, and it is only since the 1960s, with the advent of satellite observations, that a comprehensive picture can be confidently assembled. Therefore, it is important to continually update the data sets and improve the analyses. For example, probabilistic estimates of rainfall intensities for a range of event durations (from 5 minutes to 24 hours) with recurrence intervals of 20, 50, and 100 years (*e.g.*, a 10-minute rainfall that should statistically occur only once in 100 years), have long been employed by engineers when designing many types of infrastructure. In the United States, these probabilistic estimates of intense precipitation are in the process of being updated. Newer analyses based on up-to-date rainfall records often differ by more than 45% from analyses done in the 1970s (Bonnin *et al.*, 2003).

1.8 SUMMARY AND CONCLUSIONS

Weather and climate extremes have always been present. Both socioeconomic and natural systems are adapted to historical extremes. Changes from this historical range matter because people, plants, and animals tend to be more impacted by changes in extremes compared to changes in average climate. Extremes are changing, and in some cases, impacts on socioeconomic and natu-

Vulnerability is a function not only of the rate and magnitude of climate change but also of the sensitivity of the system, the extent to which it is exposed, and its adaptive capacity.

ral systems have been observed. The vulnerability of these systems is a function not only of the rate and magnitude of climate change but also of the sensitivity of the system, the extent to which it is exposed, and its adaptive capacity. Vulnerability can be exacerbated by other stresses such as social inequalities, disease, and conflict, and can be compounded by changes in other extremes events (*e.g.*, drought and heat occurring together) and by rapidly-recurring events.

Vulnerability to extreme events can be exacerbated by other stresses such as social inequalities, disease, and conflict.

Despite the widespread evidence that humans have been impacted by extreme events in the past, projecting future risk to changing climate extremes is difficult. Extreme phenomena are often more difficult to project than changes in mean climate. In addition, systems are adapting and changing their vulnerability to risk in different ways. The ability to adapt differs among systems and changes through time. Decisions to adapt to or mitigate the effect of changing extremes will be based not only on our understanding of climate processes but also on our understanding of the vulnerability of socioeconomic and natural systems.