EXECUTIVE SUMMARY

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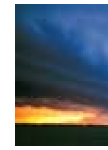


Synopsis

Changes in extreme weather and climate events have significant impacts and are among the most serious challenges to society in coping with a changing climate.

Many extremes and their associated impacts are now changing. For example, in recent decades most of North America has been experiencing more unusually hot days and nights, fewer unusually cold days and nights, and fewer frost days. Heavy downpours have become more frequent and intense. Droughts are becoming more severe in some regions, though there are no clear trends for North America as a whole. The power and frequency of Atlantic hurricanes have increased substantially in recent decades, though North American mainland land-falling hurricanes do not appear to have increased over the past century. Outside the tropics, storm tracks are shifting northward and the strongest storms are becoming even stronger.

It is well established through formal attribution studies that the global warming of the past 50 years is due primarily to human-induced increases in heat-trapping gases. Such studies have only recently been used to determine the causes of some changes in extremes at the scale of a continent. Certain aspects of observed increases in temperature extremes have been linked to human influences. The increase in heavy precipitation events is associated with an increase in water vapor, and the latter has been attributed to human-induced warming. No formal attribution studies for changes in drought severity in North America have been attempted. There is evidence suggesting a human contribution to recent changes in hurricane activity as well as in storms outside the tropics, though a confident assessment will require further study.

In the future, with continued global warming, heat waves and heavy downpours are very likely to further increase in frequency and intensity. Substantial areas of North America are likely to have more frequent droughts of greater severity. Hurricane wind speeds, rainfall intensity, and storm surge levels are likely to increase. The strongest cold season storms are likely to become more frequent, with stronger winds and more extreme wave heights.

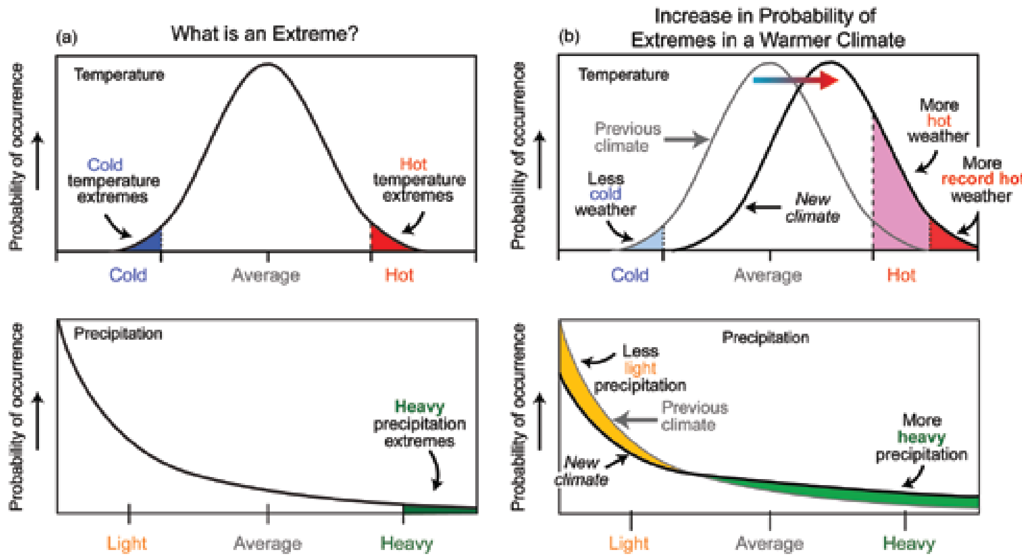
Current and future impacts resulting from these changes depend not only on the changes in extremes, but also on responses by human and natural systems.

1. WHAT ARE EXTREMES AND WHY DO THEY MATTER?

Weather and climate extremes (Figure ES1) have always posed serious challenges to society. Changes in extremes are already having impacts on socioeconomic and natural systems, and future changes associated with continued warming will present additional challenges. Increased frequency of heat waves and drought, for example, could seriously affect human health, agricultural production, water availability and quality, and other environmental conditions (and the services they provide) (Chapter 1, section 1.1).

Extremes are a natural part of even a stable climate system and have associated costs (Figure ES.2) and benefits. For example, extremes are essential in some systems to keep insect pests under control. While hurricanes cause significant disruption, including death, injury, and damage, they also provide needed rainfall

Recent and projected changes in climate and weather extremes have primarily negative impacts.



Many currently rare extreme events will become more commonplace.

Figure ES.1 Most measurements of temperature (top) will tend to fall within a range close to average, so their probability of occurrence is high. A very few measurements will be considered extreme and these occur very infrequently. Similarly, for rainfall (bottom), there tends to be more days with relatively light precipitation and only very infrequently are there extremely heavy precipitation events, meaning their probability of occurrence is low. The exact threshold for what is classified as an extreme varies from one analysis to another, but would normally be as rare as, or rarer than, the top or bottom 10% of all occurrences. A relatively small shift in the mean produces a larger change in the number of extremes for both temperature and precipitation (top right, bottom right). Changes in the shape of the distribution (not shown), such as might occur from the effects of a change in atmospheric circulation, could also affect changes in extremes. For the purposes of this report, all tornadoes and hurricanes are considered extreme.

to certain areas, and some tropical plant communities depend on hurricane winds toppling tall trees, allowing more sunlight to rejuvenate low-growing trees. But on balance, because systems have adapted to their historical range of extremes, the majority of events outside this range have primarily negative impacts (Chapter 1, section 1.4 and 1.5).

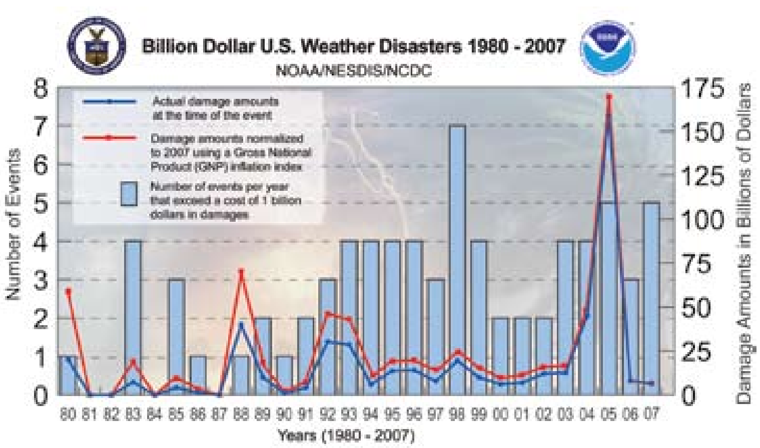


Figure ES.2 The blue bars show the number of events per year that exceed a cost of 1 billion dollars (these are scaled to the left side of the graph). The blue line (actual costs at the time of the event) and the red line (costs adjusted for wealth/inflation) are scaled to the right side of the graph, and depict the annual damage amounts in billions of dollars. This graphic does not include losses that are non-monetary, such as loss of life.

The impacts of changes in extremes depend on both changes in climate and ecosystem and societal vulnerability. The degree of impacts are due, in large part, to the capacity of society to respond. Vulnerability is shaped by factors such as population dynamics and economic status as well as adaptation measures such as appropriate building codes, disaster preparedness, and water use efficiency. Some short-term actions taken to lessen the risk from extreme events can lead to increases in vulnerability to even larger extremes. For example, moderate flood control measures on a river can stimulate development in a now "safe" floodplain, only to see those new structures damaged when a very large flood occurs (Chapter 1, section 1.6).

Human-induced warming is known to affect climate variables such as temperature and precipitation. Small changes in the averages of many variables result in larger changes in their extremes. Thus, within a changing climate system, some of what are now considered to be extreme events will occur more frequently, while others will occur less frequently (*e.g.*, more heat waves and fewer cold snaps [Figures

ES.1, ES.3, ES.4]). Rates of change matter since these can affect, and in some cases overwhelm, existing societal and environmental capacity. More frequent extreme events occurring over a shorter period reduce the time available for recovery and adaptation. In addition, extreme events often occur in clusters. The cumulative effect of compound or back-to-back extremes can have far larger impacts than the same events spread out over a longer period of time. For example, heat waves, droughts, air stagnation, and resulting wildfires often occur concurrently and have more severe impacts than any of these alone (Chapter 1, section 1.2).

2. TEMPERATURE–RELATED EXTREMES

Observed Changes

Since the record hot year of 1998, six of the last ten years (1998-2007) have had annual average temperatures that fall in the hottest 10% of all years on record for the U.S. Accompanying a general rise in the average temperature, most of North America is experiencing more unusually hot days and nights. The number of heat waves (extended periods of extremely hot weather) also has been increasing over the past fifty years (see Table ES.1). However, the heat waves of the 1930s remain the most severe in the U.S. historical record (Chapter 2, section 2.2.1).

There have been fewer unusually cold days during the last few decades. The last 10 years have seen fewer severe cold snaps than for any other 10-year period in the historical record, which dates back to 1895. There has been a decrease in frost days and a lengthening of the frost-free season over the past century (Chapter 2, section 2.2.1).

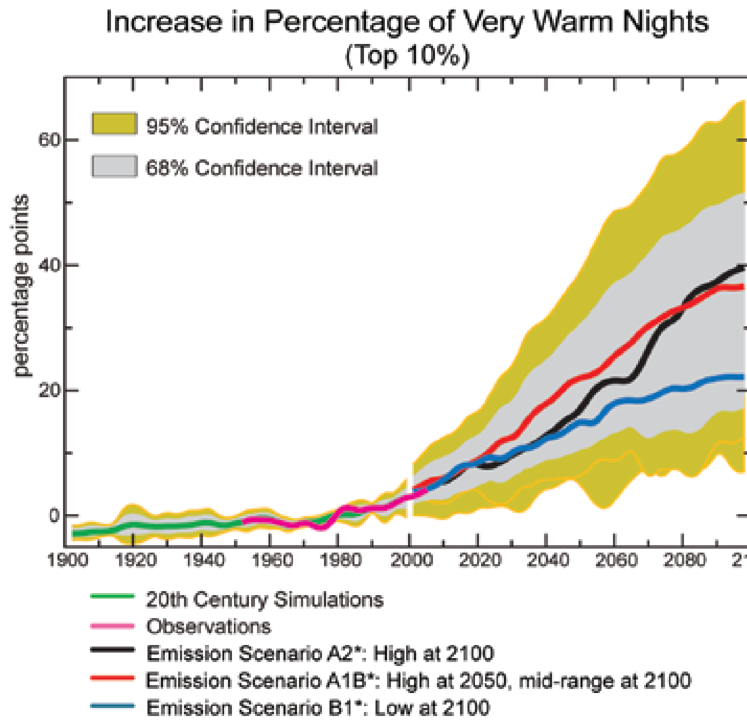


Figure ES.3 Increase in the percent of days in a year over North America in which the daily low temperature is unusually warm (falling in the top 10% of annual daily lows, using 1961 to 1990 as a baseline). Under the lower emissions scenario[a], the percentage of very warm nights increases about 20% by 2100 whereas under the higher emissions scenarios, it increases by about 40%. Data for this index at the continental scale are available since 1950.

In summary, there is a shift towards a warmer climate with an increase in extreme high temperatures and a reduction in extreme low temperatures. These changes have been especially apparent in the western half of North America (Chapter 2, section 2.2.1).

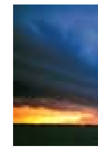
Attribution of Changes

Human-induced warming has likely caused much of the average temperature increase in North America over the past fifty years and, consequently, changes in temperature extremes. For example, the increase in human-induced

Abnormally hot days and nights and heat waves are very likely to become more frequent.

The footnote below refers to Figures 3, 4, and 7.

* Three future emission scenarios from the IPCC Special Report on Emissions Scenarios:
B1 blue line: emissions increase very slowly for a few more decades, then level off and decline
A2 black line: emissions continue to increase rapidly and steadily throughout this century
A1B red line: emissions increase very rapidly until 2030, continue to increase until 2050, and then decline.
More details on the above emissions scenarios can be found in the IPCC Summary for Policymakers (IPCC, 2007)



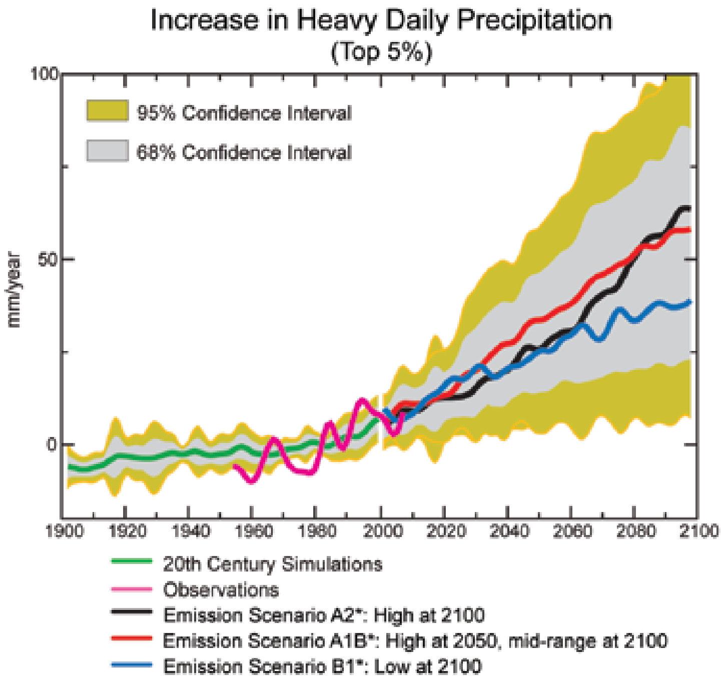


Figure ES.4 Increase in the amount of daily precipitation over North America that falls in heavy events (the top 5% of all precipitation events in a year) compared to the 1961-1990 average. Various emission scenarios are used for future projections*. Data for this index at the continental scale are available only since 1950.

emissions of greenhouse gases is estimated to have substantially increased the risk of a very hot year in the U.S., such as that experienced in 2006 (Chapter 3, section 3.2.1 and 3.2.2). Additionally, other aspects of observed increases in temperature extremes, such as changes in warm nights and frost days, have been linked to human influences (Chapter 3, section 3.2.2).

In the U.S., the heaviest 1% of daily precipitation events increased by 20% over the past century.

In the future, precipitation is likely to be less frequent but more intense.

Projected Changes

Abnormally hot days and nights (Figure ES.3) and heat waves are very likely to become more frequent. Cold days and cold nights are very likely to become much less frequent (see Table ES.1). The number of days with frost is very likely to decrease (Chapter 3, section 3.3.1 and 3.3.2).

Climate models indicate that currently rare extreme events will become more commonplace. For example, for a mid-range scenario of future greenhouse gas emissions, a day so hot that it is currently experienced only once every 20 years would occur every three years by the middle of the century over much of the continental U.S. and every five years over most of Canada. By the end of the century, it would occur every other year or more (Chapter 3, section 3.3.1).

Episodes of what are now considered to be unusually high sea surface temperature are very likely to become more frequent and widespread. Sustained (*e.g.*, months) unusually high temperatures could lead, for example, to more coral bleaching and death of corals (Chapter 3, section 3.3.1).

Sea ice extent is expected to continue to decrease and may even disappear entirely in the Arctic Ocean in summer in the coming decades. This reduction of sea ice increases extreme coastal erosion in Arctic Alaska and Canada due to the increased exposure of the coastline to strong wave action (Chapter 3, section 3.3.4 and 3.3.10).

3. PRECIPITATION EXTREMES

Observed Changes

Extreme precipitation episodes (heavy downpours) have become more frequent and more intense in recent decades over most of North America and now account for a larger percentage of total precipitation. For example, intense precipitation (the heaviest 1% of daily precipitation totals) in the continental U.S. increased by 20% over the past century while total precipitation increased by 7% (Chapter 2, section 2.2.2.2).

The monsoon season is beginning about 10 days later than usual in Mexico. In general, for the summer monsoon in southwestern North America, there are fewer rain events, but the events are more intense (Chapter 2, section 2.2.2.3).

Attribution of Changes

Heavy precipitation events averaged over North America have increased over the past 50 years, consistent with the observed increases in atmospheric water vapor, which have been associated

with human-induced increases in greenhouse gases (Chapter 3, section 3.2.3).

Projected Changes

On average, precipitation is likely to be less frequent but more intense (Figure ES.4), and precipitation extremes are very likely to increase (see Table ES.1; Figure ES.5). For example, for a mid-range emission scenario, daily precipitation so heavy that it now occurs only once every 20 years is projected to occur approximately every eight years by the end of this century over much of Eastern North America (Chapter 3, section 3.3.5).

4. DROUGHT

Observed Changes

Drought is one of the most costly types of extreme events and can affect large areas for long periods of time. Drought can be defined in many ways. The assessment in this report focuses primarily on drought as measured by the Palmer Drought Severity Index, which represents multi-seasonal aspects of drought and has been extensively studied (Box 2.1).

Averaged over the continental U.S. and southern Canada the most severe droughts occurred in the 1930s and there is no indication of an overall trend in the observational record, which dates back to 1895. However, it is more meaningful to consider drought at a regional scale, because as one area of the continent is dry, often another is wet. In Mexico and the U.S. Southwest, the 1950s were the driest period, though droughts in the past 10 years now rival the 1950s drought. There are also recent regional tendencies toward more severe droughts in parts of Canada and Alaska (Chapter 2, section 2.2.2.1).

Attribution of Changes

No formal attribution studies for greenhouse warming and changes in drought severity in North America have been attempted. Other attribution studies have been completed that link the location and severity of droughts to the geographic pattern of sea surface temperature variations, which appears to have been a factor in the severe droughts of the 1930s and 1950s (Chapter 3, section 3.2.3).

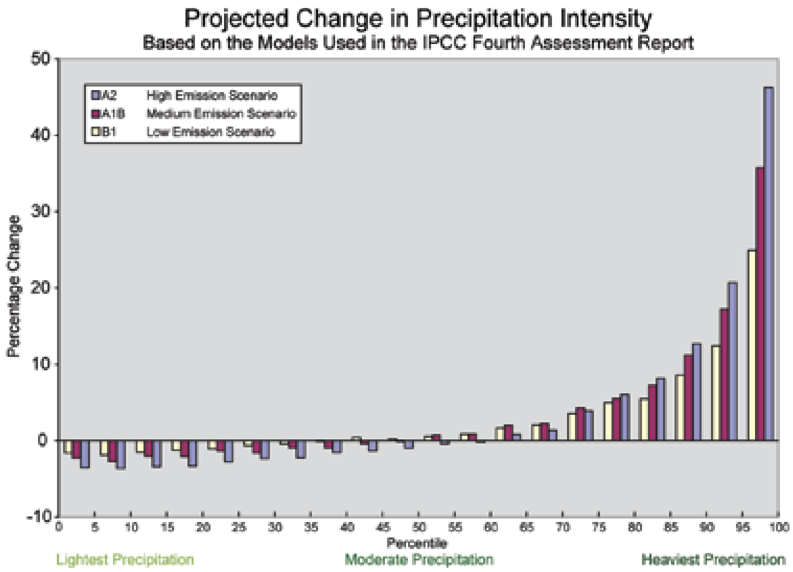


Figure ES.5 Projected changes in the intensity of precipitation, displayed in 5% increments, based on a suite of models and three emission scenarios. As shown here, the lightest precipitation is projected to decrease, while the heaviest will increase, continuing the observed trend. The higher emission scenarios yield larger changes. Figure courtesy of Michael Wehner.

Projected Changes

A contributing factor to droughts becoming more frequent and severe is higher air temperatures increasing evaporation when water is available. It is likely that droughts will become more severe in the southwestern U.S. and parts of Mexico in part because precipitation in the winter rainy season is projected to decrease (see Table ES.1). In other places where the increase in precipitation cannot keep pace with increased evaporation, droughts are also likely to become more severe (Chapter 3, section 3.3.7).

It is likely that droughts will continue to be exacerbated by earlier and possibly lower spring snowmelt run-off in the mountainous West, which results in less water available in late summer (Chapter 3, section 3.3.4 and 3.3.7).

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5. STORMS

Hurricanes and Tropical Storms

Observed Changes

Atlantic tropical storm and hurricane destructive potential as measured by the Power Dissipation Index (which combines storm intensity, duration, and frequency) has increased (see Table ES.1). This increase is substantial since about 1970, and is likely substantial since the 1950s and 60s, in association with warming Atlantic sea surface temperatures (Figure ES.6) (Chapter 2, section 2.2.3.1).

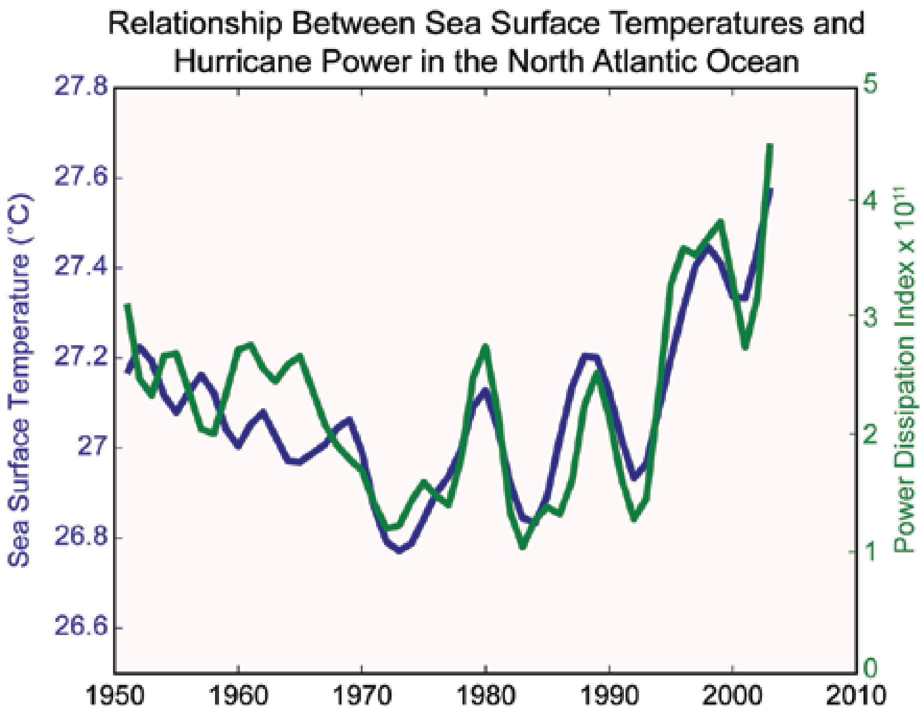
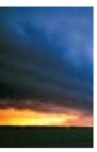


Figure ES.6 Sea surface temperatures (blue) and the Power Dissipation Index for North Atlantic hurricanes (Emanuel, 2007).



There have been fluctuations in the number of tropical storms and hurricanes from decade to decade and data uncertainty is larger in the early part of the record compared to the satellite era beginning in 1965. Even taking these factors into account, it is likely that the annual numbers of tropical storms, hurricanes and major hurricanes in the North Atlantic have increased over the past 100 years, a time in which Atlantic sea surface temperatures also increased. The evidence is not compelling for significant trends beginning in the late 1800s. Uncertainty in the data increases as one proceeds back in time. There is no observational evidence for an increase in North American mainland land-falling hurricanes since the late 1800s (Chapter 2, section 2.2.3.1). There is evidence for an increase in extreme wave height characteristics over the past couple of decades, associated with more frequent and more intense hurricanes (Chapter 2 section 2.2.3.3.2).

It is likely that hurricane rainfall and wind speeds will increase in response to human-caused warming.

Hurricane intensity shows some increasing tendency in the western north Pacific since 1980. It has decreased since 1980 in the eastern Pacific, affecting the Mexican west coast and shipping lanes. However, coastal station observations show that rainfall from hurricanes has nearly doubled since 1950, in part due to slower moving storms (Chapter 2, section 2.2.3.1).

Attribution of Changes

It is very likely that the human-induced increase in greenhouse gases has contributed to the increase in sea surface temperatures in the hurricane formation regions. Over the past 50 years there has been a strong statistical connection between tropical Atlantic sea surface temperatures and Atlantic hurricane activity as measured by the Power Dissipation Index (which combines storm intensity, duration, and frequency). This evidence suggests a human contribution to recent hurricane activity. However, a confident assessment of human influence on hurricanes will require further studies using models and observations, with emphasis on distinguishing natural from human-induced changes in hurricane activity through their influence on factors such as historical sea surface temperatures, wind shear, and atmospheric vertical stability (Chapter 3, section 3.2.4.3).

Projected Changes

For North Atlantic and North Pacific hurricanes, it is likely that hurricane rainfall and wind speeds will increase in response to human-caused warming. Analyses of model simulations suggest that for each 1ºC (1.8ºF) increase in tropical sea surface temperatures, core rainfall rates will increase by 6-18% and the surface wind speeds of the strongest hurricanes will increase by about 1-8% (Chapter 3, section 3.3.9.2 and 3.3.9.4). Storm surge levels are likely to increase due to projected sea level rise, though the degree of projected increase has not been adequately studied. It is presently unknown how late 21st century tropical cyclone frequency in the Atlantic and North Pacific basins will change compared to the historical period (~1950-2006) (Chapter 3, section 3.3.9.3).

Other Storms

Observed Changes

There has been a northward shift in the tracks of strong low-pressure systems (storms) in both the North Atlantic and North Pacific over the past fifty years. In the North Pacific, the strongest

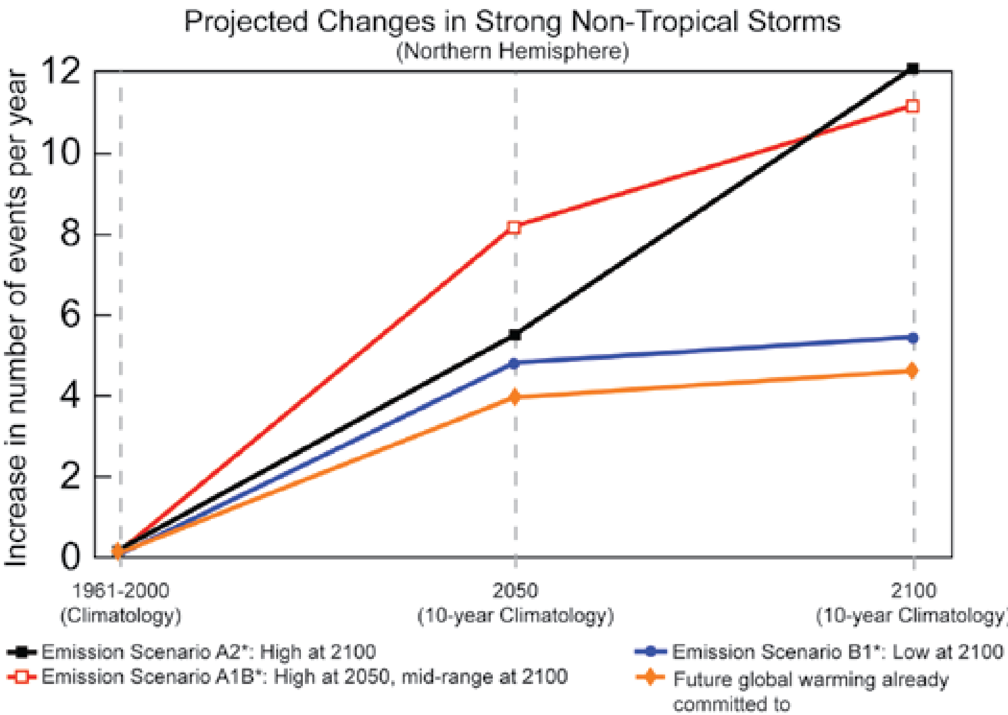
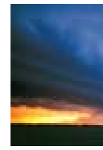


Figure ES.7 The projected change in intense low pressure systems (strong storms) during the cold season for the Northern Hemisphere for various emission scenarios* (adapted from Lambert and Fyfe; 2006).

There are likely to be more frequent strong storms outside the Tropics, with stronger winds and more extreme wave heights.



storms are becoming even stronger. Evidence in the Atlantic is insufficient to draw a conclusion about changes in storm strength (Chapter 2, section 2.2.3.2)

Increases in extreme wave heights have been observed along the Pacific Northwest coast of North America based on three decades of buoy data, and are likely a reflection of changes in cold season storm tracks (Chapter 2, section 2.2.3.3).

Over the 20th century, there has been considerable decade-to-decade variability in the frequency of snow storms (six inches or more). Regional analyses suggest that there has been a decrease in snow storms in the South and Lower Midwest of the U.S., and an increase in snow storms in the Upper Midwest and Northeast. This represents a northward shift in snow storm occurrence, and this shift, combined with higher temperature, is consistent with a decrease in snow cover extent over the U.S. In northern Canada, there has also been an observed increase in heavy snow events (top 10% of storms) over the same time period. Changes in heavy snow events in southern Canada are dominated by decade-to-decade variability (Chapter 2, section 2.2.3.4).

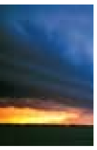
The pattern of changes in ice storms varies by region. The data used to examine changes in the frequency and severity of tornadoes and severe thunderstorms are inadequate to make definitive statements about actual changes (Chapter 2, section 2.2.3.5).

Attribution of Changes

Human influences on changes in atmospheric pressure patterns at the surface have been detected over the Northern Hemisphere and this reflects the location and intensity of storms (Chapter 3, section 3.2.5).

Projected Changes

There are likely to be more frequent deep low-pressure systems (strong storms) outside the Tropics, with stronger winds and more extreme wave heights (Figure ES.7) (Chapter 3, section 3.3.10).



Observed changes in North American extreme events, assessment of human influence for the observed changes, and likelihood that the changes will continue through the 21st century[1].

Phenomenon and direction of change	Where and when these changes occurred in past 50 years	Linkage of human activity to observed changes	Likelihood of continued future changes in this century
Warmer and fewer cold days and nights	Over most land areas, the last 10 years had lower numbers of severe cold snaps than any other 10-year period	Likely warmer extreme cold days and nights, and fewer frosts[2]	Very likely[4]
Hotter and more frequent hot days and nights	Over most of North America	Likely for warmer nights[2]	Very likely[4]
More frequent heat waves and warm spells	Over most land areas, most pronounced over northwestern two thirds of North America	Likely for certain aspects, *e.g.*, night-time temperatures; & linkage to record high annual temperature[2]	Very likely[4]
More frequent and intense heavy downpours and higher proportion of total rainfall in heavy precipitation events	Over many areas	Linked indirectly through increased water vapor, a critical factor for heavy precipitation events[3]	Very likely[4]
Increases in area affected by drought	No overall average change for North America, but regional changes are evident	Likely, Southwest USA.[3] Evidence that 1930's & 1950's droughts were linked to natural patterns of sea surface temperature variability	Likely in Southwest U.S.A., parts of Mexico and Carribean[4]
More intense hurricanes	Substantial increase in Atlantic since 1970; Likely increase in Atlantic since 1950s; increasing tendency in W. Pacific and decreasing tendency in E. Pacific (Mexico West Coast) since 1980[5]	Linked indirectly through increasing sea surface temperature, a critical factor for intense hurricanes[5]; a confident assessment requires further study[3]	Likely[4]

[1]Based on frequently used family of IPCC emission scenarios
[2]Based on formal attribution studies and expert judgment
[3]Based on expert judgment
[4]Based on model projections and expert judgment
[5]As measured by the Power Dissipation Index (which combines storm intensity, duration and frequency)

6. WHAT MEASURES CAN BE TAKEN TO IMPROVE THE UNDERSTANDING OF WEATHER AND CLIMATE EXTREMES?

Drawing on the material presented in this report, opportunities for advancement are described in detail in Chapter 4. Briefly summarized here, they emphasize the highest priority areas for rapid and substantial progress in improving understanding of weather and climate extremes.

1. The continued development and maintenance of high quality climate observing systems will improve our ability to monitor and detect future changes in climate extremes.

2. Efforts to digitize, homogenize and analyze long-term observations in the instrumental record with multiple independent experts and analyses improve our confidence in detecting past changes in climate extremes.

3. Weather observing systems adhering to standards of observation consistent with the needs of both the climate and the weather research communities improve our ability to detect observed changes in climate extremes.

4. Extended recontructions of past climate using weather models initialized with homogenous surface observations would help improve our understanding of strong extratropical cyclones and other aspects of climate variabilty.

5. The creation of annually-resolved, regional-scale reconstructions of the climate for the past 2,000 years would help improve our understanding of very long-term regional climate variability.

6. Improvements in our understanding of the mechanisms that govern hurricane intensity would lead to better short and long-term predictive capabilities.

7. Establishing a globally consistent wind definition for determining hurricane intensity would allow for more consistent comparisons across the globe.

8. Improvements in the ability of climate models to recreate the recent past as well as make projections under a variety of forcing scenarios are dependent on access to both computational and human resources.

9. More extensive access to high temporal resolution data (daily, hourly) from climate model simulations both of the past and for the future would allow for improved understanding of potential changes in weather and climate extremes.

10. Research should focus on the development of a better understanding of the physical processes that produce extremes and how these processes change with climate.

11. Enhanced communication between the climate science community and those who make climate-sensitive decisions would strengthen our understanding of climate extremes and their impacts.

12. A reliable database that links weather and climate extremes with their impacts, including damages and costs under changing socioeconomic conditions, would help our understanding of these events.