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Climate Extremes: Observations, Modeling, and Impacts

David R. Easterling,[1]* Gerald A. Meehl,[2] Camille Parmesan,[3] Stanley A. Changnon,[4] Thomas R. Karl,[1] Linda O. Mearns[2]

One of the major concerns with a potential change in climate is that an increase in extreme events will occur. Results of observational studies suggest that in many areas that have been analyzed, changes in total precipitation are amplified at the tails, and changes in some temperature extremes have been observed. Model output has been analyzed that shows changes in extreme events for future climates, such as increases in extreme high temperatures, decreases in extreme low temperatures, and increases in intense precipitation events. In addition, the societal infrastructure is becoming more sensitive to weather and climate extremes, which would be exacerbated by climate change. In wild plants and animals, climate-induced extinctions, distributional and phenological changes, and species' range shifts are being documented at an increasing rate. Several apparently gradual biological changes are linked to responses to extreme weather and climate events.

There is general agreement that changes in the frequency or intensity of extreme weather and climate events would have profound impacts on both human society and the natural environment. Recent years have seen a number of weather events cause large losses of life as well as a tremendous increase in economic losses from weather hazards. In 1998 Hurricane Mitch caused over 10,000 deaths in Central America, and more recently major flooding events with large loss of life have occurred in both Venezuela and Mozambique. In the United States, since 1987 more than 360 weather events each produced losses in excess of $5 million with several record-setting catastrophes. These include the midwest drought of 1988–1989 ($39 billion), Hurricane Andrew in South Florida in 1992 ($30 billion), and the midwest flood of 1993 ($19 billion) (*1*). These life and property losses helped raise alarm over the possibility that the recent increases were due to a shifting climate. Are these increases merely a function of decadal fluctuations, or are they indicative of longer term trends related to anthropogenic-induced climate change? Here, we review climate extremes focusing on four areas: (i) what the observational record can tell us about past changes; (ii) the potential effects of enhanced radiative forcing on climate extremes through climate modeling; (iii) the potential impacts of climate extremes on society, focusing on the United States; and (iv) the sensitivities of natural systems to climate change and climate extremes.

Climate extremes can be placed into two broad groups: (i) those based on simple climate statistics, which include extremes such as a very low or very high daily temperature, or heavy daily or monthly rainfall amount, that occur every year; and (ii) more complex event-driven extremes, examples of which include drought, floods, or hurricanes, which do not necessarily occur every year at a given location.

Because a change in climate extremes is expected with anthopogenic-induced climate change, it is important to keep in mind the difference between the detection of a change, and being able to attribute that change to some identifiable climate forcing factor. The detection of changes in extremes on the basis of climate statistics is much more likely than detection of event-driven extremes. This also holds true in attempting to attribute a detected change to some forcing factor. Currently, climate models are the main source of quantitative estimates of changes in the bid to attribute some detected change in climate, such as an increase in extreme temperatures, to some climate forcing, such as increasing greenhouse gases (GHGs). Without some quantitative sense of what expected changes in climate extremes are likely to occur with increasing GHGs, it is impossible to attribute any change detected in the observed record to observed increases in GHGs.

Observed Trends

It is clear from the observed record that there has been an increase in the global mean temperature of about 0.6°C since the start of the 20th century (*2*), and that this increase is associated with a stronger warming in daily minimum temperatures than in maximums, leading to a reduction in the diurnal temperature range (*3*). Land surface precipitation has also increased over the same period in the mid- to high latitudes, but shows a decrease in the tropics and subtropics (*2*). Given these changes, it is expected that there would also be changes in what are now considered extreme events (*4*). Therefore, if there are indeed identifiable trends in certain extreme climatic events, such as extremes in temperature or precipitation, it would add to the body of evidence that there is a discernable human effect on the climate, and potentially have important consequences on society and natural systems.

Temperature Extremes

For a variety of reasons, relatively little work has been completed on changes in high-frequency extreme temperature events such as heat waves, cold waves, and the number of days exceeding various temperature thresholds. However, two studies focused on the northeastern United States support the notion that changes in the number of days exceeding thresholds have occurred. One shows that the start of the frost-free season in the northeastern United States occurred 11 days earlier in the mid-1990s than in the 1950s (*5*). The second, also focusing on the northeastern United States, shows significant trends to fewer extreme cold days, but also trends to fewer warm maximum temperatures as well (*6*). Trends in the number of days in the United States exceeding thresholds of 0°C and 32.2°C (90°F) indicate that for the 1910–1998 period there has been a slight decrease in the number of days below freezing over the entire United States (*7*). However there is much regional variation in the trends. Trends in the number of days with the maximum temperature over both 32.2°C and the 90th percentile threshold are dominated by past large anomalies, partially because of dry land-surface conditions during the droughts of the 1930s and 1950s (*7*). Thus, overall in the United States there is a slight downward trend in the number of these extremes despite an overall warming in the mean temperature, but with cooling in the southeastern United States (*8*).

In other parts of the world different trends

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[1] National Oceanic and Atmospheric Administration (NOAA)/National Climatic Data Center, 151 Patton Avenue, Asheville, NC 28801, USA. [2] National Center for Atmospheric Research, Boulder, CO 80303, USA. [3] Integrative Biology, University of Texas, Austin, TX 78712, USA. [4] Illinois State Water Survey, Champaign, IL 61820, USA.

*To whom correspondence should be addressed. E-mail: david.r.easterling@noaa.gov

prevail. In both Australia and New Zealand, the frequency of days below freezing decreased coincident with warming in daily minimum temperatures (*9*). In New Zealand this decrease and a slight increase in the number of days exceeding 30°C appear to be in response to changes in atmospheric circulation in the region; these changes show a positive correlation with warming in mean annual temperature (*9*). In northern and central Europe, evidence has been found of a decreasing number of frost days since the 1930s, which appears to be associated with strong increases in winter minimum temperatures (*10*).

Apparent temperature, which combines temperature and humidity effects on the human body, is another important measure, particularly for human health. The number of days exceeding the 85th percentile threshold value in summer for apparent minimum, mean, and maximum temperature in the United States have increased since 1948 (*11*). Because apparent temperature includes humidity effects, part of this increase is likely due to increases in water vapor, and indeed evidence has been found of precipitable water vapor increases over North America for the 1973–1993 period (*12*).

Short-duration episodes of extreme heat or cold are often responsible for the major impacts on health, as evidenced by the 1995 heat wave in the midwestern United States that resulted in hundreds of fatalities in the Chicago area (*13*). Although this heat wave was one of the worst short-duration heat waves of the 20th century (*14*, *15*), an analysis of multiday extreme heat and cold episodes where the temperature exceeds the 10-year return period do not show any overall trend for the period of 1931–1997 (*16*). The most notable feature of the temporal distribution of these extreme heat waves is the high frequency in the 1930s compared with the rest of the record.

Absolute daily extremes of both maximum and minimum temperature by month and annually for the United States and the former Soviet Union show little or no trend for the maximum temperatures, but generally show strong increases for the minimum temperature from 1951 to 1989 (*17*). Furthermore, in China there has been a slight decrease in the 1-day extreme maximum temperature during every season except spring, but the extreme minimum temperature exhibited a strong increasing trend in each season (*18*).

It is clear that for every country where the number of frost days has been examined, they have become fewer in number. This is consistent with the warming in average minimum temperature found for each country (*3*). However, results for other temperature extremes are much less consistent, particularly warm maximum-temperature extremes. Again, this is broadly consistent with trends found for average maximum temperatures (*3*).

Extreme Precipitation

Trends in 1-day and multiday heavy precipitation events in the United States and other countries show a tendency toward more days with heavy precipitation totals over the 20th century (*18*–*20*). The annual number of days exceeding 50.8 mm (2 inches) and 101.6 mm (4 inches) of precipitation has increased in the United States since 1910 (*8*, *21*). Also, the frequency of 1- to 7-day precipitation totals exceeding station-specific thresholds, for 1 in 1 year and 1 in 5 year recurrences, and the upper 5 percentiles, have been increasing since the 1930s (*18*, *20*). Increases are largest in the southern Mississippi River valley, Southwest, Midwest, and Great Lakes regions of the United States, and increases in extreme events are responsible for a disproportionate share of the observed 5 to 10% increase in total annual precipitation since the early 20th century (*20*).

Most countries that experienced a significant increase or decrease in monthly or seasonal precipitation also experienced a disproportionate change in the amount of precipitation falling during the heavy and extreme precipitation events (*7*, *22*) (Fig. 1). Furthermore, in some areas there was no increase in the seasonal total, but there was still an increase in the frequency of 1-day heavy precipitation events, as in Japan (*23*).

Depending on the analysis technique, some researchers analyzing changes in heavy precipitation have found increases over the 20th century in Australia, except in southwestern Australia, where there has been a decrease in both rain days and heavy events (*24*). In the United Kingdom, heavy wintertime events have increased and heavy summertime events have decreased (*25*), and in the Sahel region of Nigeria and throughout all Sudano-Sahel Zone, including Abissinian Plateau, the heaviest daily precipitation amounts have decreased, coincident with an overall decrease in annual rainfall (*26*). Recent results show that, although the Canadian prairie has experienced increased annual rainfall and heavy precipitation over the last 40 years, this increase appears mainly due to an increase in the number of lighter (<5 mm) daily rainfall totals (*27*). However, others (*28*) examining Canadian precipitation trends for most of the 20th century find precipitation increases in southern Canada resulting from increases in all levels of precipitation intensity, and in the latter half of the century increases are greatest in intermediate and heavy events, particularly in Arctic Canada (*28*).

Droughts and Wet Periods

The overall areas of the world affected either by drought or excessive wetness have increased (*29*). Examination of drought over the 20th century in the United States shows considerable variability, the droughts of the 1930s and 1950s dominating any long-term trend (*7*, *14*). Recent investigation of longer term U.S. Great Plains drought variability over the past 2000 years with the use of paleoclimatic data suggests that no droughts as intense as those of the 1930s have occurred since the 1700s. However, before the 16th century some droughts appear to have occurred that were of greater spatial and temporal intensity than any of the 20th-century U.S. droughts (*30*). Although these results are compiled from widely spatially varying locations, and taken individually represent only local conditions, when taken as a whole they appear to create a coherent picture of Great Plains drought variability over the past two millennia (*30*).

Although there appear to be no long-term

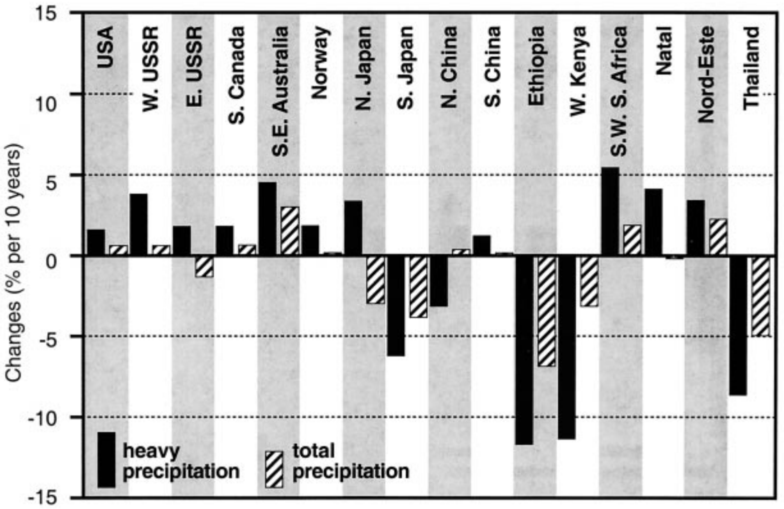

Fig. 1. Linear trends in total seasonal precipitation and frequency of heavy precipitation events for various countries (*7*).

trends in drought, the area of the United States experiencing excessive wetness appears to be increasing, particularly since the 1970s (*8*). This is consistent with long-term increases in annual precipitation, and increases in heavy precipitation events. Analysis of drought for other regions of the world shows some trends to more drought. Droughts have increased in Hungary and wet spells have decreased (*31*), and over China, a decrease in mean precipitation (*32*) has been accompanied by an increase in the area of droughts and a decrease in the area with excessive precipitation (*2*).

Tropical Storms

Overall, occurrences of Atlantic hurricanes do not show a significant long-term trend over the 20th century, although the number of intense hurricanes, those that cause the most damage, has declined from 1944 to the mid-1990s (*33*, *34*). Furthermore, large variations of hurricane activity on interdecadal time scales have been observed during the 20th century (*35*). Because most coastal settlement occurred in a period of relatively low hurricane landfall frequency, the potential societal impacts of hurricane landfall in more active decades have yet to be fully realized (*36*).

Recent work documenting the contribution of hurricanes to extreme rainfall events shows that each individual event doubles the monthly rainfall being measured in that month in the mid-Atlantic and New England regions of the United States (*37*). For the 67-year period studied, eastern Massachusetts and much of the Appalachians experience such extreme rainfall events on average every 5 to 6 years, and the return period drops to 2 to 4 years when hurricane rainfall contributions result in monthly rainfall anomalies of 150% above average.

In the North Pacific basin a positive trend has been observed both in tropical storm activity and typhoons since the mid-1970s (*38*). Before the mid-1970s, tropical storm activity in the western North Pacific region had been dropping, demonstrating a nonlinear longer term variation in tropical storm frequency in this most active region of the globe. Since 1969 a strong downward trend in tropical storm frequency has been observed in the Australian region, south of the equator (105°E to 160°E), which has been attributed largely to variations in the El Niño–Southern Oscillation (*39*).

Climate Model Results

Recent climate model improvements have resulted in an enhanced ability to simulate many aspects of climate variability and extremes. However, they are still characterized by systematic errors and limitations in accurately simulating regional climate conditions.

Yet, encouragingly, much of what climate model studies show could happen to weather and climate extremes in the future with increased GHGs is what would intuitively be expected from our understanding of how the climate system works. For example, an increase of GHGs produces increased surface heating with warmer surface temperatures, more evaporation, an increase in the ability of the atmosphere to hold more moisture, and thus an increase in atmospheric moisture content with enhanced precipitation rates (*40*), which has been seen in some climate model simulations. Additionally, a number of changes in future weather and climate extremes from climate models have already been seen in observations in various parts of the world as noted above (e.g., decreased diurnal temperature range, warmer mean temperatures associated with increased extreme warm days and decreased extreme cold days, and increased intensity of rainfall events).

Some of the results of model studies published since the IPCC Second Assessment Report (*41*) have corroborated the previous results. This gives us increased confidence in their credibility (though agreement among models does not guarantee those changes will occur in the real climate system). These results include increases in mean temperatures that lead to more extreme high temperatures and fewer extreme low temperatures, along with reduced diurnal temperature range (*42*). Other recent model studies that corroborate earlier results for future climate include increased intensity of precipitation events (*43*, *44*), and a general drying of midcontinental areas during summer (*45*) with an increased chance of drought (*46*) and increased frequency of low summer precipitation, the probability of dry soil, and the occurrence of long dry spells (*47*). This general drying occurs because of enhanced potential evaporation and strong temperature increases outweighing any precipitation increases. An increase in interannual variability of the Indian monsoon has also been seen, thus increasing the likelihood of droughts and floods in that region (*48*, *49*). Also in agreement with earlier modeling results, some current models show the future mean Pacific climate base state could more resemble an El Niño–like state [i.e., slackened west-east sea surface temperature (SST) gradient with associated eastward shifts of precipitation] (*50*–*53*), although it is not the case for all models and thus remains model-dependent. For such an El Niño–like climate change, or even for a more uniform future warming of SSTs across the tropical Pacific as shown in some other models, future seasonal precipitation extremes associated with a given El Niño would be more intense than present owing to the nonlinear relation between SST and evaporation. Thus, with warmer SSTs in a future climate, a given SST anomaly associated with a future El Niño event would produce proportionately more evaporation and more intense precipitation in the central and eastern Pacific, with even less precipitation over Australasia.

Although the climate-impacts community has some history in examining changes in second-order climate variables, such as heating and cooling degree days, a number of recent modeling results have explored new aspects of changes in extremes since the IPCC Second Assessment Report. For example, the changes of temperature extremes noted above produce a decrease in heating degree days for Canada and an increase in cooling degree days in the southwestern United States (*43*). In concert with increased atmospheric moisture, these temperature extremes lead to an increase in a July mean heat index in one model that would lead to greater discomfort and stress on the human body (*54*). The greatest increase in the 20-year return value of daily maximum temperature is found in central and southeast North America, central and Southeast Asia, and tropical Africa where there is a decrease in soil moisture content, and also over the dry surface of north Africa (*42*). Furthermore, the West Coast of North America was found to be affected by increased precipitation, resulting in moister soil and more moderate increases in extreme temperature (*42*). Increases in the return values of daily minimum temperature are larger than those of daily maximum temperature over land areas and where snow and ice retreat, whereas precipitation extremes increase more than the mean, and the return period for a current 20-year extreme precipitation event decreases almost everywhere (e.g., a 20-year event would occur once every 10 years over North America). Increases in the variability of El Niño have been found in some models (*55*–*59*), with little significant change in others (*59*). Still others find that the largest changes in the amplitude of El Niño occur on decadal time scales with increased multidecadal modulation of ENSO (*58*, *59*). Assessing possible future changes of El Niño simulated in climate models remains difficult, and it is likely that model-dependent aspects such as ocean resolution, and atmospheric physics play important roles in the future extremes associated with ENSO in the models.

In addition to El Niño, several other aspects of Earth's climate related to future changes of extremes remain equivocal at the present. For example, there is little agreement among models concerning the possible future behavior of mid-latitude storms, their intensity or frequency changes, or storm track changes. However, improved global climate models have only recently become more credible in this area, and new studies have indicated a possible increase in the number of deep cyclones (*60–62*). An increase in upper-air storm track activity (with implied increases in extremes associated with the greater number of intense storms) over the east Atlantic and western Europe is seen in one model with increasing GHGs (Fig. 2) (*63*). Model studies of future changes in tropical cyclone frequency remain inconclusive as well, although two recent studies using relatively high-resolution (~1°) global climate models both indicate a decrease in tropical storm frequency in a CO_2-warmed climate (*64*, *65*). Additionally, some global climate model studies have suggested the possibility of more intense tropical cyclones in the future (*66*). However, the merits of using current global climate models to project future changes in tropical storm frequency has been the subject of active debate (*67*). Recent experiments with a nested high-resolution regional model (resolution of up to 0.17°, or 18 km) indicate a 5 to 11% increase in surface wind speeds and a 28% increase in near-storm precipitation, based on a comparison of strong north Pacific typhoons simulated under present-day and high-CO_2 conditions (*68*, *69*). A comparable technique applied to the Australian region has shown similar increases in tropical cyclone intensity as well as possible poleward shifts in occurrence (*70*). This approach, along with higher resolution global models, holds promise for better estimates of future tropical and extratropical cyclone behavior.

One of the biggest problems in determining whether extreme events have changed in the observed record, and if these changes are consistent with what we may expect from an increase in GHGs in the climate models, is that investigators have often used quite different criteria to define an extreme climate event (*71*). This lack of consensus on the definition of extreme events, coupled with other problems, such as a lack of suitable homogeneous data for many parts of the world, likely means that it will be difficult, if not impossible, to say that extreme events in general have changed in the observed record (*71*).

Table 1 contains a brief summary of results for both the observed record of the 20th century and modeling results for the 21st century. The assessment of extremes here relies on relatively large-scale changes from the models that are physically plausible or representative of changes over many areas. Certain changes in observed extremes may not have been specifically itemized from model simulations, but are physically consistent with changes of related extremes in the future climate experiments. In Table 1 we break down changes in extremes to those based on climate statistics (a statistical change that would occur nearly every year) and event-driven extremes (those associated with particular weather or climate events or phenomena. The qualitative consistency among the observations over the 20th century, and the models for the end of the 21st century, suggests that at least some of the changes we have observed to date are likely associated with changes in forcing that we have already experienced over the 20th century. The implication is that these could continue to increase into the 21st century with the ongoing rise in forcing from ever greater amounts of GHGs in the atmosphere.

Societal Impacts in the United States

Losses caused by catastrophes, defined by the property insurance industry as storms causing insured losses >$5 million in the year of occurrence, have grown steadily in the United States from about $100 million annually in the 1950s to $6 billion per year in the 1990s, and the annual number of catastrophes grew from 10 in the 1950s to 35 in the 1990s (*72*). The 1990–1997 total insured property losses were $49 billion, and federal relief payments for weather-caused disasters were $12 billion. The 1990s experienced a record number of damaging storms. Those causing property insurance losses >$100 million (1992 dollars) occurred 72 times during 1990–1996, whereas only 142 such $100-million storms (1992 dollars) had occurred in the preceding 40 years (*73*). However, weather events causing losses >$1 billion (1992 dollars) have not been increasing over time, and these 22 very costly events since 1949 are scattered randomly throughout the 1949–1997 period (*74*). Crop-hail insurance losses, another relatively long-term and consistent measure of losses from hail and wind, have also grown steadily, rising from an annual average of $30 million (year of occurrence) in the 1950s to $320 million in the 1990s (*74*). Federal relief payments for weather disasters grew from $670 million in 1966–1970 (in 1994 dollars) to $4 billion in 1991–1995 (*75*). The growth of insured property losses in the United States, based on the catastrophic weather losses since 1949, shows a comparable rate of increase in both the number of events and their losses (Fig. 3) (*72*).

Losses created by various weather types have also grown. Annual hurricane losses have grown from $5 billion in the 1940s to

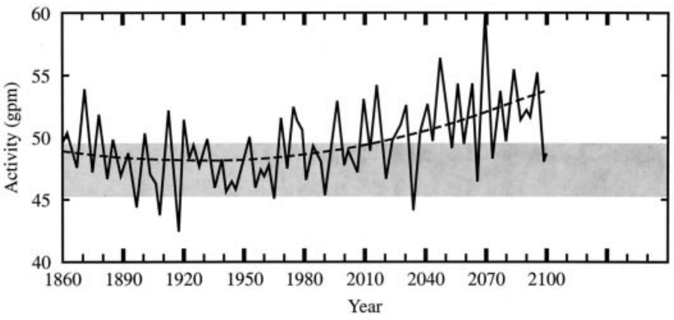

Fig. 2. Storm track activity [defined as the standard deviation (SD) of the 500 hPa height] averaged over northwestern Europe (6°W to 20°E, 40° to 70°N, a 4-year low pass filter has been applied), showing an increase of storm activity in a future climate. The gray stippling indicates the variability of this index in the control run as measured by 1 SD. The nonlinear climate trend optimally obtained from a quadratic curve fitting is marked by the dashed line. The *y* axis is storm track activity in geopotential meters (gpm), and the *x* axis is calendar years (*56*).

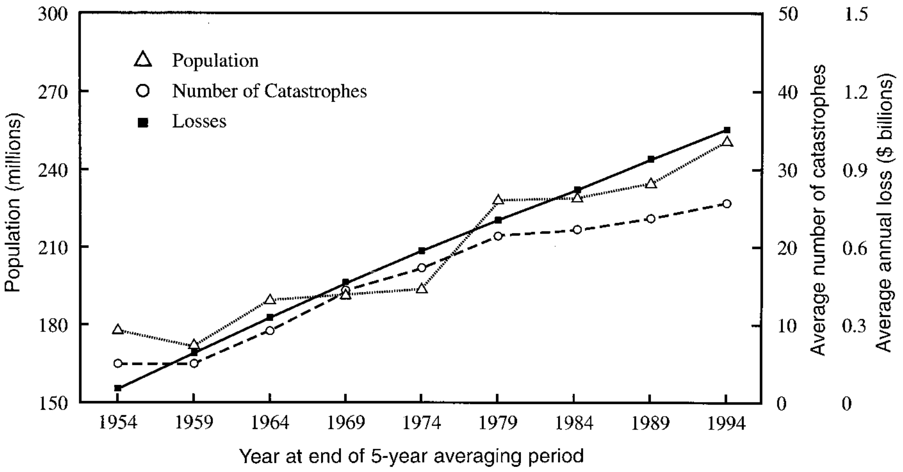

Fig. 3. The time series, based on catastrophes that caused losses between $10 million and $100 million (adjusted values), for 5-year periods of the number of catastrophes, the amount of loss from these catastrophes, and the U.S. population (*63*).

more than $40 billion in the 1990s (adjusted for inflation to 1990 dollars) (36). Flood damages, which rank as the top weather-caused losses in the nation, also continue to increase with annual losses of $1 billion in the 1940s, growing to $6 billion per year (all in 1997 dollars) during the 1980s to 1990s (76). Damaging hailstorms causing urban losses in excess of $300 million have become common in the 1990s as evidenced by record storms in Denver, Dallas, Oklahoma City, Wichita, Orlando, and Fort Worth (77).

Trends in insured loss statistics show sharp regional differences. In the West Coast, the Arizona–Colorado–New Mexico–Texas area, and the southeastern coastal states, the number of property catastrophes causing >$100 million in losses during 1990–1997 has been double those in the previous 40 years (73). Elsewhere, recent costly storms have increased, but only by 20 to 40% over the preceding 40-year period. Crop-hail insurance losses show major regional differences too, with rapid increases during the 1990s in the High Plains but with decreases since 1980 in the Midwest (77).

Table 1. Summary of analyses of different types of climate extremes, including extremes based on climate statistics and event-driven extremes (see text for explanation). The assessment of extremes here relies on very large scale changes that are physically plausible or representative of changes over many areas. In some regions the changes of certain extremes may not agree with the larger scale changes. Therefore, the assessment here is a general one where observed and model changes appear to be representative and physically consistent with a majority of changes globally. Additionally, certain changes in observed extremes may not have been specifically itemized from model simulations, but are physically consistent with changes of related extremes in the future climate experiments and are denoted as such. The definitions of the uncertainty estimates for the possibility of changes in extremes differ between observations and models. For observations they are based on the following probability ranges: Virtually certain, >99%; Very likely, 90 to 99%; Likely, 67 to 90%; Possible, 33 to 66%; Unlikely, 10 to 33%; Very unlikely, 1 to 10%; Improbable, <1%. For models they are based on the following degree of model agreement or physically plausibility: Virtually certain, many models have been analyzed for this change and all show it; Very likely, a number of models that have been analyzed have shown such a change, or that change is physically plausible and can readily be shown for a larger group of models; Likely, some models that have been analyzed have shown such a change, or the change is physically plausible and could be shown for a larger group of models; Possible, only a few models have shown such a change, it is not physically obvious that such a change should occur, or the results from analyses from various models are mixed; Unlikely, some models that have been analyzed have shown that such a change specifically did not occur, or it is physically implausible and could be shown for a larger group of models; Very unlikely, a number of models that have been analyzed have not shown such a change, or that change is physically implausible and could readily be shown for a larger group of models; Improbable, many models have been analyzed for this change and none show it. Note that changes in observations have already occurred, and the changes from models are projected to occur mainly as a result of increases in GHGs. Thus, where the observed changes agree with the models, they are qualitatively consistent with climate changes expected from increasing GHGs.

	Observed (20th century)	Modeling (end of 21st century)
	Simple extremes based on climate statistics	
Higher maximum temperatures	Very likely	Very likely
More hot summer days	Likely	Very likely
Increase in heat Index	Likely	Very likely
Higher minimum temperatures	Virtually certain	Very likely
Fewer frost days (higher minimum temperatures)	Virtually certain	Likely*
More heavy 1-day precipitation Events (increased intensity of precipitation events)	Likely	Very likely
More heavy multiday precipitation events (increased intensity of precipitation events)	Likely	Very likely
	Complex event-driven climate extremes	
More heat waves	Possible	Very likely* (higher maximum temperatures)
Fewer cold waves	Very likely	Very likely* (higher minimum temperatures)
More drought	Unlikely	Very likely (reduced mid-latitude summer soil moisture)
More wet spells	Likely	Likely (increased precipitation at mid- and high latitudes in winter)
More tropical storms	Unlikely	Possible
More intense tropical storms	Unlikely	Possible
More intense mid-latitude storms	Possible	Possible
More intense El Niño events	Possible	Possible
More common El Niño–like conditions	Likely	Likely*

*No direct model analyses, but these changes are physically plausible on the basis of other simulated model changes; comparable changes simulated by the models are noted in parentheses.

Most of the increase has been due to societal shifts and not to major increases in weather extremes. The growth of population, demographic shifts to more storm-prone locations, and the growth of wealth have collectively made the nation more vulnerable to climate extremes. Future climate shifts leading to more extremes will greatly exacerbate the loss problem.

Weather-related loss of life has not shown the overall increase found in dollar losses. The number of deaths related to tornadoes, hurricanes, and severe storms have either decreased or remained unchanged over the past 20 years (14). The lack of an increase in weather deaths, given an increasing population, is largely attributed to better forecasting, improved warning systems, and greater awareness of risks. The only weather hazards showing increases in mortality have been those due to flooding and to heat waves (14). Heat-wave deaths were exceptionally high in 1980, 1988, and 1995 (78).

Impacts on Natural Systems

Recent documentation of systematic change across a broad range of species spread over many continents now provides convincing evidence that 20th-century climate trends have impacted natural systems (79–82). Many of the observed biotic changes were predicted by global warming scenarios more than a decade ago (83). However, most of these studies relate mean climate trends to averaged biotic trends, with little analyses of more detailed linkages.

Thus, it is well documented that a gradual change in climate, as well as local or regional climate characteristics, can affect population abundance (84, 85), species' distribution (86–91), morphology (92, 93), and behavior (94), ultimately impacting community structure as well (95, 96). Much less studied are the mechanistic links between small- and large-scale processes, and the relative roles in these processes of climate means as compared with climatic variability or extreme events. In spite of these gaps, knowledge from basic ecological and physiological research provides clear evidence that natural systems should be strongly influenced by extremes of weather and climate. One of the very first such studies dates back to the last century. In the late 1800s, Bumpus (97) documented that a severe winter storm over Lake Michigan, in the United States, disproportionately killed off both the largest and the smallest sparrows, thereby generating strong natural selection on body size.

Many biological processes undergo sudden shifts at particular thresholds for temperature or precipitation (*98–100*). Tolerances to frost and to low levels of precipitation often determine plant and animal range boundaries (*86–88*). Single extreme temperature events can alter physical characteristics. For example, the adult sex of many turtle species (and hence population sex ratio) is determined by the maximum temperature experienced by the growing embryo (*101*, *102*). Periods of unusually heavy precipitation have been shown to alter breeding systems. Under high-rain, high-resource conditions, the Galapagos mockingbird (*Nesomimus parvulus*) becomes more polygamous (*103*), and in African elephants (*Loxodonta africana*), a few dominant males go into musth and capture all the matings (*104*). Single drought years have been shown to affect individual fitness and population dynamics of many insects, causing drastic crashes in some species (*105–107*), while leading to population booms in others (*108*). An extended drought in New Mexico in the 1950s caused the boundary between pine and piñon/juniper forest to shift by 2 km, where it remains today (*109*). Drought years in the Galapagos, induced by El Niño, cause evolution of larger beak size in Darwin's finches (*Geospiza fortis*), while extremely wet years cause evolution of small beak (and body) size (*110*). Many studies have related El Niño events to changes in marine biotic systems (*111*, *112*). Particularly striking were widespread massive coral bleaching events that followed the 1982–1983 intense El Niño (*113*, *114*). Finally, ecosystem structure and function are impacted by disturbance events, many of which are associated with tornadoes, floods, and tropical storms (*95*, *96*).

It is likely, then, that changes in the proportions of days exceeding species-specific temperature thresholds, or changes in the frequency of droughts or extreme seasonal precipitation, will lead to physical and behavioral changes in a few species and to dramatic changes in the distributions of many other species (*115*). For most of the studies of response to climate change, data have been gathered over too short a period, or contain too many temporal gaps, to indicate whether these changes during the past several decades stem from specific climatic events or from longer term response to a gradual shift of mean climate. However, a few studies contain direct observations through time. These cases indicate that the mechanistic basis of many of these gradual long-term biotic changes may indeed lie in responses to a few, brief, extreme events (*115*).

In western North America, Edith's Checkerspot butterfly has shifted its range northward (by 92 km) and upward (by 124 m) during this century (*116*). This closely matches the temperature increase over the same region and time period where mean temperature isotherms shifted 105 km northward and 105 m upward (*8*). The mechanism of this shift has been a higher rate of local population extinction in the south (Mexico) than in the north (Canada), and at low elevations compared to high (*116*). Previous studies showed that fluctuations in population size were strongly associated with variance of both temperature and precipitation (*117–121*). A diversity of extreme weather events, including drought, "false springs," and midsummer frost, have been directly observed to cause extinction of local populations of this butterfly (*85*, *105*, *106*). Thus, the gradual northward and upward movement of the species' range since 1904 is likely due to the effects of a few extreme weather events on population extinction rates (*122*).

Changes in oceanic circulation also appear to drive biotic change. In Monteverde preserve (Costa Rica), 40% of the 50 local amphibian species have become extinct since 1983 (*123*). A detailed analysis of four frog species showed that extinction followed a series of drastic population declines in each of three severe droughts associated with El Niño events. The North Atlantic Oscillation (NAO) has been implicated in several trends in northern Europe, with data spanning as far back as 60 years. In British birds, 31% of species since 1971, and 53% of species since 1939, show long-term, significant trends toward earlier breeding, and only one species is nesting later (n = 65 and 36, respectively) (*124*, *125*). Among six species of British amphibians, five are breeding significantly earlier since 1978 (*126*). Over the last 20 to 25 years, the shift in breeding has been almost 9 days earlier in birds and up to 7 weeks earlier in amphibians. For the Red Deer in Norway, warm NAO winters have been shown to select for small females and large males. Over the past 40 years, the deer population has gradually shifted in these directions, with the result that the size difference between the sexes has grown larger (*125*). All of these trends, in birds, amphibians, and deer, have been linked to the periodicity and severity of NAO (*127*, *128*).

For most other cases, the potential links between biotic and climatic changes must be inferred from more indirect measures of the influence of climate, such as from biogeographic or physiological studies. One limitation of such inference is that many of these relationships have been studied with respect to mean climatological values, even though the underlying mechanisms may involve extreme weather events. Furthermore, predictive power is hindered by the barrage of nonclimatic anthropogenic forces affecting natural systems—urbanization, land conversion, water diversion, and pollution (*129*). Thus, not only are scenarios of global climate change predicting nonlinearities and "surprises" in the climate system, but if we incorporate the complexities of modern, human-dominated environments, then wildlife should also be expected to exhibit novel, unpredictable responses (*130*).

One prescription for these large uncertainties in predictive scenarios is to build more bridges between disciplines—between field and laboratory biologists and among climatologists, biologists, and social scientists. Climatic analyses on ecologically relevant scales of time and space are needed so that current changes in wild species can be better linked to specific suites of climatological variables (*131*), including analyses of weather extremes. Large data gaps exist in the biological literature, and to a lesser extent in the climatological literature, which impede global assessments for both climatic and biological systems. Exploration of unorthodox sources, as well as increased efforts to synthesize small, isolated data sets, would improve geographic and temporal coverage, leading to more robust global interpretations of trends.

Although the direct link between societal and biological impacts and climate change is often difficult to make, a growing body of evidence linking climatic and biological changes suggests systematic global increases in both the frequency and impact of extreme weather and climate events. Furthermore, as climate models become better developed, climate simulations will provide a much better idea of the kinds of changes in climate extremes to be expected with increasing GHGs, which will allow the observed record to be examined for further evidence of these kinds of changes. Lastly, it must be kept in mind that the kinds of climate changes discussed here are often nonlinear, and that both temporal and regional variability are associated with any kind of climate change.

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