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 socio-economic 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. The latter is shaped by factors such as population dynamics and poverty as well as by development and utilization of climate change adaptation measures such as appropriate building codes, disaster preparedness, and water use efficiency.
- Changes in extreme events are already observed to be having impacts on socio-economic 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 is 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 can lead to increases in vulnerability to larger extremes in the long-term.

1.1 Extremes Matter Because They Impact People, Plants, and Animals

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 climate could change without extremes changing as well. Extreme events drive natural systems much more than average climate (Parmesan *et al.*, 2000). Extreme events cause property damage, injury, loss of life and threaten the existence of some species. Society recognizes the need to plan for the protection of communities from extreme events of various kinds. Structural measures (such as engineering works), governance measures (such as zoning and building codes), financial instruments (such as insurance and contingency funds) and emergency measures practices have all been used to lessen the impacts of historical extremes. To the extent that changes in extremes can be reliably forecast, society can engage in practices that would mitigate future impacts.

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 orbital parameters, volcanic eruptions, and fluctuations in solar output. Since the late nineteenth century, atmospheric concentrations of carbon dioxide and other trace greenhouse gases (GHG) have been increasing due to human activity, such as fossil-fuel combustion and land-use change. On average, the world has warmed by 0.74°C over the last century with most of that coming in the last three decades, as documented by instrumental 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 shift in ecosystem functioning, shrinking sea ice (Arctic Climate Impact Assessment, 2004), earlier spring events 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 has very likely 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 by the end of this Century (IPCC, 2007a).

Extremes are already having significant impacts on North America. As examination of Figure 1.1 reveals, it is a rare year when the United States doesn't have any billion dollar weather and climate-related disasters. Furthermore, the costs of weather and climate-related disasters in the U.S. have been increasing faster than non-weather related disaster costs (Hazards and Vulnerability Research Institute, 2007). 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 socio-economic vulnerability to weather and climate extremes are changing, although their relative contributions to observed increases in disaster costs are subject to debate. For example the extent to which increases in coastal building damage is due to population growth[1] in vulnerable coastal locations versus increase in storm intensity is not easily quantified. 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.

Hurricanes and tropical storms are the leading cause of billion dollar weather and climate events followed by floods, droughts and heat waves.. It should be noted that 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. The annual mean loss of life from weather extremes in the U.S. exceeds 1,500 per year (Kunkel *et al.*, 1999) without including such factors as fog-related traffic fatalities. Approximately half

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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).

of these deaths are related to hypothermia due to extreme cold, with extreme heat responsible for another one-fourth of the fatalities. There appears to be no trend in the number of these deaths (Goklany and Straja, 2000). However, it should be noted that 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 amelioration 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). The observed warming-related biological changes may have direct adverse effects on biodiversity, which in turn may 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.

This introductory chapter addresses various questions that are relevant to the points raised above. Section 1.2 focuses on defining characteristics of extremes. Section 1.3 discusses the sensitivities of socio-economic 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 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 text boxes, which highlight a number of topics related to particular extremes and their impacts, as well as analysis tools for assessing impacts.

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 temporal considerations, 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 of values far away from the average. Extreme temperatures are in the tails of such distributions, as shown in the top panel of Figure 1.2.

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. Definitions of *rare* vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile[2] of

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[2] On average, one in every ten temperature values is cold enough to be at or below the 10th percentile just as one in every ten temperature values is hot enough to be at or above the 90th percentile.

the observed probability density function[3]. By definition, the characteristics of what is called 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 similarly to the tails on the temperature distribution.

Daily precipitation, however, has a distribution which is very different than the temperature distribution. Over most of 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 a few have heavy precipitation, as illustrated by the bottom panel of Figure 1.2. 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 natural variability that public health services were unprepared for the excess mortality (see Figure 1.3). 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 is an extreme. This is because most extreme wind events are

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[3] A probability density function is the distribution of the probabilities of all different possible weather or climate events which is depicted by the heavy black lines in Figure 1.2.

generated by special meteorological conditions that are well known. For purposes of this report, all tornadoes and hurricanes are considered extreme. 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 are just one aspect of the measure of intensity of these storms.

Most considerations of extreme weather and climate events are limited to discrete occurrences. However, in some cases, events that occur repeatedly can have impacts greater than the simple sum of each individual event. For example, the ice storm that occurred in eastern Ontario and southern Quebec in 1998 was the most destructive and disruptive storm in Canada in recent memory. The storm featured record amounts of freezing rain and sleet in a series of storms over a record number of hours. Further, the storm brutalized an area extending nearly 1000 km which included one of the largest urban areas of Canada, leaving more than 4 million people freezing in the dark for hours, if not days. The conditions were so severe that no clean-up action could be taken between storms and the ice built up, stranding even more people at airports, bringing down high-tension transmission towers, and straining food supplies. Such cumulative events need special consideration.

Also, compound extremes are conditions that depend on two or more parameters. For example, heat waves have greater impacts on human health when they are accompanied by high humidity. Additionally, problems with one extreme, such as a windstorm, may only be present if it is preceded by a different extreme, such as drought, which would, in this example, result in far more wind-blown dust than the storm would generate without the drought.

As the global climate continues to adjust to changes in radiative forcing brought on by increasing concentrations of GHG in the atmosphere, many different aspects of extremes have the potential to change as well (Easterling *et al.*, 2000a,b). The most commonly considered parameter 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. Are, for example, hurricanes becoming more intense? This is important because, as explained in the box on hurricanes, damage increases exponentially with the speed of the wind so a more 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 snow melt in the western mountains has become earlier (Johnson *et al.*, 1999; Cayan *et al.* 2001). Earlier snowmelt in the Sierra Nevada 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, human-induced warming of summer temperatures has a detectable influence on the increased 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. The duration of events (such as heat waves, flood-inducing rains, and droughts), is also potentially subject to change. Spatial characteristics also 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 1.4 illustrates how the tails of the distribution of temperature and precipitation are anticipated to change in a warming world. For temperature both the 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 indicates an increase in the number of heavy rain events which are balanced by a proportionate decrease in the number of light precipitation events.

1.3 Systems Are Sensitive to Changes in Extremes

Climate sensitivity is defined as the degree to which a system is affected by climate-related stimuli. The effect may be direct, such as changing crop yield 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 climate sensitivity can include changes in, timing of life events, or distributions of individual species, or alteration of whole ecosystem functioning (Parmesan and Yohe, 2003; Parmesan and Galbraith, 2004).

Climate sensitivity 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. 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 climate sensitivity of the community. 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 mid to late 1500s contributed to conditions that caused tremendous population declines as illustrated by Figure 1.5 — socio-economic 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 an anticipated gradual decline in impacts, 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 measures to reduces 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). The nine-banded armadillo (Dasypus novemcinctus) cannot tolerate more than nine consecutive days below freezing (Taulman and Robbins, 1996). The high sea surface temperature (SST) 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 the box 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 and subsequent population declines and extirpation in certain butterfly species (Parmesan, 1996, 2005).

By far, most of the documented impacts on natural systems have been ecological in nature. 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 of a magnitude approximately equal to the degree expected from the observed shift in thermal isotherms from 0.7 C warming – about 100 km northward and 100 m upward (Parmesan, 1996; Karl *et al.*, 1996). Phenological (*e.g.*, timing) changes includes 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 of the clearest examples of the impacts of warming on whole ecosystem functioning comes from the Arctic tundra, where warming trends have been considerably stronger than in the contiguous U.S. Melting and drying of the permafrost layer has caused an increase in decomposition rates of dead organic matter during winter, which ultimately in some areas has already resulted in a shift from the tundra being a carbon sink to being a carbon source (Oechel *et a.*, 1993; Oechel *et al.*, 2000).

Very few behavioral changes have been observed, but there is some evidence that individuals of the sooty shearwater 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 productivity 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, 2007). The best example comes from the bacteria which causes human cholera, *Vibrio cholerae,* which lives in brackish rivers and sea water and uses a diversity of marine life as reservoirs, including many shellfish, some fish, and even water hyacinth. Two-hundred years of observational records strong repeated patterns in which extreme warm water temperatures cause algae blooms which then promote rapid increases in zooplankton abundances, and hence also in their associated *V. cholerae* bacteria (Colwell, 1996). Analyses of long-term data sets from Peru and Bangladesch (from 18 years up to 70 years) show that cholera has recently become associated with El Niño events, suggesting a threshold for high transmission as only recently been commonly surpassed as El Niño events have become stronger and more frequent in the past three decades (Pascual *et al.*, 2000: Rodó *et al.,* 2002). Even when known epidemiological dynamics are taken into account (such as cycling of immunity in human populations), a strong El Niño signal in cholera dynamics is maintained (Koelle *et al.*, 2005). In summary, there is compelling evidence for links between climate variability, climate change (via increases in strength of El Niño), native plankton dynamics, bacterial dynamics in the wild, and cholera disease epidemics.

1.4 Future Impacts of Changing Extremes Also Depend on System 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, extreme events are important precisely because 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 socio-economic 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 variation to which a system is exposed, its sensitivity, and its adaptive capacity. A system can be sensitive to change but not vulnerable, such as agriculture in North America; 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, which is not correlated with temperatures in the U.S. because of highly-developed sanitation facilities, shows a strong correlation with high temperatures in Lima, Peru (Checkley *et al.*, 2000; WHO, 2003, 2004). Thus, vulnerability is highly dependent on robust societal infrastructures, which have been shown to break down under flood events even in the U.S. (Curreriero *et al.*, 2001). Systems that normally survive are 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 quickly recover.

The adaptive capacity of socio-economic systems is determined largely by their 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). The first major industry sector to pay attention to the threats posed by climate change was insurance, which 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 policy-holders 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 1.6.

Extreme events themselves can alter vulnerability and expose underlying stresses. There are obvious 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 for recovery can exacerbate the impacts as illustrated in the bottom panel of Figure 1.6. For example, in 2005 there was a series of hurricanes that 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. Hardware stores and lumberyards were not able to restock quickly enough. A multitude or sequence of extreme events can also strain the abilities of insurance and re-insurance companies to compensate victims. Extremes can also initiate adaptive responses. For example, droughts in the 1930s triggered waves of human migration that altered the demographics 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 in the Great Lakes region to 50 mm for Newfoundland and Labrador (Canadian Standards Association, 2001).

Factors such as societal exposure, vulnerability, and sensitivity to weather and climate can play a significant role in determining whether a weather or climate 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 an exposure unit[4] 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, consider the different effects and responses in a city with a well-developed water supply infrastructure

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[4] An exposure unit can be a person, home, city, or animal or plant community.

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 socio-economic 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 socio-economic 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 (Cutter *et al.*, 2007). 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.

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 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 over the past few decades, even after accounting for the effects of inflation (see Figure 1.1). 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. Similarly, those 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. In addition, the potential for an increase in storm intensity (*e.g.*, tropical cyclone wind speeds and precipitation) (Knutson and Tuleya, 2003) and the intensity of the hydrological cycle[5] (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” 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 in British Columbia has been warmly greeted as a dinner bell by woodpeckers.

1.5 Systems are Adapted to Particular Morphologies of Extremes so Changes in Extremes Pose Challenges

Over time, socio-economic and natural systems adapt to their climate, including extremes. Snowstorms that bring traffic to a standstill in Atlanta are shrugged off in Minneapolis. 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

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[5] 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.

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 happening. 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). 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 time series, 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 global climate model projections. It is also involves translating the projected changes in 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. Changing extreme statistics will influence the adaptation. As noted earlier, a change in the frequency of extreme events may be relatively large, even though the change in mean 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.

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 1.7, 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 event will be accompanied by both autonomous and planned adaptation, which will further complicate calculating losses due to extremes.

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 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 1.8). 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. Already due to changing locations of plant hardiness zones, people are 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 (dams, revetments, beach nourishment) 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 safety (*e.g.*, flood control) 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 which 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 out of normal experience can wake society up 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-recovery phase, reconstruction requires weighing, prioritizing, and sequencing of policy programming, and there are usually too many mainstreaming agendas for most decision makers and operational actors to digest with attendant requests for resources for various actions. Thus, there is pressure to quickly return to the “normal” conditions prior to the event, rather than incorporate longer-term development strategies (Berube and Katz, 2005; Christoplos, 2006). In addition, while adaptive institutions clearly matter, they are 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 interannual variability through long-term change) if it is to be embedded into effective response strategies.

According to the Stern Review on the economics of climate change (Stern, 2006), "many developing countries are already struggling to cope with their current climate. Both the economic costs of natural disasters and their frequency have increased dramatically in the recent past. Global losses from weather-related disasters amounted to a total of around $83 billion during the 1970s, increasing to a total of around $440 billion in the 1990s with the number of 'great natural catastrophe' events increasing from 29 to 74 between those decades. The financial costs of extreme weather events represent a greater proportion of GDP loss in developing countries, even if the absolute costs are more in developed countries given the higher monetary value of infrastructure. And over 96% of all disaster-related deaths worldwide in recent years have occurred in developing countries. Climatic shocks can - and do - cause setbacks to economic and social development in developing countries. The IMF, for example, estimates costs of over 5% of GDP per large disaster on average in low-income countries between 1997 and 2001." Given the high costs, wise adaptation has ample opportunity to save money in the long run.

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 hydrometeorological 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 in demographic distributions and wealth. It is likely that part of the increase in economic losses shown in Figure 1.1 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), our vulnerability to extreme events is very likely to increase. Unfortunately, because many extreme events occur at small temporal and spatial scales, where model 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 is very likely to affect the distribution of extreme events, 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 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 put together. 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 durations, from 5 minutes to 24 hours for return periods, or recurrence intervals of 20, 50, and 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 analysis 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

For good and for ill, weather and climate extremes have always been present. Both socio-economic 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 socio-economic and natural systems have been observed. The vulnerability of these systems is a function not only of the rate and magnitude of climate change but also depends on 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.

Despite the widespread evidence that humans have been impacted by extreme events in the past, predicting future risk to changing climate extremes is difficult. Extreme phenomena are often more difficult to predict 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 socio-economic and natural systems.

BOX 1.1: Warm Temperature Extremes and Coral Bleaching

Corals are marine animals that obtain much of their nutrients from symbiotic unicellular algae that live protected within the coral's calcium carbonate skeleton. Elevated sea surface temperatures (SST), one degree C above long-term summer averages, lead to the loss of algal symbionts resulting in bleaching of tropical corals (Hoegh-Guldberg, 1999). While global SST has risen an average of 0.13°C per decade since 1950 (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 (up to 95% of corals bleached in the Indian Ocean), ultimately resulting in 16% of corals dying globally (Hoegh-Guldberg, 1999, 2005; Wilkinson, 2000).

Recent evidence for genetic variation in temperature thresholds among the obligate algal symbionts suggests that some evolutionary response to higher water temperatures may be possible (Baker, 2001; Rowan, 2004). Changes in genotype frequencies toward increased frequency of high temperature-tolerant symbionts 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 symbionts 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 anthropogenic 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 socio-economic impacts.

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 (see Figure 1.9). 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 warm summers, which enable the mountain pine beetle (*Dendroctonus ponderosae*), in the contiguous United States, to have 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 winter temperatures, specifically 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. The supercooling threshold, which is the temperature at which the insect freezes and dies, for spruce beetle larvae, is −41°C[6] and for adults −37°C (Werner *et al*., 2006). Recent warming, limiting the frequency of sub−40°C occurrences, has reduced over-winter mortality of mountain pine beetle larvae in British Columbia. It has led to an explosion of the beetle population, with tree losses covering an area of 8.7 million hectares[7] 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 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

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[6] The freezing point of water is 0°C or 32°F. The boiling point of water is 100 degrees higher in Celsius (100°C) and 180 degrees higher in Fahrenheit (212°F). Therefore, to convert from Celsius to Fahrenheit, multiply the Celsius temperature by 1.8 and then add 32.

[7] One hectare is 10,000 square meters or the area in a square with sides of 100 meters and equals 2.5 acres.

hectares, approximately 40% more forest area than had infested the state the previous 70 years (Werner *et al*., 2006). The economic loss goes well beyond the millions of board feet of dead 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).

The beetle-forest relationships are much more complex than just climate and beetle survival and life cycle. 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 risks. Forest managers are struggling to keep up with changing conditions brought about by changing climate extremes.

BOX 1.3: Heavy Precipitation and Human Health

Anthropogenic climate change is already affecting human health (WHO 2002, 2003, 2004). For the year 2000, the World Health Organization 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). Precipitation extremes also cause increases in malnutrition due to drought and flood-related crop failure. For all impacts combined, WHO estimated that for a single year, total deaths due to climate change of 150,000 people (WHO 2002).

There is general agreement that the health sectors are 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 socio-economic status (Patz *et al.,* 2001; IPCC 2001b; Gubler *et al.,* 2001; Campbell-Lendrum *et al.,* 2003; Wilkinson *et al.,* 2003; WHO 2004, IPCC 2007b).

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). Studies for the U.S., however, indicate that the assumption that developed countries have low 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 waterborne disease outbreaks were preceded by precipitation events above the 90th percentile, with 68% of outbreaks preceded by precipitation above the 80th percentile (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 overcrowding arising from the wet-year/population boom, caused greater spillover rodent activity. Subsequent increased human contact and 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).

BOX 1.4: Drought

Drought should not be viewed as merely a physical phenomenon. Its impacts on society result from the interplay between a physical event (less precipitation than expected) and the demand 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 1.10. FEMA (1995) estimates that 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 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[8] (maf) per year, lower than the driest period during the Dust Bowl years of (1931-35 with 11.4 maf), and the 1950s with (10.2 maf) (Pulwarty *et al*., 2005). For the winter of 2004-5, average precipitation in the Basin was around 100% of normal. However, the combination of low antecedent soil moisture (absorption into soil and 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[9] 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

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[8] One acre foot is equal to 325,853 U.S. gallons or 1233.5 cubic meters.

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

Colorado River Compact[10] prioritizes the delivery of water to the Lower Basin states of Arizona, 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).

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 but 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 1.5: Hurricanes

There are substantial vulnerabilities from hurricanes along the Atlantic seaboard of the United States. Four major concentrations of economic vulnerability (capital stock greater

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[10] 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.

than $100 billion) are along the Miami coast, 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*., 2007; Collins and Lowe, 2001).

Property damages are well correlated to hurricane intensity. The formula for the kinetic energy of a moving object, be it a baseball or the wind, is one half the mass times the square of the speed. The mass of the wind in a hurricane does not change significantly. However because the kinetic energy increases with the square of the wind speed, faster winds have much more energy, dramatically increasing damages, as shown in Figure 1.11. 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 with the eighth power of maximum wind speed. The 2005 total hurricane economic damage of $174 billion was primarily due to the cost of Katrina ($135 billion). 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.

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*., 2007). However, 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) actually conditions 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 drought in the United States and Africa, tropical cyclones in Bangladesh, and floods and hurricanes in the United States. On the other hand, a reduction in 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 1.6: Impacts Tools

There are a variety of impact tools that help users 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 1.8. However, as illustrated, using the example of a catastrophe risk model, the model has clear linkages to all the other boxes in Figure 1.8.

A catastrophe risk model can be divided into four main components, as shown in Figure 1.12. 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.

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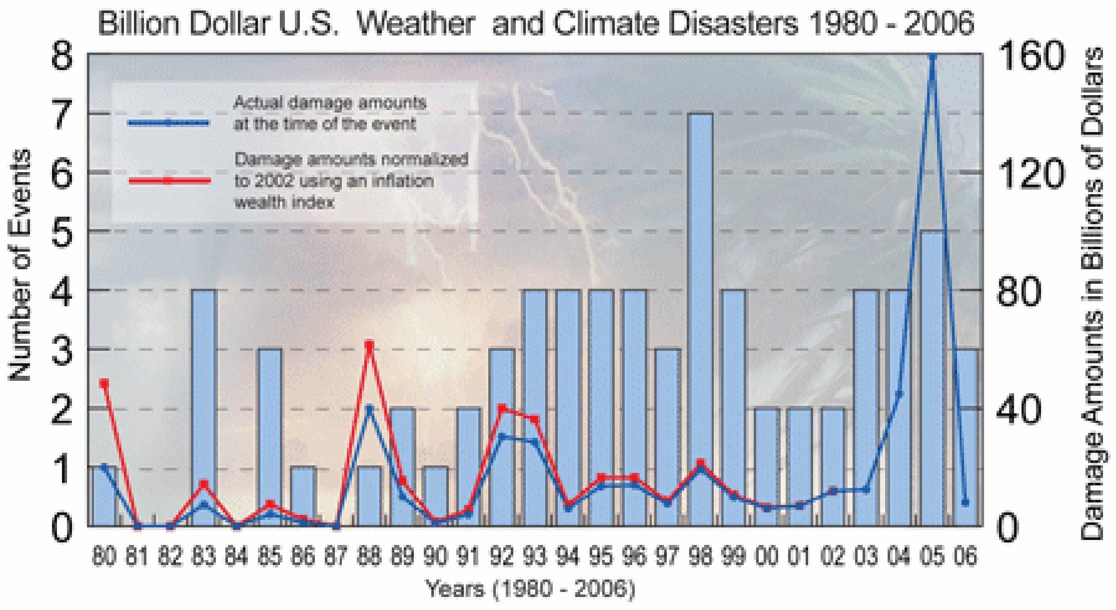

Figure 1.1 The blue bars show the number of events per year that exceed a cost of 1 billion dollars (these are scaled to the left side of the graph). The blue line (actual costs at the time of the event) and the red line (costs adjusted for wealth/inflation) are scaled to the right side of the graph, and depict the annual damage amounts in billions of dollars. Over the last 27 years, the U.S. averaged between two and three weather and climate-related disasters a year that exceeded one billion dollars in cost. Data from NOAA's National Climatic Data Center.

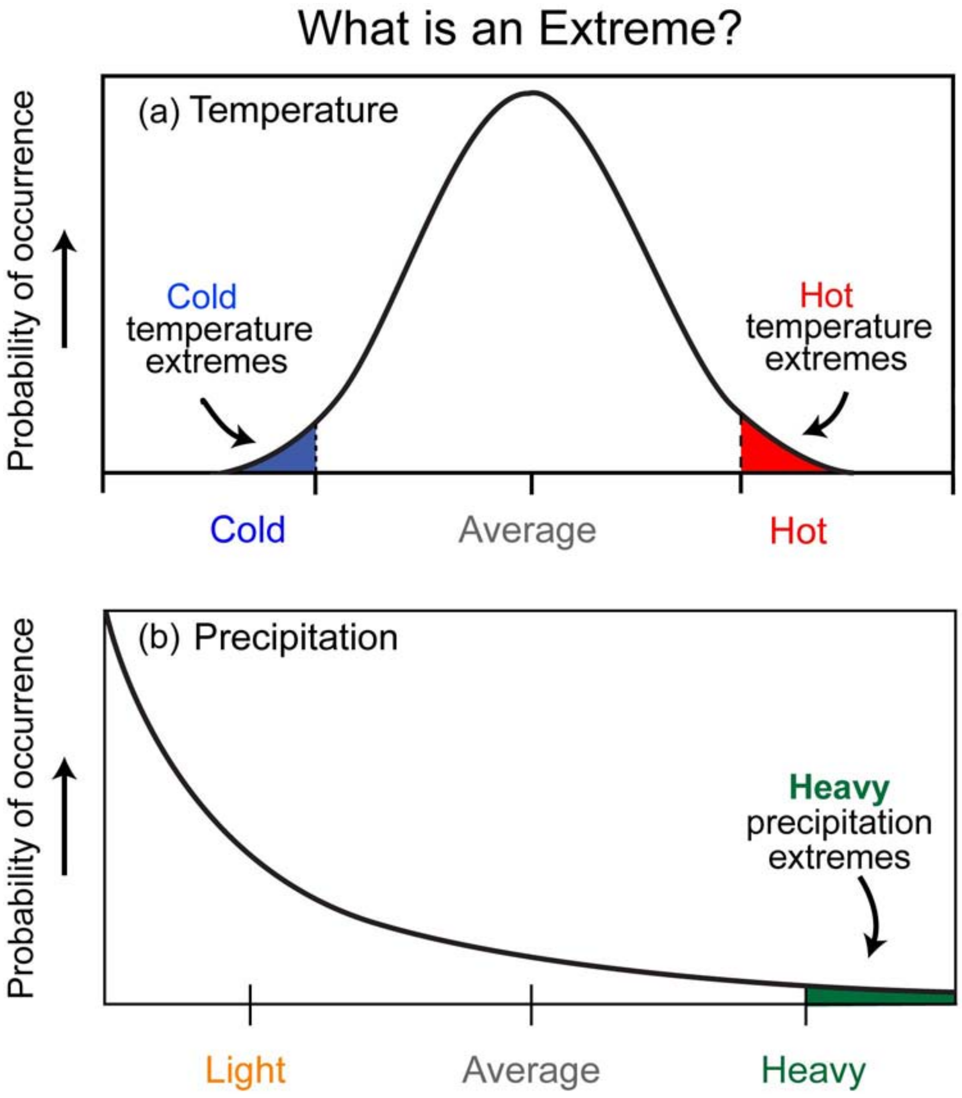

Figure 1.2 Probability distributions of daily temperature and precipitation. The higher the black line, the more often weather with those characteristics occurs.

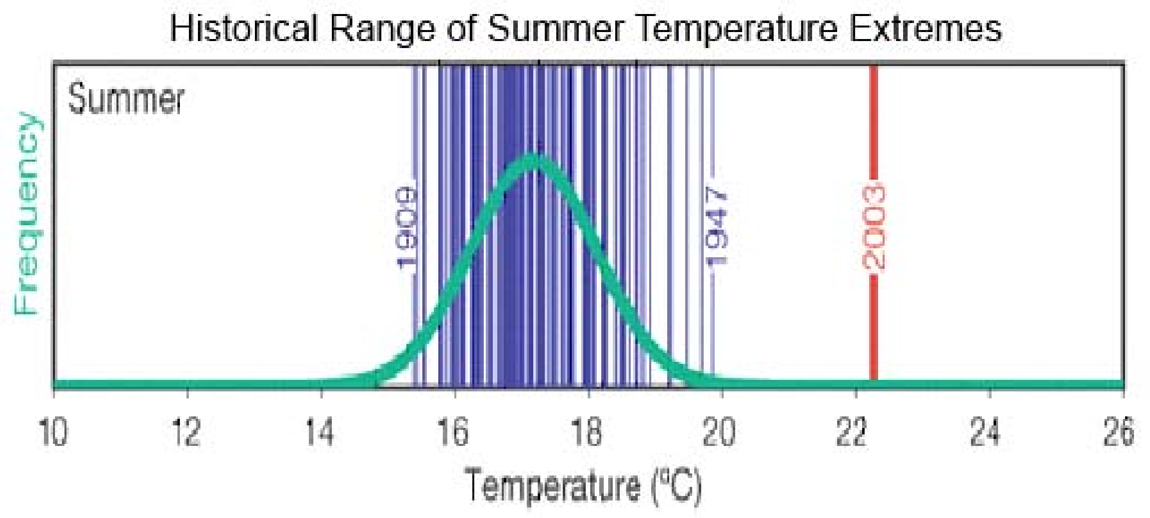

Figure 1.3 Like the European summer temperature of 2003, some extremes that are more likely to be experienced in the future will be far outside the range of historical observations. Each vertical line represents the summer temperature for a single year with the extreme values from the years 1909, 1947 and 2003 identified. From Schär *et al*., 2004.

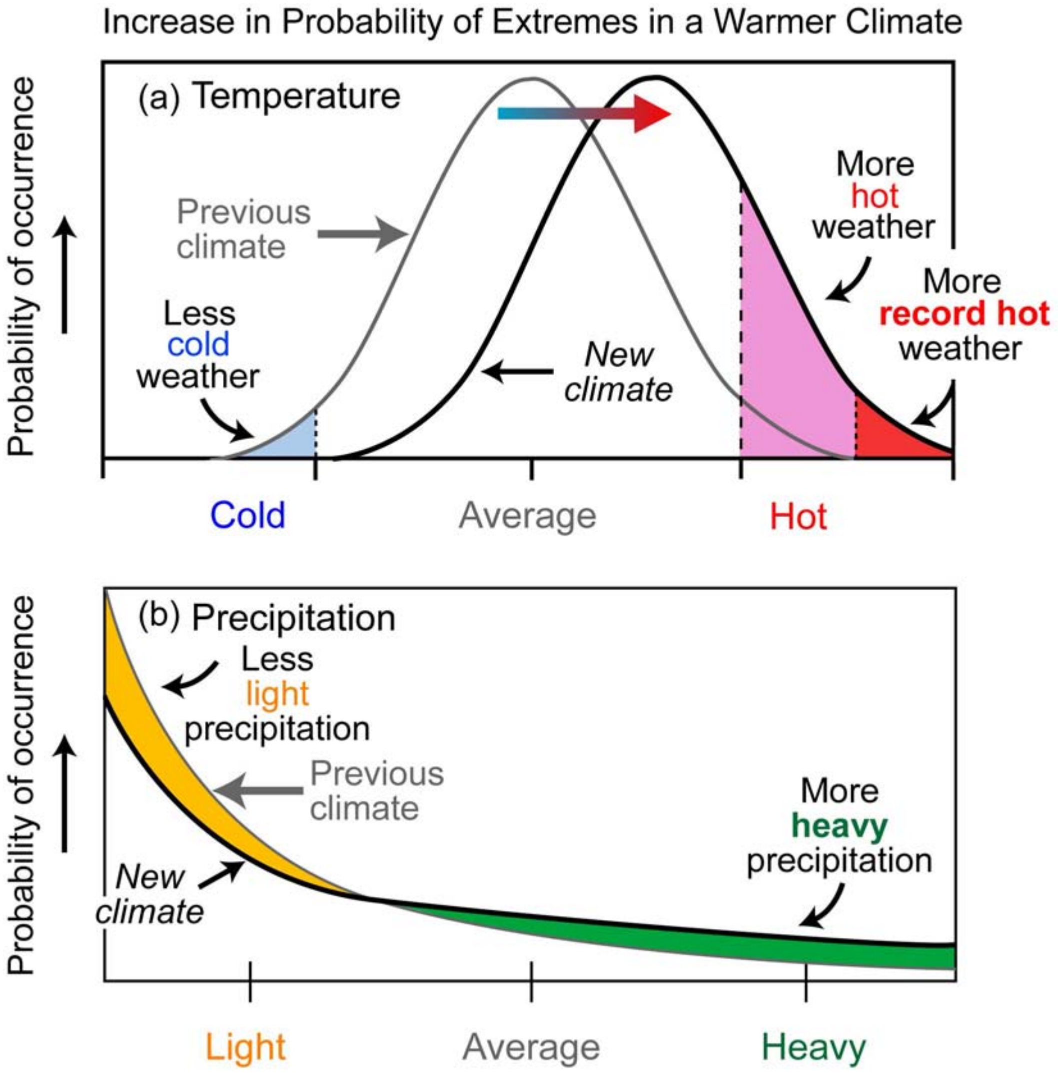

Figure 1.4 Simplified depiction of the changes in temperature and precipitation in a warming world.

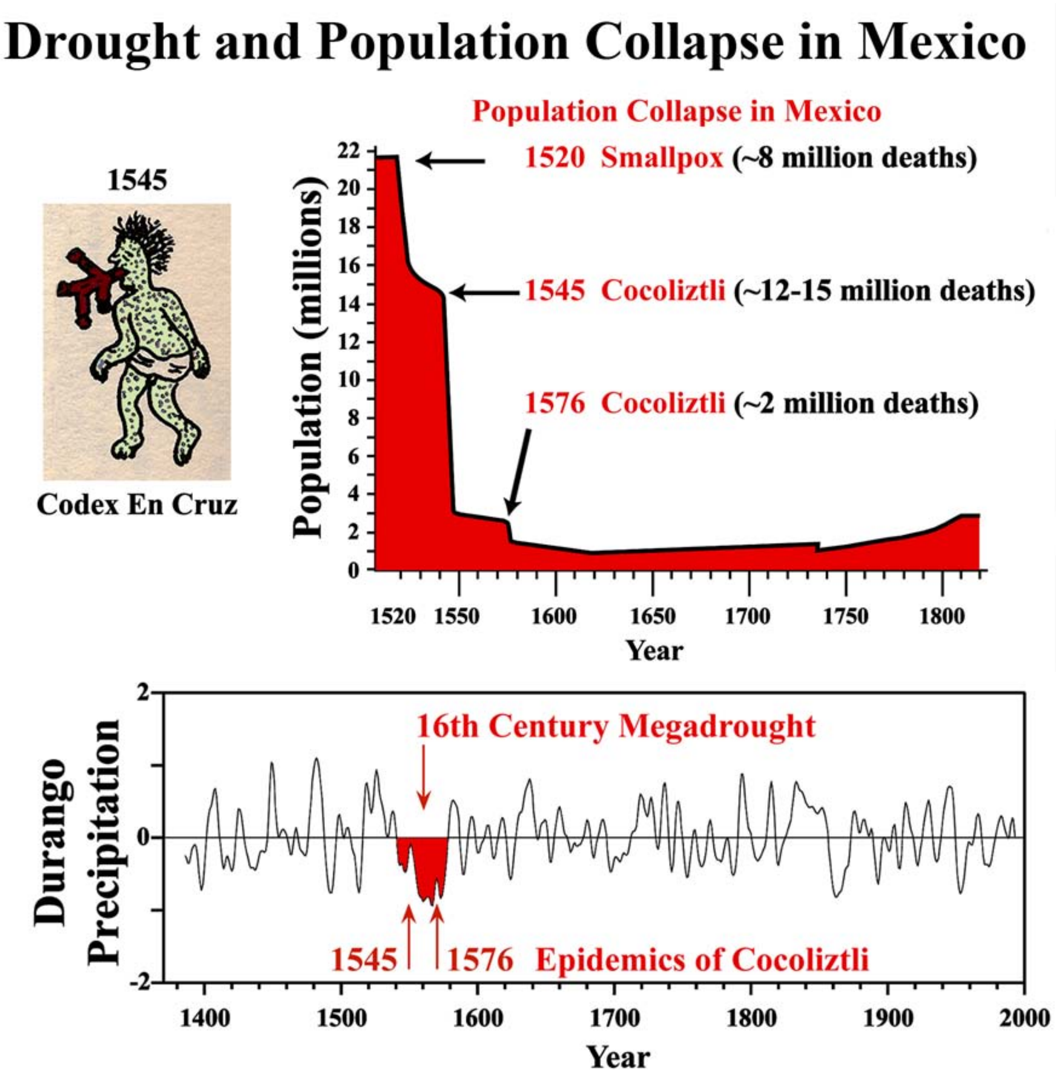

Figure 1.5 Megadrought and megadeath in 16th Century Mexico. Four hundred years ago the Mexican socio-economic and natural systems were so sensitive to extremes that a mega-drought in Mexico led to a massive population declines (Acuna-Soto *et al.*, 2002). The 1545 Codex En Cruz depicts the effects of the cocoliztli epidemic which has symptoms similar to rodent-borne hantavirus hemorrhagic fever.

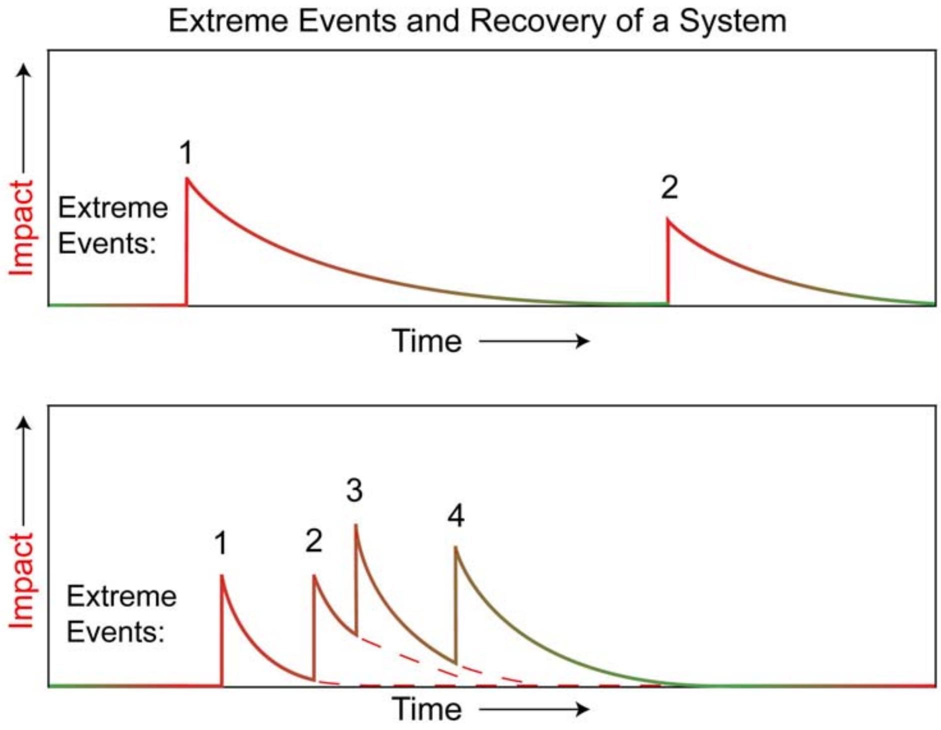

Figure 1.6 Extreme events such as hurricanes can have significant sudden impacts that take some time to recover from. Top: Two similar magnitude events take place but after the first one, new adaptation measures are undertaken, such as changes in building codes, so the second event doesn't have as great 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.

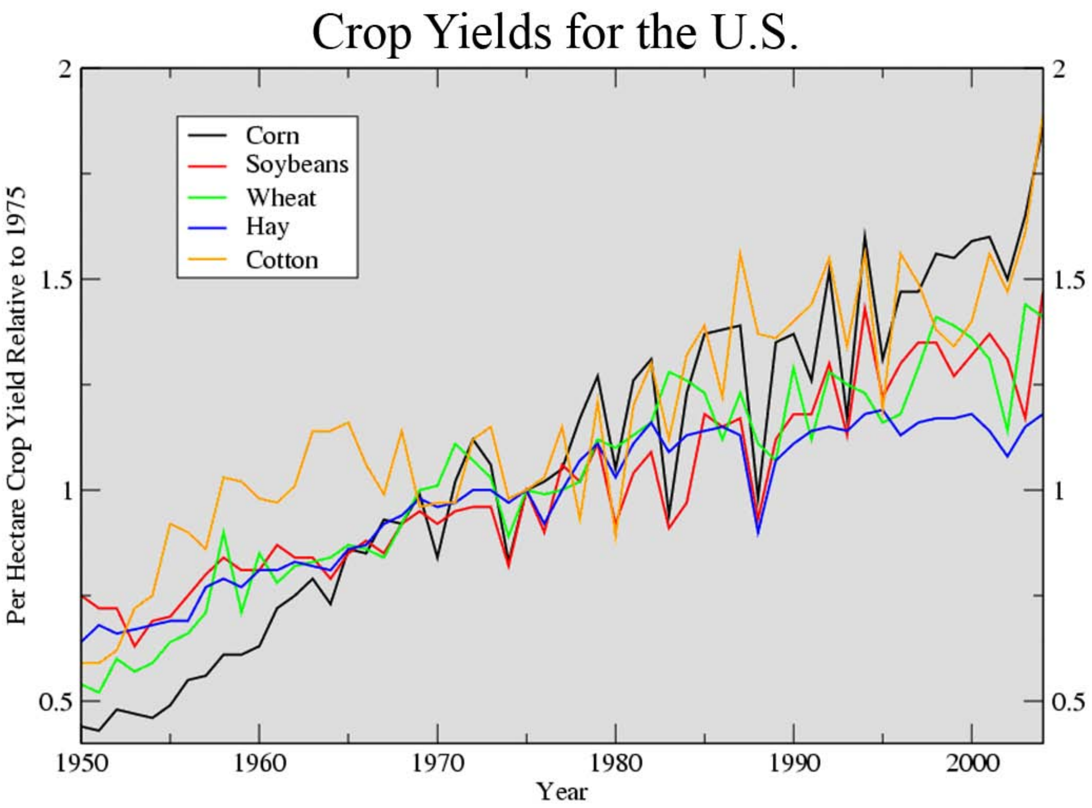

Figure 1.7 Climate variability may reduce crop yield, but because of technological improvements, a poor yield in the 1990s can still be higher than a good yield in the 1950s indicating a changing relationship between climate and agricultural yield. Data are in units of cubic meters or metric tons per unit area with the yield in 1975 defined as 1. Data from USDA National Agricultural Statistics Service via update to Heinz Center (2002).

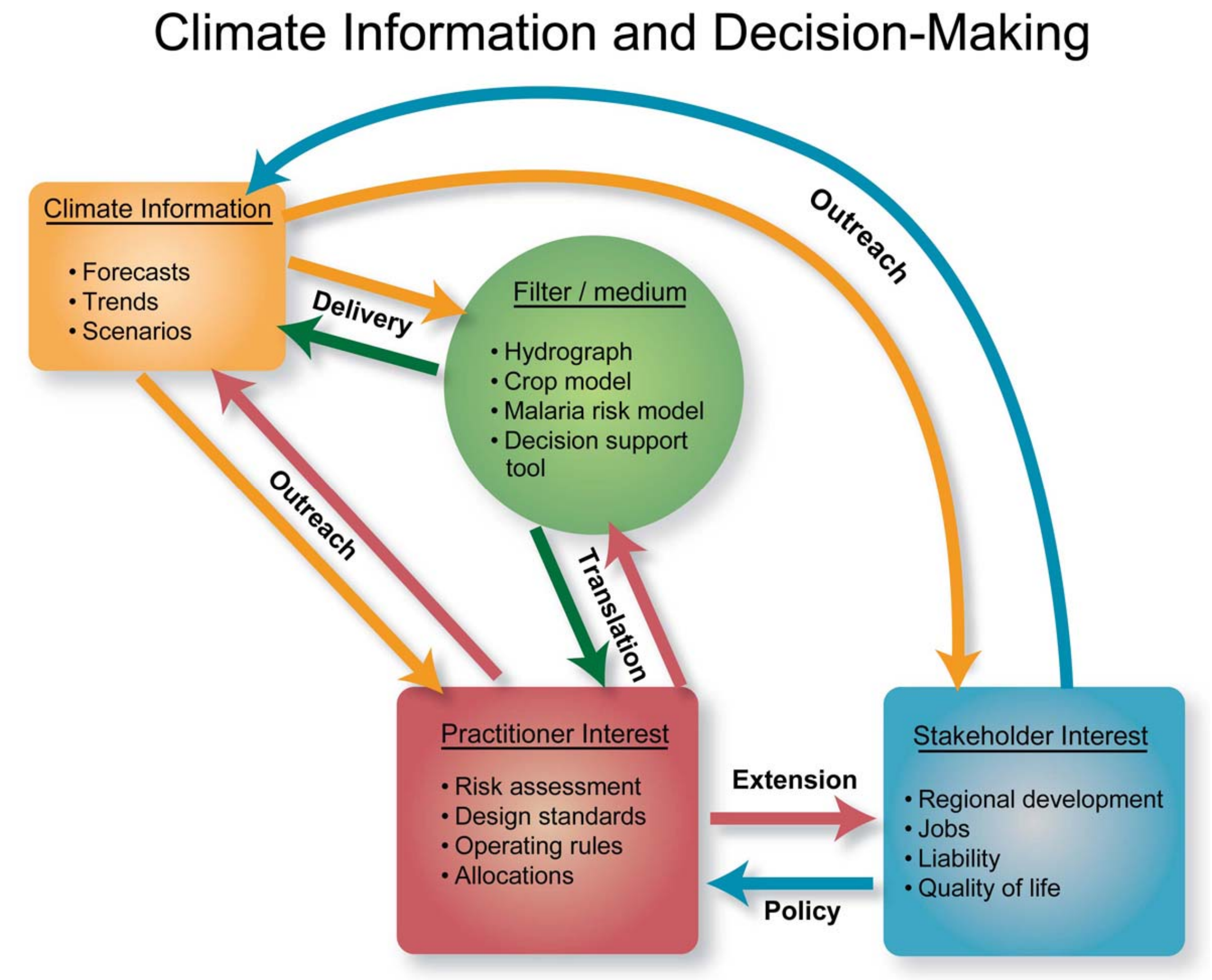

Figure 1.8 Illustration of how climate information is processed, filtered, and combined with other information in the decision process relevant to stakeholder interests.

Beetle Damage to Pine Trees in Canada

Figure 1.9 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 control beetle populations as well as hotter summers that increase populations are leading to a greater likelihood of beetle infestations. (Figure inclusion in Final Document subject to copyright permission).

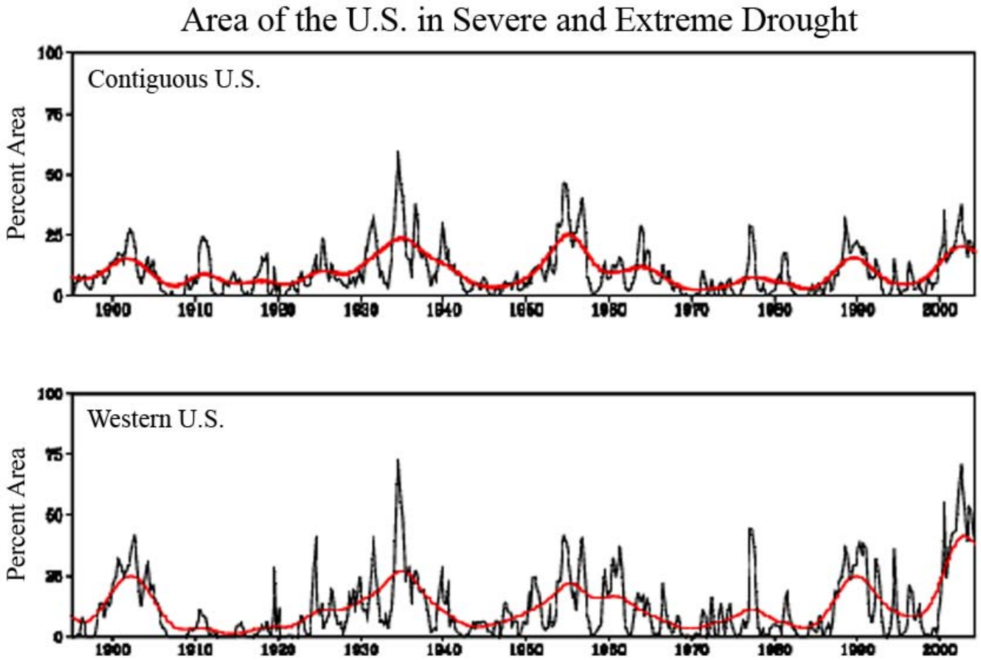

Figure 1.10 Percent of area in the contiguous U.S. and western U.S. affected by severe and extreme drought as indicated by Palmer Drought Severity Index (PDSI) values of less than or equal to −3. Data from NOAA's National Climatic Data Center.

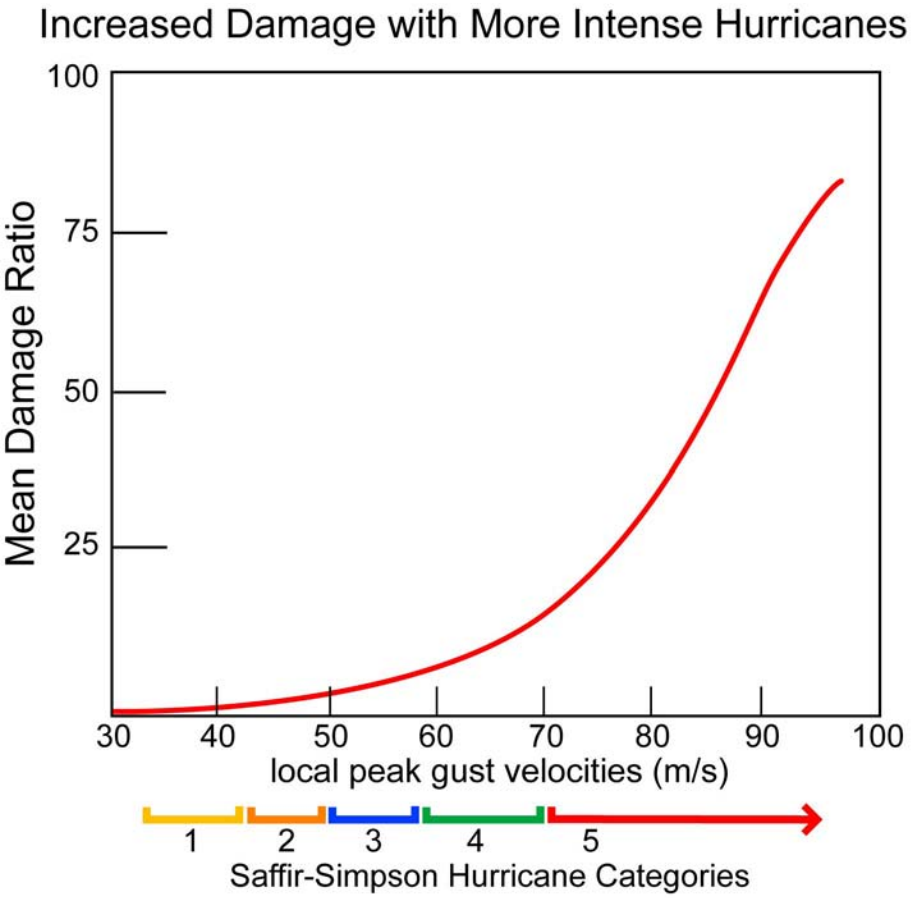

Figure 1.11 More intense hurricanes cause much greater losses. Mean damage ratio is the average expected loss as a percent of the total insured value. Adapted from Meyer *et al*. (1997).

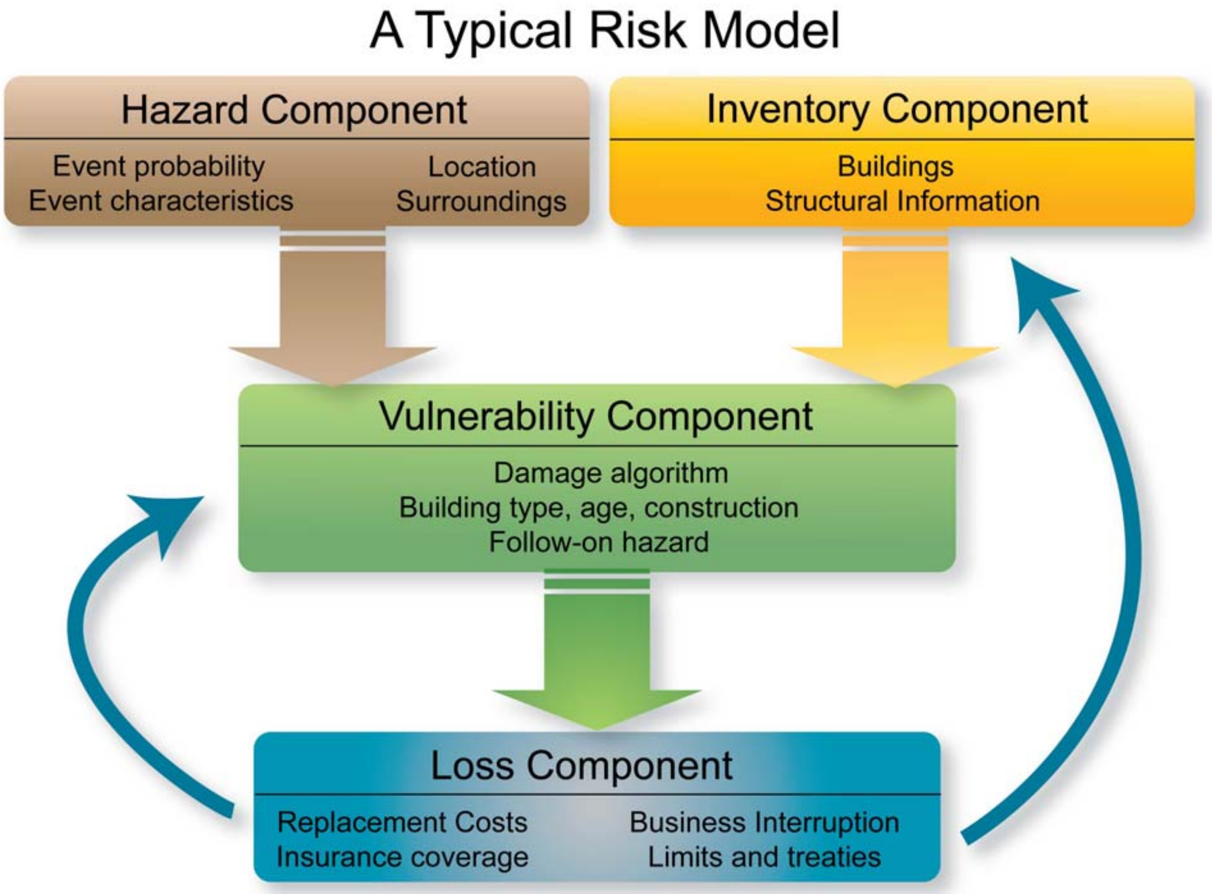

Figure 1.12 Schematic diagram of a typical risk model used by the insurance industry. The diagram highlights the three major components (hazard, damage, and loss) of a risk model. What happens to the loss component feedbacks to the vulnerability and inventory components.