CHAPTER 3

Causes of Observed Changes in Extremes and Projections of Future Changes

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KEY FINDINGS

Attribution of Observed Changes

Changes in some weather and climate extremes are attributable to human-induced emissions of greenhouse gases.

- Human-induced warming has likely caused much of the average temperature increase in North America over the past 50 years. This affects changes in temperature extremes.
- 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.
- 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

Projected Changes

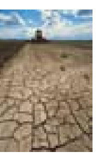
- Future changes in extreme temperatures will generally follow changes in average temperature:
    - Abnormally hot days and nights and heat waves are very likely to become more frequent.
    - Cold days and cold nights are very likely to become much less frequent.
    - The number of days with frost is very likely to decrease.
- Droughts are likely to become more frequent and severe in some regions as higher air temperatures increase the potential for evaporation.
- Over most regions, precipitation is likely to be less frequent but more intense, and precipitation extremes are very likely to increase.
- For North Atlantic and North Pacific hurricanes and typhoons:
    - It is likely that hurricane/typhoon wind speeds and core rainfall rates will increase in response to human-caused warming. Analyses of model simulations suggest that for each 1°C increase in tropical sea surface temperatures, hurricane surface wind speeds will increase by 1 to 8% and core rainfall rates by 6 to 18%.

  - Frequency changes are currently too uncertain for confident projec-tions.
  - The spatial distribution of hurricanes /typhoons will likely change.
  - Storm surge levels are likely to increase due to projected sea level rise, though the degree of projected increase has not been adequately studied.
- There are likely to be more frequent deep low-pressure systems (strong storms) outside the tropics, with stronger winds and more extreme wave heights.

3.1 INTRODUCTION

Understanding physical mechanisms of extremes involves processes governing the timing and location of extreme behavior, such as El Niño-Southern Oscillation (ENSO) cycles, as well as the mechanisms of extremes themselves (*e.g.*, processes producing heavy precipitation). This includes processes that create an environment conducive to extreme behavior, processes of the extreme behavior itself, and the factors that govern the timing and location of extreme events.

Climate models are important tools for understanding the causes of observed changes in extremes, as well as projecting future changes.



A deeper understanding of physical mechanisms is of course important for understanding why extremes have occurred in the past and for predicting their occurrence in the future. Climate models also facilitate better understanding of the physical mechanisms of climate change. However, because climate-change projections simulate conditions many decades into the future, strict verification of projections is not always possible. Other means of attaining confidence in projections are therefore needed. Confidence in projected changes in extremes increases when the physical mechanisms producing extremes in models are consistent with observed behavior. This requires careful analysis of the observed record as well as model output. Assessment of physical mechanisms is also necessary to determine the realism of changes in extremes. Physical consistency of simulations with observed behavior is necessary though not sufficient evidence for accurate projections.

Climate model results are used throughout this report. State-of-the-art climate models are based on physical principles expressed as equations, which the model represents on a grid and integrates forward in time. There are also processes with scales too small to be resolved by the model's grid. The model represents these processes through combinations of observations and physical theory usually called parameterizations. These parameterizations influence the climate model projections and are the source of a substantial fraction of the range associated with models' projections of future climate. For more details, see SAP 3.1, SAP 3.2, and Randall *et al*. (2007).

Once developed, the climate model simulations are evaluated against observations. In general, models do a good job of simulating many of the large-scale features of climate (Randall *et al*., 2007). An important application is the use of climate models to project changes in extremes. Evaluation of observed changes in extremes and model simulation of observed behavior is essential and an important part of this report. As noted above, such evaluation is a necessary step toward confidence in projected changes in extremes.

3.2 WHAT ARE THE PHYSICAL MECHANISMS OF OBSERVED CHANGES IN EXTREMES?

3.2.1 Detection and Attribution: Evaluating Human Influences on Climate Extremes Over North America

Climate change detection, as discussed in this chapter, is distinct from the concept that is used in Chapter 2. In that chapter, detection refers to the identification of change in a climate record that is statistically distinguishable from the record's previous characteristics. A typical example is the detection of a statistically significant trend in a temperature record. Here, detection and attribution involves the assessment of observed changes in relation to those that are expected to have occurred in response to external forcing. Detection of climatic changes in extremes involves demonstrating statistically significant changes in properties of extremes over time. Attribution further links those changes with variations in climate forcings, such as changes in greenhouse gases (GHGs), solar radiation, or volcanic eruptions. Attribution is a necessary step toward identifying the physical causes of changes in extremes. Attribution often uses quantitative comparison between climate-model simulations and observations, comparing expected changes due to physical understanding integrated in the models with those that have been observed. By comparing observed changes with those anticipated to result from external forcing, detection and attribution studies also provide an assessment of the performance of climate models in simulating climate change. The relationships between observed and simulated climate change that are diagnosed in these studies also provide an important means of constraining projections of future change made with those models.

A challenge arises in attribution studies if the available evidence linking cause and effect in the phenomenon of interest is indirect. For example, global climate models are able to simulate the expected responses to anthropogenic and natural forcing in sea surface temperature (SST) in tropical cyclone formation regions, and thus these expected responses can be compared with observed SST changes to make an attribution assessment of the causes of the observed changes in SSTs. However, global climate models are not yet able to simulate tropical cyclone activity with reasonable fidelity, making an "end-to-end" attribution of cause and effect (Allen, 2003) more difficult. In this case, our judgment of whether an external influence has affected tropical cyclone frequency or intensity depends upon our understanding of the links between SST variability and tropical cyclone variability on the one hand, and upon the understanding of how external influence has altered SSTs on the other. In these cases, it is difficult to quantify the magnitude and significance of the effect of the external influences on the phenomenon of interest. Therefore, attribution assessments become difficult, and estimates of the size of the anthropogenic contribution to an observed change cannot be readily derived. This problem often occurs in climate-change impacts studies and has sometimes been termed "joint attribution" (Rosenzweig *et al*., 2007).

3.2.1.1 Detection and Attribution: Human-Induced Changes in AVERAGE Climate That Affect Climate Extremes

This section discusses the present understanding of the causes of large-scale changes in the climatic state over North America. Simple statistical reasoning indicates that substantial changes in the frequency and intensity of extreme events can result from a relatively small shift in the average of a distribution of temperatures, precipitation, or other climate variables (Mearns *et al*., 1984; Katz and Brown, 1992). Expected changes in temperature extremes are largely, but not entirely, due to changes in seasonal mean temperatures. Some differences between changes in means and extremes arise because moderate changes are expected in the shape of the temperature distribution affecting climate extremes; for example, due to changes in snow cover, soil moisture, and cloudiness (*e.g.*, Hegerl *et al*., 2004; Kharin *et al*., 2007). In contrast, increases in mean precipitation are expected to increase the precipitation variance, thus increasing precipitation extremes, but decreases in mean precipitation do not necessarily

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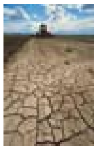
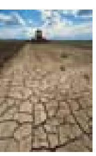


imply that precipitation extremes will decrease because of the different physical mechanisms that control mean and extreme precipitation (*e.g.*, Allen and Ingram, 2002; Kharin *et al.*, 2007). Therefore, changes in the precipitation background state are also interesting for understanding changes in extremes, although more difficult to interpret (Groisman *et al.*, 1999). Relevant information about mean temperature changes appears in Chapter 2. More detailed discussion of historical mean changes appears in CCSP Synthesis and Assessment Products 1.1, 1.2, and 1.3.

Global-scale analyses using space-time detection techniques have robustly identified the influence of anthropogenic forcing on the 20th century near-surface temperature changes. This result is robust to applying a variety of statistical techniques and using many different climate simulations (Hegerl *et al.*, 2007). Detection and attribution analyses also indicate that over the past century there has likely been a cooling influence from aerosols and natural forcings counteracting some of the warming influence of the increasing concentrations of greenhouse gases. Spatial information is required in addition to temporal information to reliably detect the influence of aerosols and distinguish them from the influence of increased greenhouse gases.



A human influence has been detected in trends of a U.S. climate extremes index that shows increasing extreme heat and extreme precipitation.

A number of studies also consider sub-global scales. Studies examining North America find a detectable human influence on 20th century temperature changes, either by considering the 100-year period from 1900 (Stott, 2003) or the 50-year period from 1950 (Zwiers and Zhang, 2003; Zhang *et al.*, 2006). Based on such studies, a substantial part of the warming over North America has been attributed to human influence (Hegerl *et al.*, 2007).

Further analysis has compared simulations using changes in both anthropogenic (greenhouse gas and aerosol) and natural (solar flux and volcanic eruption) forcings with others that neglect anthropogenic changes. There is a clear separation in North American temperature changes of ensembles of simulations including just natural forcings from ensembles of simulations containing both anthropogenic and natural forcings (Karoly *et al.*, 2003; IADAG, 2005; Karoly and Wu, 2005; Wang *et al.*, 2006; Knutson *et al.*, 2006; Hegerl *et al.*, 2007), especially for the last quarter of the 20th century, indicating that the warming in recent decades is inconsistent with natural forcing alone.

Attribution of observed changes on regional (subcontinental) scales has generally not yet been accomplished. One reason is that as spatial scales considered become smaller, the uncertainty becomes larger (Stott and Tett, 1998; Zhang *et al.*, 2006) because internal climate variability is typically larger than the expected responses to forcing on these scales. Also, small-scale forcings and model uncertainty make attribution on these scales more difficult. Therefore, interpreting changes on sub-continental scales is difficult (see discussion in Hegerl *et al.*, 2007). In central North America, there is a relatively small warming over the 20th century compared to other regions around the world (Hegerl *et al.*, 2007) and the observed changes lie (just) within the envelope of changes simulated by models using natural forcing alone. In this context, analysis of a multi-model ensemble by Kunkel *et al.* (2006) for a central U.S. region suggests that the region's warming from 1901 to 1940 and cooling from 1940 to 1979 may have been a consequence of unforced internal variability.

Burkholder and Karoly (2007) detected an anthropogenic signal in multidecadal trends of a U.S. climate extremes index. The observed increase is largely due to an increase in the number of months with monthly mean daily maximum and daily minimum temperatures that are much above normal and an increase in the area of the U.S. that experienced a greater than normal proportion of their precipitation from extreme one-day events. Twentieth century simulations from coupled climate models show a similar, significant increase in the same U.S. climate extremes index for the late 20th century. There is some evidence of an anthropogenic signal in regions a few hundred kilometers across (Karoly and Wu, 2005; Knutson *et al.*, 2006; Zhang *et al.*, 2006; Burkholder and Karoly, 2007), suggesting the potential for progress in regional attribution if careful attention is given to the choice of appropriate time scales, region sizes, and fields analyzed, and if all relevant forcings are considered.

Warming from greenhouse gas increases is expected to increase the moisture content of the atmosphere. Human-induced warming has been linked to water vapor increases in surface observations (Willett *et al*., 2007) and satellite observations over the oceans (Santer *et al*., 2007). The greater moisture content should yield a small increase in global mean precipitation. More important, the increase in water-holding capacity of the atmosphere is expected to more strongly affect changes in heavy precipitation, for which the Clausius-Clapeyron relation provides an approximate physical constraint (*e.g.*, Allen and Ingram, 2002). Observed changes in moisture content and mean and extreme precipitation are generally consistent with these expectations (Chapter 2 this report, Trenberth *et al*., 2007). In addition, greenhouse gas increases are also expected to cause increased horizontal transport of water vapor that is expected to lead to a drying of the subtropics and parts of the tropics (Kumar *et al.,* 2004; Neelin *et al.,* 2006), and a further increase in precipitation in the equatorial region and at high latitudes (Emori and Brown*,* 2005; Held and Soden*,* 2006).

Several studies have demonstrated that simulated global land mean precipitation in climate model simulations including both natural and anthropogenic forcings is significantly correlated with the observations (Allen and Ingram*,* 2002; Gillett *et al.,* 2004; Lambert *et al.,* 2004), thereby detecting external influence in observations of precipitation. This external influence on global land mean precipitation during the 20th century is dominated by volcanic forcing. Anthropogenic influence on the spatial distribution of global land precipitation, as represented by zonal-average precipitation changes, has also been detected (Zhang *et al*., 2007). Both changes are significantly larger in observations than simulated in climate models, raising questions about whether models underestimate the response to external forcing in precipitation changes (see also Wentz *et al*., 2007). Changes in North American continental-mean rainfall have not yet been formally attributed to anthropogenic influences. A large part of North America falls within the latitude band identified by Zhang *et al*. (2007) where the model simulated response to forcing is not in accord with the observed response. However, both models and observations show a pattern of increasing precipitation north of 50°N and decreasing precipitation between 0-30°N, and this, together with agreement on decreasing precipitation south of the equator, provides support for the detection of a global anthropogenic influence

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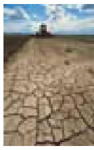
3.2.1.2 Changes in Modes of Climate-system Behavior Affecting Climate Extremes

North American extreme climate is also substantially affected by changes in atmospheric circulation (*e.g.*, Thompson and Wallace, 2001). Natural low frequency variability of the climate system is dominated by a small number of large-scale circulation patterns such as the ENSO, the Pacific Decadal Oscillation (PDO), and the Northern Annular Mode (NAM). The impact of these modes on terrestrial climate on annual to decadal time scales can be profound. In particular, there is considerable evidence that the state of these modes affects substantially the likelihood of extreme temperature (Thompson and Wallace, 2001; Kenyon and Hegerl, 2008), droughts (Hoerling and Kumar, 2003), and short-term precipitation extremes (*e.g.*, Gershunov and Cayan, 2003; Eichler and Higgins, 2006) over North America.

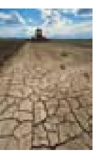
Some evidence of anthropogenic influence on these modes appears in surface-pressure analyses. Gillett *et al*. (2003, 2005) diagnosed anthropogenic influence on Northern Hemisphere sea-level pressure change, although the model-simulated change is not as large as has been observed. Model-simulated changes in

The water-holding capacity of the atmosphere has increased in response to human-induced warming, allowing more and heavier precipitation.



Climate extremes in North America are also affected by modes of climate variability such as ENSO in the Pacific and the North Atlantic Oscillation.

extremes related to circulation changes may therefore be affected. The change in sea-level pressure largely manifests itself through an intensification of the NAM, with reduced pressure above the pole and equatorward displacement of mass, changes that are closely related to changes in another circulation pattern, the North Atlantic Oscillation (NAO) (Hurrell, 1996). However, apart from the NAM, the extent to which modes of variability are excited or altered by external forcing remains uncertain. While some modes might be expected to change as a result of anthropogenic effects such as the intensified greenhouse effect, there is little *a priori* expectation about the direction or magnitude of such changes. In addition, models may not simulate well the behavior of these modes in some regions and seasons.



ENSO is the leading mode of variability in the tropical Pacific, and it has impacts on climate around the globe (Trenberth *et al*., 2007, see also Chapter 1 this report). There have been multidecadal oscillations in the ENSO index throughout the 20th century, with more intense El Niño events since the late 1970s, which may reflect in part a mean warming of the eastern equatorial Pacific (Mendelssohn *et al.,* 2005). There is presently no clear consensus on the possible impact of anthropogenic forcing on observed ENSO variability (Merryfield, 2006; Meehl *et al*., 2007a).

Decadal variability in the North Pacific is characterized by variations in the strength of the Aleutian Low coupled to changes in North Pacific SST. The leading mode of decadal variability in the North Pacific is usually termed the PDO and has a spatial structure in the atmosphere and upper North Pacific Ocean similar to the pattern that is associated with ENSO. Pacific decadal variability can also be characterized by changes in sea-level pressure in the North Pacific, termed the North Pacific Index (Deser *et al*., 2004). One recent study showed a consistent tendency towards the positive phase of the PDO in observations and model simulations that included anthropogenic forcing (Shiogama *et al.,* 2005), though differences between the observed and simulated PDO patterns, and the lack of additional studies, limit confidence in these findings.

ENSO and Pacific decadal variability affect the mean North American climate and its extremes (*e.g.*, Kenyon and Hegerl, 2008), particularly when both are in phase, at which time considerable energy is propagated from tropical and northern Pacific sources towards the North American land mass (Yu *et al*., 2007; Yu and Zwiers, 2007).

The NAM is an approximately zonally symmetric mode of variability in the Northern Hemisphere (Thompson and Wallace*,* 1998), and the NAO (Hurrell*,* 1996) may be viewed as its Atlantic counterpart. The NAM index exhibited a pronounced trend towards its positive phase between the 1960s and the 1990s, corresponding to a decrease in surface pressure over the Arctic and an increase over the subtropical North Atlantic (*e.g.*, Hurrell*,* 1996; Thompson *et al.,* 2000; Gillett *et al.,* 2003). Several studies have shown this trend to be inconsistent with simulated internal variability (Osborn *et al.,* 1999; Gillett *et al.,* 2000; Gillett *et al.,* 2002; Osborn*,* 2004; Gillett*,* 2005) and similar to, although larger than, simulated changes in coupled climate models in response to 20th century forcing, particularly greenhouse gas forcing and ozone depletion (Gillett *et al.,* 2002; Osborn*,* 2004; Gillett, 2005; Hegerl *et al*., 2007). The mechanisms underlying Northern Hemisphere circulation changes also remain open to debate (see *e.g.*, Hoerling *et al.,* 2005; Hurrell *et al.,* 2005; Scaife *et al*., 2005).

Over the period 1968–1997, the trend in the NAM was associated with approximately 50% of the winter surface warming in Eurasia, a decrease in winter precipitation over Southern Europe, and an increase over Northern Europe due to the northward displacement of the storm track (Thompson *et al.,* 2000). Such a change would have substantial influence on North America, too, reducing the probability of cold extremes in winter even over large areas (for example, Thompson and Wallace, 2001; Kenyon and Hegerl, 2008), although part of the northeastern U.S. tends to show a tendency for more cold extremes with the NAO trend (Wettstein and Mearns, 2002).

3.2.2 Changes in Temperature Extremes

As discussed in Chapter 2, observed changes in temperature extremes are consistent with the observed warming of the climate (Alexander *et al.,* 2006). Globally, in recent decades, there has been an increase in the number of hot extremes, particularly very warm nights, and a reduction in the number of cold extremes, such as very cold nights, and a widespread reduction in the number of frost days in mid-latitude regions.

There is now evidence that anthropogenic forcing has likely affected extreme temperatures. Christidis *et al.* (2005) analyzed a new dataset of gridded daily temperatures (Caesar *et al.,* 2006) using the indices shown by Hegerl *et al.* (2004) to have potential for attribution; namely, the average temperature of the most extreme 1, 5, 10 and 30 days of the year. Christidis *et al.* (2005) detected robust anthropogenic changes in a global analysis of indices of extremely warm nights using fingerprints from the Hadley Centre Coupled Model, version 3 (HadCM3), with some indications that the model over-estimates the observed warming of warm nights. Human influence on cold days and nights was also detected, but in this case the model under-estimated the observed changes significantly, so in the case of the coldest day of the year, anthropogenic influence was not detected in observed changes in extremely warm days. Tebaldi *et al.* (2006) find that changes simulated by an ensemble of eight global models that include anthropogenic and natural forcing changes agrees well with observed global trends in heat waves, warm nights, and frost days over the last four decades.

North American observations also show a general increase in the number of warm nights, but with a decrease in the center of the continent that models generally do not reproduce (*e.g.*, Christidis *et al.*, 2005). However, analysis for North America of models (Table 3.1) used by Tebaldi *et al.* (2006) shows reasonable agreement between observed and simulated changes in the frequency of warm nights, number of frost days, and growing season length over the latter half of the 20th century when averaged over the continent (Figure 3.1a,b,c). There is also good agreement between the observed and ensemble mean simulated spatial pattern of change in frost days (Figure 3.2a,b) over the latter half of the 20th century. Note that the observational estimate has a much greater degree of temporal (Figure 3.1) and spatial (Figure 3.2) variability than the model result. The model result is derived from an ensemble of simulations produced by many models, some of which contributed multiple realizations. Averaging over many simulations reduces much of the spatial and temporal variability that arises from internal climate variability. The variability of individual model realizations is comparable to the single set of observations, which is well bounded by the two standard deviation confidence interval about the model ensemble average. Furthermore, Meehl *et al.* (2007b) demonstrate that ensemble simulations using two coupled climate models driven by human and natural forcings approximate well the observed changes, but when driven with natural forcings only cannot reproduce the observed changes, indicating a human

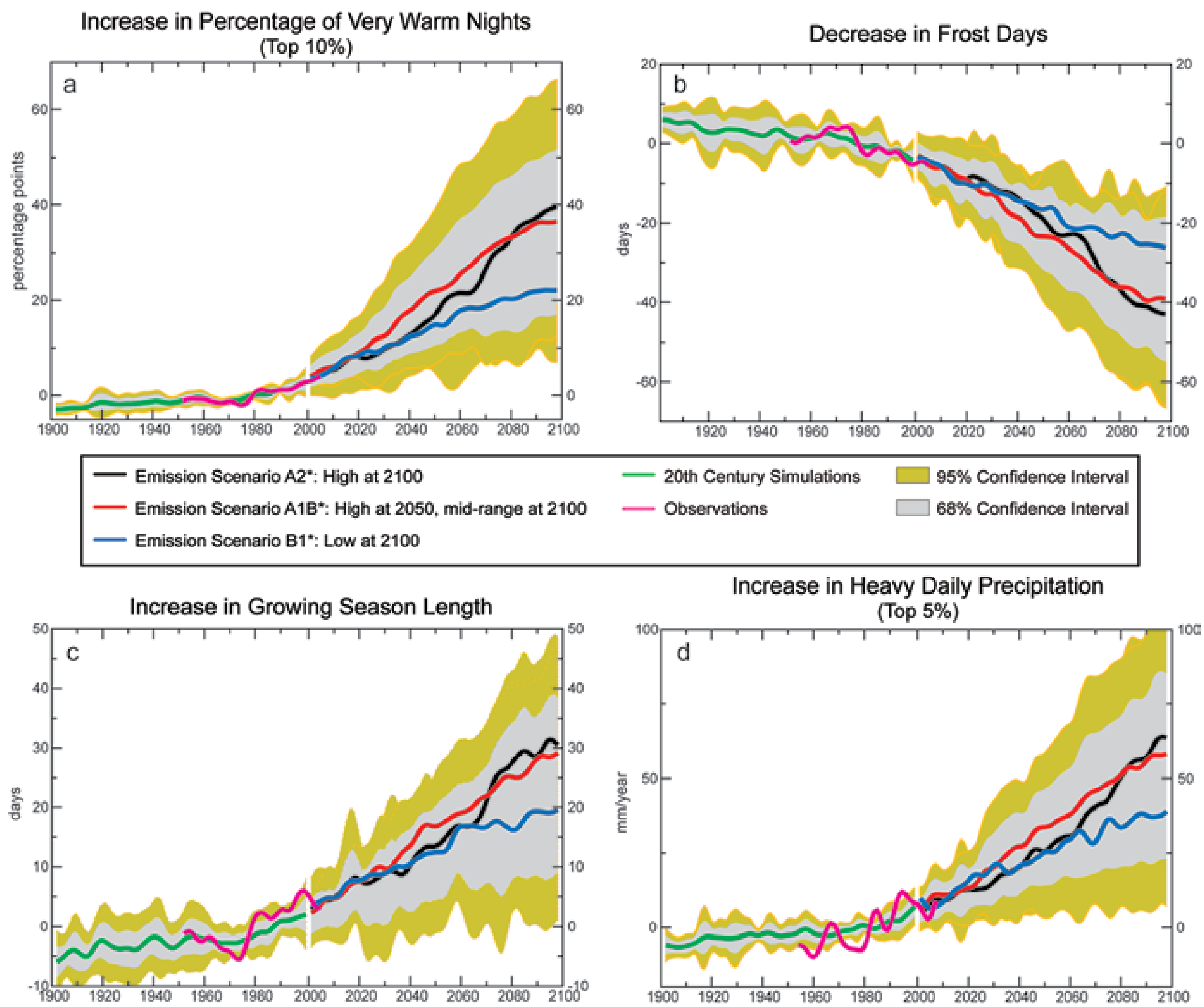
Table 3.1 Models and scenarios used for computing the Frich *et al.* (2002) indices for North America that appear in this document.

Scenario	Models
SRES A1B	ccsm3.0 cnrm gfdl2.0 gfdl2.1 inmcm3 ipsl miroc3_2_medres miroc3_2_hires mri_cgcm2_3_2a
SRES A2	cnrm gfd2.0 gfdl2.1 inmcm3 ipsl miroc3_2_medre mri_cgcm2_3_2a
SRES B1	ccsm3.0 cnrm gfdl2.0 gfdl2.1 inmcm3 ipsl miroc3_2_medres miroc3_2_hires

Analyses using climate models and observations provide evidence of a human influence on temperature extremes in North America.

contribution to observed changes in heat waves, frost days, and warm nights. Output from one of these ensembles, produced by the Parallel Climate Model, also shows significant trends in the Karl-Knight heat-wave index (Karl and Knight, 1997) in the eastern half of the U.S. for 1961-1990 that are similar to observed trends (Figure 3.3).

There have also been some methodological advances whereby it is now possible to estimate the impact of external forcing on the risk of a particular extreme event. For example, Stott *et al.* (2004), assuming a model-based estimate of temperature variability, estimate that past human influence may have more than doubled the risk of European mean summer temperatures as high as those recorded in 2003. Such a meth-



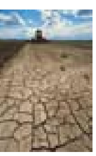


Figure 3.1 Indices (Frich *et al.*, 2002) averaged over North America for model simulations and observations for the 20th and 21st centuries showing changes relative to 1961-1990 in the a) percentage of days in a year for which daily low temperature is in the top 10% of warm nights for the period 1961-1990, b) number of frost days per year, c) growing season length (days), and d) sum of precipitation on days in the top 5% of heavy precipitation days for the period 1961-1990. In the 20th century, the confidence intervals are computed from the ensemble of 20th century simulations. In the future, the bounds are from an ensemble of simulations that used the A1B, A2, or B1 scenarios*. The bounds are the max (or min) standard deviation plus (or minus) signal over all three scenarios. The model plots are obtained from the CMIP-3 multi-model data set at PCMDI and the observations are from Peterson *et al.* (2008).

*Three future emission scenarios from the IPCC Special Report on Emissions Scenarios:
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.
B1 blue line: emissions increase very slowly for a few more decades, then level off and decline.
More details on the above emission scenarios can be found in the IPCC Summary for Policymakers (IPCC, 2007).

odology has not yet been applied extensively to North American extremes, though Hoerling *et al*. (2007) have used the method to conclude that the increase in human induced greenhouse gases has substantially increased the risk of a very hot year in the U.S., such as that experienced in 2006.

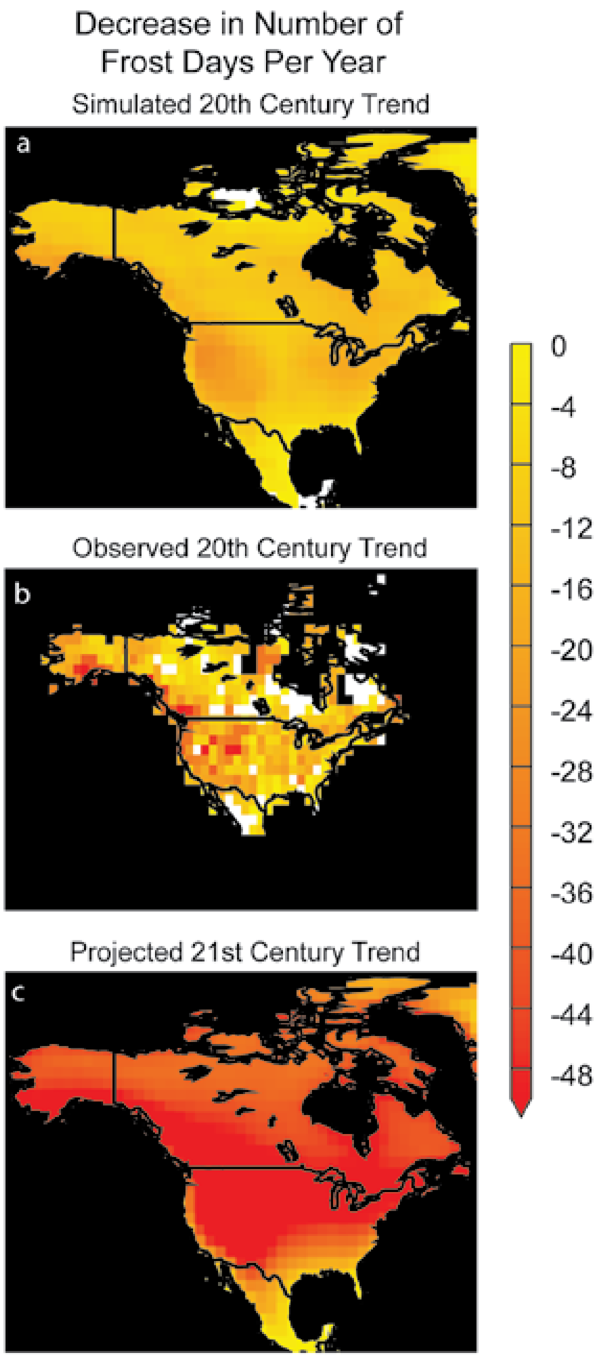


Figure 3.2 Indices (Frich *et al*., 2002) for frost days over North America for model simulations and observations: a) 20th century trend for model ensemble, b) Observed 20th century trend, and c) 21st century trend for emission scenario A2 from model ensemble. The model plots are obtained from the CMIP-3 multi-model data set at PCMDI and the observations are from Peterson *et al.* (2008).

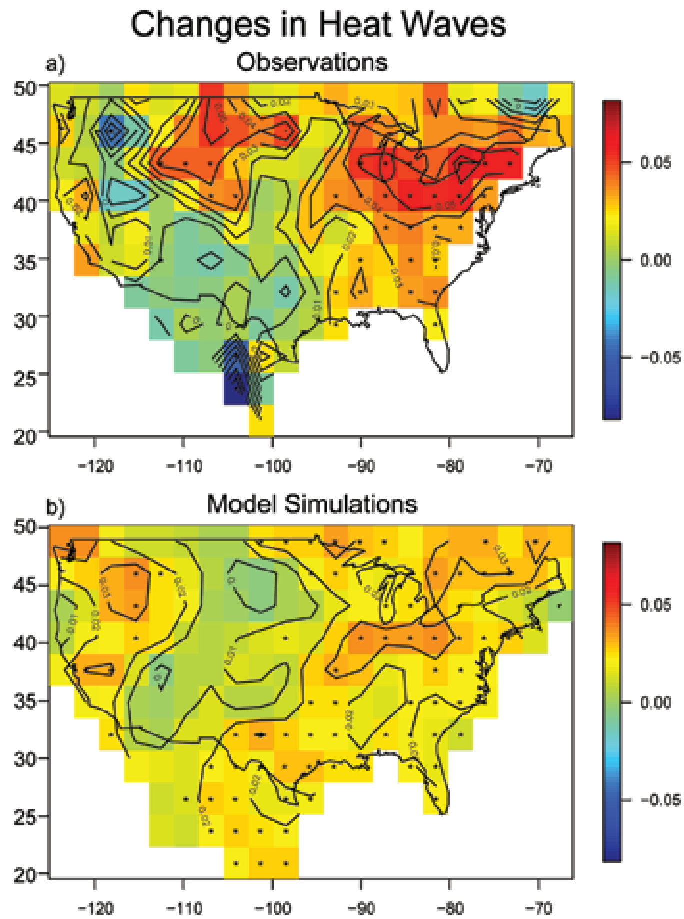


Figure 3.3 Trends in the Karl-Knight heat-wave index (Karl and Knight, 1997) for 1961-1990 in observations (top panel) and in an ensemble of climate simulations by the Parallel Climate Model (bottom panel). Dots mark trends that are significant at the 95% level.

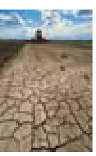
3.2.3 Changes in Precipitation Extremes

3.2.3.1 Heavy Precipitation

Allen and Ingram (2002) suggest that while global annual mean precipitation is constrained by the energy budget of the troposphere, extreme precipitation is constrained by the atmospheric moisture content, as governed by the Clausius-Clapeyron equation, though this constraint may be most robust in extratropical regions and seasons where the circulation's fundamental dynamics are not driven by latent heat release (Pall *et al*., 2007). For a given change in temperature, the constraint predicts a larger change in extreme precipitation than in mean precipitation, which is consistent with changes in precipitation extremes simulated by the ensemble of General Circulation Models (GCMs) available for the

IPCC Fourth Assessment Report (Kharin *et al*., 2007). Emori and Brown (2005) discuss physical mechanisms governing changes in the dynamic and thermodynamic components of mean and extreme precipitation, and conclude that changes related to the dynamic component (*i.e.*, that due to circulation change) are secondary factors in explaining the larger increase in extreme precipitation than mean precipitation seen in models. On the other hand, Meehl *et al*. (2005) demonstrate that while tropical precipitation intensity increases are related to water vapor increases, mid-latitude intensity increases are related to circulation changes that affect the distribution of increased water vapor.

Climatological data show that the most intense precipitation occurs in warm regions (Easterling *et al.,* 2000) and diagnostic analyses have shown that even without any change in total precipitation, higher temperatures lead to a greater proportion of total precipitation in heavy and very heavy precipitation events (Karl and Trenberth*,* 2003). In addition, Groisman *et al.* (1999) have demonstrated empirically, and Katz (1999) theoretically, that as total precipitation increases, a greater proportion falls in heavy and very heavy events if the frequency of raindays remains constant. Trenberth *et al.* (2005) point out that a consequence of a global increase in precipitation intensity should be an offsetting global decrease in the duration or frequency of precipitation events, though some regions could have differing behavior, such as reduced total precipitation or increased frequency of precipitation.



Significant increases in observed extreme precipitation have been reported over the United States, where the increase is similar to changes expected under greenhouse warming.

Simulated changes in globally averaged annual mean and extreme precipitation appear to be quite consistent between models. The greater and spatially more uniform increases in heavy precipitation as compared to mean precipitation may allow extreme precipitation change to be more robustly detectable (Hegerl *et al.,* 2004).

Evidence for changes in observations of short-duration precipitation extremes varies with the region considered (Alexander *et al.,* 2006) and the analysis method that is employed (*e.g.*, Trenberth *et al*., 2007). Significant increases in observed extreme precipitation have been reported over the United States, where the increase is qualitatively similar to changes expected under greenhouse warming (*e.g.*, Karl and Knight*,* 1998; Semenov and Bengtsson*,* 2002; Groisman *et al.,* 2005). However, a quantitative comparison between area-based extreme events simulated in models and station data remains difficult because of the different scales involved (Osborn and Hulme*,* 1997; Kharin and Zwiers, 2005), and the pattern of changes does not match observed changes. Part of this difference is expected since most current GCMs do not simulate small-scale (< 100 km) variations in precipitation intensity, as occurs with convective storms. Nevertheless, when compared with a gridded reanalysis product (ERA40), the ensemble of currently available Atmosphere-Ocean General Circulation Models (AOGCMs) reproduces observed precipitation extremes reasonably well over North America (Kharin *et al*., 2007). An attempt to detect anthropogenic influence on precipitation extremes using global data based on the Frich *et al*. (2002) indices used fingerprints from atmospheric model simulations with prescribed sea surface temperature (Kiktev *et al.,* 2003). This study found little similarity between patterns of simulated and observed rainfall extremes. This is in contrast to the qualitative similarity found in other studies (Semenov and Bengtsson, 2002; Groisman *et al*., 2005; Figure 3.4). Tebaldi *et al*. (2006) reported that an ensemble of eight global climate models simulating the 20th century showed a general tendency toward more frequent heavy-precipitation events over the past four decades, most coherently in the high latitudes of the Northern Hemisphere, broadly consistent with observed changes (Groisman *et al.,* 2005). This is also seen when analyzing these models for North America (Figure 3.1d). The pattern similarity of change in precipitation extremes over this period is more difficult to assess, particularly on continental and smaller scales.

3.2.3.2 Runoff and Drought

Changes in runoff have been observed in many parts of the world, with increases or decreases corresponding to changes in precipitation. Climate models suggest that runoff will increase in regions where precipitation increases faster than evaporation, such as at high northern latitudes (Milly *et al.,* 2005; Wu *et al.,* 2005). Gedney *et al.* (2006a) attributed increased continental

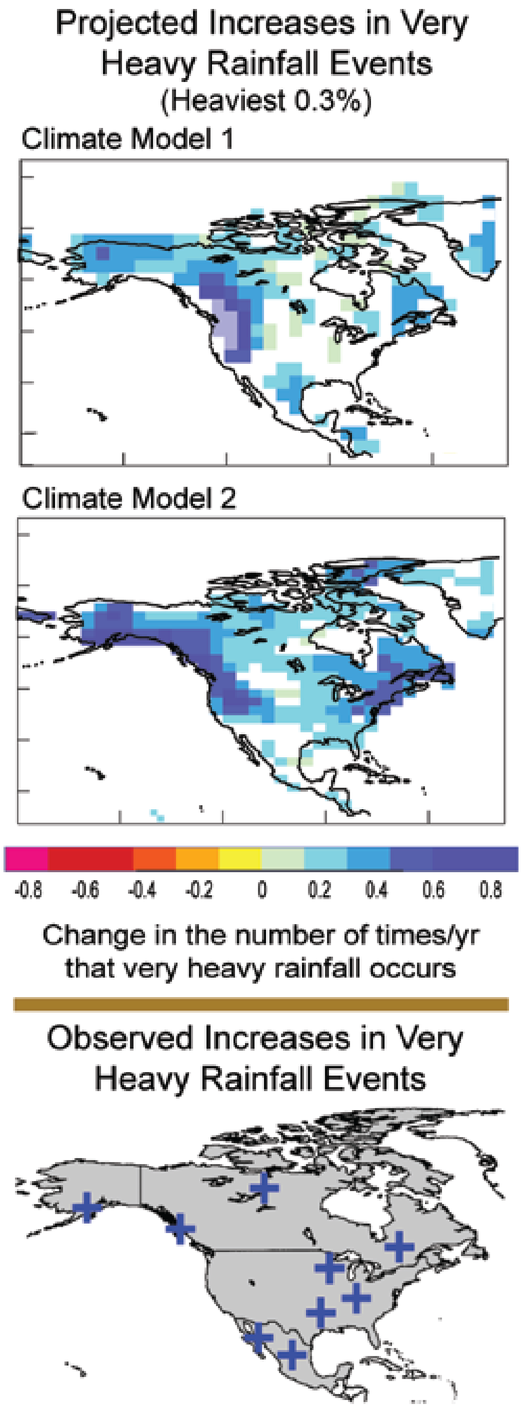


Figure 3.4 Top two panels: Projected changes at the time of carbon dioxide (CO_2) doubling in the number of occurrences per year of the heaviest daily rainfall events in two climate models. For each model, these events were defined as those that exceed the 99.7 percentile of simulated daily rainfall in a $1xCO_2$ control simulation. An increase of 0.3 events per year corresponds to a 100% increase in the frequency of such events in locations where there are 100 precipitation days per year. Model 1 is the CGCM2 and Model 2 is the HadCM3. The bottom panel shows areas of North America which have observed increases in very heavy rainfall. After Groisman *et al.* (2005), Stone *et al.* (2000, updated), and Cavazos and Rivas (2004).

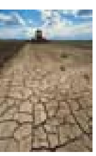
runoff in the latter decades of the 20th century in part to suppression of transpiration due to carbon dioxide (CO_2)-induced stomatal closure. However, their result is subject to considerable uncertainty in the runoff data (Peel and McMahon, 2006; Gedney *et al.*, 2006b). Qian *et al.* (2006) simulate observed runoff changes in response to observed temperature and precipitation alone, and Milly *et al.* (2005) demonstrate that 20th century runoff trends simulated by several global climate models are significantly correlated with observed runoff trends. Wu *et al.* (2005) find that observed increases in Arctic river discharge are simulated in a global climate model with anthropogenic and natural forcing, but not in the same model with natural forcings only. Anthropogenic changes in runoff may be emerging, but attribution studies specifically on North American runoff are not available.

Mid-latitude summer drying is another anticipated response to greenhouse gas forcing (Meehl *et al.*, 2006), and drying trends have been observed in both the Northern and Southern Hemispheres since the 1950s (Trenberth *et al.*, 2007). Burke *et al.* (2006), using the HadCM3 model with all natural and anthropogenic external forcings and a global Palmer Drought Severity Index (PDSI) dataset compiled from observations by Dai *et al.* (2004), detect the influence of anthropogenic forcing in the observed global trend towards increased drought in the second half of the 20th century, although the model trend was weaker than observed and the relative contributions of natural external forcings and anthropogenic forcings was not assessed. Nevertheless, this supports the conclusion that anthropogenic forcing has influenced the global occurrence of drought. However, the spatial pattern of observed PDSI change over North America is dissimilar to that in the coupled model, so no anthropogenic influence has been detected for North America alone.

Mid-latitude summer drying is another anticipated response to the human-induced increase in greenhouse gases, and global drying trends have been observed since the 1950s.

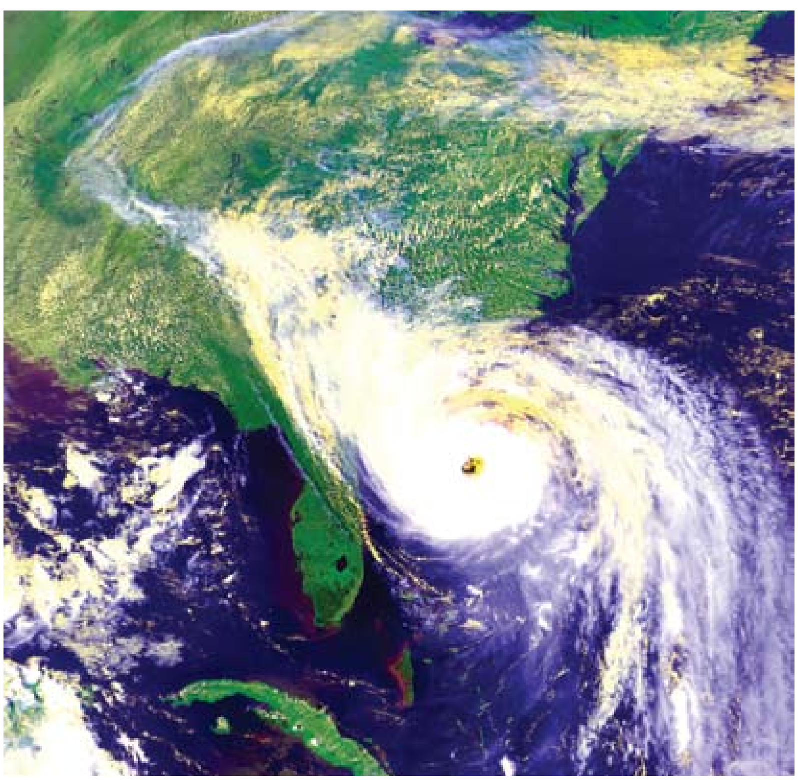
Nevertheless, the long term trends in the precipitation patterns over North America are well reproduced in atmospheric models driven with observed changes in sea surface temperatures (Schubert *et al.*, 2004; Seager *et al.*, 2005), indicating the importance of sea surface temperatures in determining North American drought (see also, for example, Hoerling and Kumar, The long-term trends in precipitation patterns over North America are well reproduced in atmospheric models driven with observed changes in sea-surface temperatures.

2003). Specifically, Schubert *et al*. (2004) and Seager *et al*. (2005), using AGCMs forced with observed SSTs, show that some SST anomaly patterns, particularly in the tropical Pacific, can produce drought over North America. Using the observed SST anomalies, both studies successfully reproduce many aspects of the 1930s drought. Only the Seager *et al*. (2005) model simulates the 1950s drought over North America, indicating that more modeling studies of this kind are needed.



3.2.4 Tropical Cyclones

Long-term (multidecadal to century) scale observational records of tropical cyclone activity (frequency, intensity, power dissipation, *etc*.) were described in Chapter 2. Here, discussion focuses on whether any changes can be attributed to particular causes, including anthropogenic forcings. Tropical cyclones respond to their environment in quite different manners for initial development, intensification, determination of overall size, and motion. Therefore, this section begins with a brief summary of the major physical mechanisms and understanding.



3.2.4.1 Criteria and Mechanisms For tropical cyclone development

Gray (1968) drew on a global analysis of tropical cyclones and a large body of earlier work to arrive at a set of criteria for tropical cyclone development, which he called Seasonal Genesis Parameters:

- Sufficient available oceanic energy for the cyclone to develop, usually defined as a requirement for ocean temperatures > 26°C down to a depth of 60 m;
- Sufficient cyclonic (counterclockwise in Northern Hemisphere, clockwise in Southern Hemisphere) rotation to enhance the capacity for convective heating to accelerate the vertical winds;
- A small change in horizontal wind with height (weak shear) so that the upper warming can become established over the lower vortex;
- A degree of atmospheric moist instability to enable convective clouds to develop;
- A moist mid-level atmosphere to inhibit the debilitating effects of cool downdrafts; and
- Some form of pre-existing disturbance, such as an easterly wave, capable of development into a tropical cyclone.

A more recent study by Camargo *et al*. (2007) has developed a new genesis index, which is based on monthly mean values of 850 hPa relative vorticity, 700 hPa humidity, 850-250 hPa wind shear, and Potential Intensity (Bister and Emanuel, 1997). Some skill has been demonstrated in applying it to reanalysis data and global climate models to estimate the frequency and location of storms.

In the North Atlantic, the bulk of tropical cyclone developments arise from easterly waves, though such development is a relatively rare event, with only around 10-20% of waves typically developing into a tropical cyclone (Dunn, 1940; Frank and Clark, 1980; Pasch *et al*., 1998; Thorncroft and Hodges, 2001). Thus, any large-scale mechanism that can help produce more vigorous easterly waves leaving Africa, or provide an environment to enhance their development, is of importance. ENSO is a major influence; during El Niño years, tropical cyclone development is suppressed by a combination of associated increased vertical wind shear, general drying of the mid-levels, and oceanic cooling (*e.g.*, Gray, 1984). The Madden-Julian Oscillation (MJO) influences cyclogenesis in the Gulf of Mexico region on 1-2 month time scales (Maloney and Hartmann, 2000). Approximately half of the North Atlantic tropical cyclone developments are associated with upper-level troughs migrating into the tropics (*e.g.*, Pasch *et al*., 1998; Davis and Bosart, 2001, 2006). The large-scale zonal wind flow may also modulate development of easterly wave troughs into tropical cyclones (Holland, 1995; Webster and Chang, 1988). The easterly wave development process is particularly enhanced in the wet, westerly phase of the MJO.

The eastern and central North Pacific experience very little subtropical interaction and appear to be dominated by easterly wave development (*e.g.*, Frank and Clark, 1980). The two major environmental influences are the ENSO and MJO, associated with the same effects as described for the North Atlantic. The MJO is a particularly large influence, being associated with a more than 2:1 variation in tropical cyclone frequency between the westerly-easterly phases (Liebmann *et al*., 1994; Molinari and Vollaro, 2000).

Suitable conditions in the western Pacific development region are present throughout the year. Developments in this region are associated with a variety of influences, including easterly waves, monsoon development, and mid-latitude troughs (*e.g.,* Ritchie and Holland, 1999). The dominant circulation is the Asiatic monsoon, and tropical cyclones typically form towards the eastern periphery of the main monsoonal trough or further eastward (Holland, 1995), though development can occur almost anywhere (*e.g.*, Lander, 1994a). ENSO has a major impact, but it is opposite to that in the eastern Pacific and Atlantic, with western Pacific tropical cyclone development being enhanced during the El Niño phase (Chan, 1985; Lander, 1994b; Wang and Chan, 2002).

Mesoscale influences include those that occur on scales similar to, or smaller than, the tropical cyclone circulation and seem to be operative in some form or other to all ocean basins. These influences include interactions amongst the vorticity fields generated by Mesoscale Convective Complexes (MCCs), which may enhance cyclogenesis under suitable atmospheric conditions, but also may introduce a stochastic element in which the interactions may also inhibit short-term development (Houze, 1977; Zipser, 1977; Ritchie and Holland, 1997; Simpson *et al*., 1997; Ritchie, 2003; Bister and Emanuel, 1997; Hendricks *et al*., 2004; Montgomery *et al*., 2006) and inherent barotropic instability (*e.g.*, Schubert *et al*., 1991; Ferreira and Schubert, 1997).

3.2.4.1.1 Factors Influencing Intensity and Duration

Once a cyclone develops, it proceeds through several stages of intensification. The maximum achievable intensity of a tropical cyclone appears to be limited by the available energy in the ocean and atmosphere. This has led to various thermodynamic assessments of the Potential Intensity (PI) that can be achieved by a cyclone for a given atmospheric/oceanic thermodynamic state (Emanuel, 1987, 1995, 2000; Holland, 1997; Tonkin *et al*., 2000; Rotunno and Emanuel, 1987). The basis for these assessments is characteristically the sea surface temperature and the thermodynamic structure of the near-cyclone atmospheric environment, with particular emphasis on the temperature at the outflow level of air ascending in the storm core.

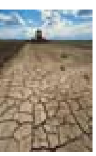
In most cases, tropical cyclones do not reach this thermodynamic limit, due to a number of processes that have a substantial negative influence on intensification. Major negative impacts may include: vertical shear of the horizontal wind (Frank and Ritchie, 1999; DeMaria, 1996); oceanic cooling by cyclone-induced mixing of cool water from below the mixed layer to the surface (Price, 1981; Bender and Ginis, 2000; Schade and Emanuel, 1999); potential impacts of sea spray on the surface exchange process (Wang *et al*., 2001; Andreas and Emanuel, 2001); processes that force the cyclone into an asymmetric structure (Wang, 2002; Corbosiero and Molinari, 2003); ingestion of dry air, perhaps also with suspended dust (Neal and Holland, 1976; Dunion and Velden,

During El Niño years, tropical cyclone development in the Atlantic is suppressed by a combination of increased vertical wind shear, general drying of the mid-levels, and oceanic cooling.

2004); and internal processes. Since many of these factors tend to be transitory in nature, the longer a cyclone can spend in a region with plentiful thermodynamic energy, the better its chances of approaching the PI. This is reflected in, for example, the observation that over 80% of major hurricanes in the North Atlantic occur in systems that formed at low latitudes in the eastern region, the so-called Cape Verde storms.

Determining the causal influences on the observed changes in tropical cyclone characteristics is currently a subject of vigorous community debate.

A weakening tropical cyclone may merge with an extratropical system, or it may redevelop into a baroclinic system (Jones *et al*., 2003). Since the system carries some of its tropical vorticity and moisture, it can produce extreme rains and major flooding. The transition is also often accompanied by a rapid acceleration in translation speed, which leads to an asymmetric wind field with sustained winds that may be of hurricane force on the right (left) side of the storm track in the Northern (Southern) Hemisphere, despite the overall weakening of the cyclone circulation.



3.2.4.1.2 Movement Mechanisms

Tropical cyclones are steered by the mean flow in which they are embedded, but they also propagate relative to this mean flow due to dynamical effects (Holland, 1984; Fiorino and Elsberry, 1989). This combination leads to the familiar hyperbolic (recurving) track of tropical cyclones as storms initially move westward, embedded in the low-latitude easterly flow, then more poleward and eventually eastward, as they encounter the mid-latitude westerlies.

An important result of this pattern of movement is that storms affecting the Caribbean, Mexico, Gulf States, Lower Eastern Seaboard, and Pacific Trust Territories have mostly developed in low latitudes (which also comprise the most intense systems). Eastern Pacific cyclones tend to move away from land, and those that recurve are normally suffering from combined negative effects of cold water and vertical shear. Upper Eastern U.S. Seaboard and Atlantic Canada cyclones are typically recurving and undergoing various stages of extratropical transition.

3.2.4.2 Attribution Preamble

Determining the causal influences on the observed changes in tropical cyclone characteristics is currently a subject of vigorous community debate. Chief among the more contentious topics are data deficiencies in early years, natural variability on decadal time scales, and trends associated with greenhouse warming. A summary of the published contributions to this debate at the end of 2006 is contained in a report and accompanying statement that was composed by attendees at the World Meteorological Organization's Sixth International Workshop on Tropical Cyclones (IWTC-VI) held in November 2006 (WMO, 2006) and later endorsed by the American Meteorological Society. The IPCC has also assessed understanding of the issues through roughly the same point in time and assigned probabilities to human influence on observed and future changes (IPCC, 2007). In both cases, these documents represent consensus views.

One area of interest is the North Pacific. Emanuel (2005) and Webster *et al*. (2005) have shown a clear increase in the more intense Northwest Pacific tropical cyclones (as seen in category 4 and 5 frequency or PDI) since the commencement of the satellite era. These increases have been closely related to concomitant changes in SSTs in this region. However, there are concerns about the quality of the data (WMO, 2006) and there has been little focused research on attributing the changes in this region. For these reasons, this report accepts the overall findings of WMO (2006) and IPCC (2007) as they relate to the North Pacific. These include a possible increase in intense tropical cyclone activity, consistent with Emanuel (2005) and Webster *et al.* (2005), but no clear trend in tropical cyclone numbers. The remainder of the attribution section on tropical cyclones concentrates on the North Atlantic, where the available data and published work enables more detailed attribution analysis compared to other basins.

3.2.4.3 Attribution of North Atlantic Changes

Chapter 2 provides an overall summary of the observed variations and trends in storm frequency, section 3.3.9.6 considers future scenarios, and Holland and Webster (2007) present a detailed analysis of the changes in North Atlantic tropical storms, hurricanes, and major hurricanes over the past century, together with a critique of the potential attribution mechanisms. Here we examine these changes in terms of the potential causative mechanisms.

3.2.4.3.1 Storm Intensity

There has been no distinct trend in the mean intensity of all storms, hurricanes, or major hurricanes (Chapter 2). Holland and Webster (2007) also found that there has been a marked oscillation in major hurricane proportions, which has no observable trend. The attribution of this oscillation has not been adequately defined, but it is known that it is associated with a similar oscillation in the proportion of hurricanes that develop in low latitudes and thus experience environmental conditions that are more conducive to development into an intense system than those at more poleward locations. The lack of a mean intensity trend or a trend in major hurricane proportions is in agreement with modeling and theoretical studies that predict a relatively small increase of up to 5% for the observed 0.5 to 0.7°C trend in tropical North Atlantic SSTs (See Section 3.3.9.2 for more details on this range; see also Henderson-Sellers *et al*., 1998; Knutson *et al*., 1998, 2001; Knutson and Tuleya, 2004, 2008).

Multidecadal increases of maximum intensity due to multidecadal increases of SST may play a relatively small role in increases of overall hurricane activity and increases in frequency (discussed in the next section), for which variations in duration due to large-scale circulation changes may be the dominant factors. The relationship between SST, circulation patterns, and hurricane activity variability is not as well understood as the thermodynamic relationships that constrain maximum intensity.

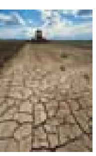
3.2.4.3.2 Storm Frequency and Integrated Activity Measures

Emanuel (2005, 2007) examined a PDI, which combines the frequency, lifetime, and intensity, and is related to the cube of the maximum winds summed over the lifetime of the storm. In Chapter 2, it was concluded that there has been a substantial increase in tropical cyclone activity, as measured by the PDI, since about 1970, strongly correlated with low-frequency variations in tropical Atlantic SSTs. It is likely that hurricane activity (PDI) has increased substantially since the 1950s and '60s in association with warmer Atlantic SSTs. It is also likely that PDI has generally tracked SST variations on multidecadal time scales in the tropical Atlantic since 1950. Holland and Webster (2007) have shown that the PDI changes have arisen from a combination of increasing frequency of tropical cyclones of all categories: tropical storms, hurricanes, and major hurricanes and a multidecadal oscillation in the proportion of major hurricanes. They found no evidence of a trend in the major hurricane proportions or in overall intensity, but a marked trend in frequency.

Recent increases in sea surface temperatures have been associated with a shift towards increased tropical cyclone developments in the low latitudes and eastern Atlantic.

While there is a close statistical relationship between low frequency variations of tropical cyclone activity (*e.g.*, the PDI and storm frequency) and SSTs (Chapter 2), this almost certainly arises from a combination of factors, including joint relationships to other atmospheric processes that effect cyclone development, such as vertical windshear (Shapiro, 1982; Kossin and Vimont, 2007; Goldenberg *et al*., 2001; Shapiro and Goldenberg, 1998). It is also notable that the recent SST increases have been associated with a concomitant shift towards increased developments in low latitudes and the eastern Atlantic, regions where the conditions are normally more conducive to cyclogenesis and intensification (Holland and Webster, 2007, Chapter 2). Thus, over the past 50 years there is a strong statistical connection between tropical Atlantic sea surface temperatures and Atlantic hurricane activity as measured by the PDI. The North Atlantic is the region where the relationship between hurricane power and tropical sea surface temperature is most significant, but some correlation is evident in the western

It is very likely that human-caused increases in greenhouse gases have contributed to the increase in sea surface temperatures in the North Atlantic and the Northwest Pacific hurricane formation regions over the 20th century.



North Pacific as well (Emanuel, 2007), while no such relationship is observed in the Eastern North Pacific. In general, tropical cyclone power dissipation appears to be modulated by potential intensity, vertical wind shear, and low-level vorticity of the large-scale flow, while sea surface temperature itself should be regarded as a co-factor rather than a causative agent (Emanuel, 2007). The observed complex relationship between power dissipation and environmental determinants is one reason why a confident attribution of human influence on hurricanes is not yet possible.

Low-frequency variations in Atlantic tropical cyclone activity have previously been attributed to a natural variability in Atlantic SSTs associated with the Atlantic Multidecadal Oscillation (Bell and Chelliah, 2006; Goldenberg *et al*., 2001). However, these studies either did not consider the trends over the 20th century in SST (Goldenberg *et al*., 2001) or did not cover a long enough period to confidently distinguish between oscillatory (internal climate variability) behavior and radiatively forced variations or trends. For example, the multidecadal AMM2 mode in Bell and Chelliah (2006) first obtains substantial amplitude around 1970. Their circulation-based indices are of insufficient length to determine whether they have a cyclical or trend-like character, or some combination thereof.

While there is undoubtedly a natural variability component to the observed tropical Atlantic SSTs, a number of studies suggest that increasing greenhouse gases have contributed to the warming that has occurred, especially over the past 30-40 years. For example, Santer *et al.* (2006) have shown that the observed trends in Atlantic tropical SSTs are unlikely to be caused entirely by internal climate variability, and that the pronounced Atlantic warming since around 1970 that is reproduced in their model is predominantly due to increased greenhouse gases. These conclusions are supported by several other studies that use different methodologies (*e.g.*, Knutson *et al*., 2006; Trenberth and Shea, 2006; Mann and Emanuel, 2006; Karoly and Wu, 2005). There is also evidence for a detectable greenhouse gas-induced SST increase in the Northwest Pacific tropical cyclogenesis region (Santer *et al*., 2006; see also Knutson *et al*., 2006 and Karoly and Wu, 2005).

We conclude that there has been an observed SST increase of 0.5-0.7°C over the past century in the main development region for tropical cyclones in the Atlantic. Based on comparison of observed SST trends and corresponding trends in climate models with and without external forcing, it is very likely that human-caused increases in greenhouse gases have contributed to the increase in SSTs in the North Atlantic and the Northwest Pacific hurricane formation regions over the 20th century.

Chapter 2 also notes that there have been fluctuations in the number of tropical storms and hurricanes from decade to decade and that 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, Chapter 2 concludes that 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 less compelling for significant trends beginning in the late 1800s. The existing data for hurricane counts and one adjusted record of tropical storm counts both indicate no significant linear trends beginning from the mid- to late 1800s through 2005. In general, there is increasing uncertainty in the data as one proceeds back in time. There is no evidence for a long-term increase in North American mainland land-falling hurricanes.

Attribution of these past changes in tropical storm/hurricane activity (*e.g.*, PDI) and frequency to various climate forcings is hampered by the lack of adequate model simulations of tropical cyclone climatologies. In the case of global scale temperature, increased formal detection-attribution studies have detected strong evidence for the presence of the space-time pattern of warming expected due to greenhouse gas increases. These studies find that other plausible explanations, such as solar and volcanic forcing together with climate variability alone, fail to explain the observed changes sufficiently. The relatively good agreement between observed and simulated trends based on climate model experiments with estimated past forcings lends substantial confidence to attribution statements for SST. However, since adequate model-based reconstructions of historical tropical cyclone variations are not currently available, we do not have estimates of expected changes in tropical cyclone variations due to a complete representation of the changes in the physical system that would have been caused by greenhouse gas increases and other forcing changes. (Relevant anthropogenic forcing includes changes in greenhouse gas concentrations, as well as aerosols [*e.g.*, Santer *et al*., 2006]. In addition, stratospheric ozone decreases and other factors associated with recent cooling upper atmospheric [at approximately 100 mb] temperature changes may be important [Emanuel, 2007]). Given this state of the sciences, we therefore must rely on statistical analyses, existing modeling, and theoretical information and expert judgement to make the following attribution assessment:

> 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.

3.2.4.3.3 Storm Duration, Track, and Extratropical Transition

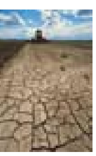
There has been insufficient research on these important aspects of tropical cyclones to arrive at any firm conclusions about possible changes.

3.2.5 Extratropical Storms

Chapter 2 documents changes in strong extratropical storms during the 20th century, especially for the oceanic storm track bordering North America. Changes include altered intensity and tracks of intense storms (Wang *et al*., 2006; Caires and Sterl, 2005). Analysis of physical mechanisms is lacking. Natural cycles of large-scale circulation affect variability, through the NAO (*e.g.*, Lozano and Swail, 2002; Caires and Sterl, 2005) or the related NAM (Hurrell, 1995; Ostermeier and Wallace, 2003). Changes in sea-surface temperature (Graham and Diaz, 2001) and baroclinicity (Fyfe, 2003) may also play a role. Analysis of a multi-century GCM simulation by Fischer-Bruns *et al*. (2005) suggests that changes in solar activity and volcanic activity have negligible influence on strong-storm activity. However, it is likely that anthropogenic influence has contributed to extratropical circulation change during the latter half of the 20th century (Hegerl *et al*., 2007; see also Gillett *et al*., 2003, 2005), which would have influenced storm activity. On the other hand, the WASA Group (1998), using long records of station data, suggest that observed changes in storminess in Northern Europe

The Power Dissipation Index, which combines storm frequency, lifetime, and intensity, has increased substantially since about 1970, strongly correlated with changes in Atlantic tropical sea surface temperatures.

over the latter part of the 20th century are not inconsistent with natural internal low-frequency variability. However, analyses based on direct observations suffer from incomplete spatial and temporal coverage, especially in storm-track regions over adjacent oceans, and generally cover regions that may be too small to allow detection of externally forced signals (Hegerl *et al*., 2007). Studies of global reanalysis products generally cover less than 50 years. While 50-year records are generally considered adequate for detection and attribution research (Hegerl *et al*., 2007), a difficulty with reanalysis products is that they are affected by inhomogeneities resulting from changes over time in the type and quantity of data that is available for assimilation (*e.g.*, Trenberth *et al*., 2005).



As a consequence of rising temperatures, the amount of moisture in the atmosphere is likely to rise much faster than total precipitation. This should lead to an increase in the intensity of thunderstorms.

A number of investigations have considered the climate controls on the storm intensities or on the decadal trends of wave heights generated by those storms. Most of this attention has been on the North Atlantic, and as noted above, the important role of the NAO has been recognized (*e.g.*, Neu, 1984; WASA Group, 1998; Gulev and Grigorieva, 2004). Fewer investigations have examined the climate controls on the storms and waves in the North Pacific, and with less positive conclusions (Graham and Diaz, 2001; Gulev and Grigorieva, 2004). In particular, definite conclusions have not been reached concerning the climate factor producing the progressive increase seen in wave heights, apparently extending at least back to the 1960s.

A clear influence on the wave conditions experienced along the west coast of North America is occurrences of major El Niños such as those in 1982-83 and 1997-98. Both of these events in particular brought extreme wave conditions to south central California, attributed primarily to the more southerly tracks of the storms compared with non-El Niño years. Allan and Komar (2006) found a correlation between the winter-averaged wave heights measured along the west coast and the multivariate ENSO index, showing that while the greatest increase in wave heights during El Niños takes place at the latitudes of south central California, some increase occurs along the entire west coast, evidence that the storms are stronger as well as having followed more southerly tracks. The wave climates of the west coast therefore have been determined by the decadal increase found by Allan and Komar (2000, 2006), but further enhanced during occurrences of major El Niños.

3.2.6 Convective Storms

Trenberth *et al*. (2005) point out that as a consequence of rising temperatures, the amount of moisture in the atmosphere is likely to rise much faster than total precipitation. This should lead to an increase in the intensity of storms, accompanied by decreases in duration or frequency of events. Environmental conditions that are most often associated with severe and tornado-producing thunderstorms have been derived from reanalysis data (Brooks *et al*., 2003). Brooks and Dotzek (2008) applied those relationships to count the frequency of favorable environments for significant severe thunderstorms (hail of at least 5 cm diameter, wind gusts of at least 33 meters per second, and/or a tornado of F2 or greater intensity) for the area east of the Rocky Mountains in the U.S. for the period 1958-1999. The count of favorable environments decreased by slightly more than 1% per year from 1958 until the early-to-mid 1970s, and increased by approximately 0.8% per year from then until 1999, so that the frequency was approximately the same at both ends of the analyzed period. They went on to show that the time series of the count of reports of very large hail (7 cm diameter and larger) shows an inflection at about the same time as the inflection in the counts of favorable environments. A comparison of the rate of increase of the two series suggested that the change in environments could account for approximately 7% of the change in reports from the mid-1970s through 1999, with the rest coming from non-meteorological sources.

3.3 PROJECTED FUTURE CHANGES IN EXTREMES, THEIR CAUSES, MECHANISMS, AND UNCERTAINTIES

Projections of future changes of extremes are relying on an increasingly sophisticated set of models and statistical techniques. Studies assessed in this section rely on multi-member ensembles (3 to 5 members) from single models, analyses of multi-model ensembles ranging from 8 to 15 or more AOGCMs, and a perturbed physics ensemble with a single mixed layer model with over 50 members. The discussion here is intended to identify the characteristics of changes of extremes in North America and set them in the broader global context.

3.3.1 Temperature

The IPCC Third Assessment Report concluded that it is very likely that there is an increased risk of high temperature extremes (and reduced risk of low temperature extremes), with more extreme heat episodes in a future climate. This latter result has been confirmed in subsequent studies (e.g., Yonetani and Gordon, 2001), which are assessed in the 2007 IPCC report (Meehl et al, 2007a; Christensen et al. 2007). An ensemble of more recent global simulations projects marked an increase in the frequency of very warm daily minimum temperatures (Figure 3.1a). Kharin *et al.* (2007) show in a large ensemble of models that over North America, future increases in summertime extreme maximum temperatures follow increases in mean temperature more closely than future increases in wintertime extreme minimum temperatures. This increase in winter extreme temperatures is substantially larger than increases in mean temperature, indicating the probability of very cold extremes decreases and hot extremes increases. They also show a large reduction in the wintertime cold temperature extremes in regions where snow and sea ice decrease due to changes in the effective heat capacity and albedo of the surface. Kharin and Zwiers (2005) show in a single model that summertime warm temperature extremes increase more quickly than means in regions where the soil dries due to a smaller fraction of surface energy used for evaporation. Clark *et al.* (2006), using another model, show that an ensemble of doubled-CO_2 simulations produces increases in summer warm extremes for North America that are roughly the same as increases in median daily maximum temperatures. Hegerl *et al.* (2004) show that for both models, differences in warming rates between seasonal mean and extreme temperatures are statistically significant over most of North America in both seasons; detecting changes in seasonal mean temperature is not a substitute for detecting changes in extreme temperatures.

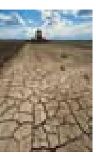
Events that are rare could become more commonplace. Recent studies using both individual models (Kharin and Zwiers, 2005) and an ensemble of models (Wehner 2005, Kharin, *et al.*, 2007) show that events that currently reoccurr on average once every 20 years (*i.e.*, have a 5% chance of occurring in a given year) will become signficantly more frequent over North America. For example, by the middle of the 21st century, in simulations of the SRES A1B scenario, the recurrence period (or expected average waiting time) for the current 20-year extreme in daily average surface-air temperature reduces to three years over most of the continental United States and five years over most of Canada (Kharin, *et al.*, 2007). By the end of the century (Figure 3.5a), the average reoccurrence time may further reduce to every other year or less (Wehner, 2005).

In a future warmer world, the probability of very cold extremes decreases, and that of hot extremes increases.

Similar behavior occurs for seasonal average temperatures. For example, Weisheimer and Palmer (2005) examined changes in extreme seasonal (DJF and JJA) temperatures in 14 models for 3 scenarios. They showed that by the end of 21st century, the probability of such extreme warm seasons is projected to rise in many areas including North America. Over the North American region, an extreme seasonal temperature event that occurs 1 out of 20 years in the present climate becomes a 1 in 3-year event in the A2 scenario by the end of this century. This result is consistent with that from the perturbed physics ensemble of Clark *et al.* (2006) where, for nearly all land areas, extreme JJA temperatures were at least 20 times, and in some areas 100 times, more frequent compared to the control ensemble mean, making these changes greater than the ensemble spread.

Others have examined possible future cold-air outbreaks. Vavrus *et al.* (2006) analyzed

In a future climate there is an increased likelihood of more intense, longer-lasting, and more frequent heat waves.



seven AOGCMs run with the A1B scenario, and defined a cold air outbreak as two or more consecutive days when the daily temperatures were at least two standard deviations below the present-day winter-time mean. For a future warmer climate, they documented a decline in frequency of 50 to 100% in Northern Hemisphere winter in most areas compared to present-day, with some of the smallest reductions occurring in western North America due to atmospheric circulation changes (blocking and ridging on the West Coast) associated with the increase of GHGs.

Several recent studies have addressed explicitly possible future changes in heat waves (very high temperatures over a sustained period of days), and found that in a future climate there is an increased likelihood of more intense, longer-lasting and more frequent heat waves (Meehl and Tebaldi, 2004; Schär *et al.*, 2004; Clark *et al.*, 2006). Meehl and Tebaldi (2004) related summertime heat waves to circulation patterns in the models and observations. They found that the more intense and frequent summertime heat waves over the southeast and western U.S. were related in part to base state circulation changes due to the increase in GHGs. An additional factor for extreme heat is drier soils in a future warmer climate (Brabson *et al.*, 2005; Clark *et al.*, 2006).

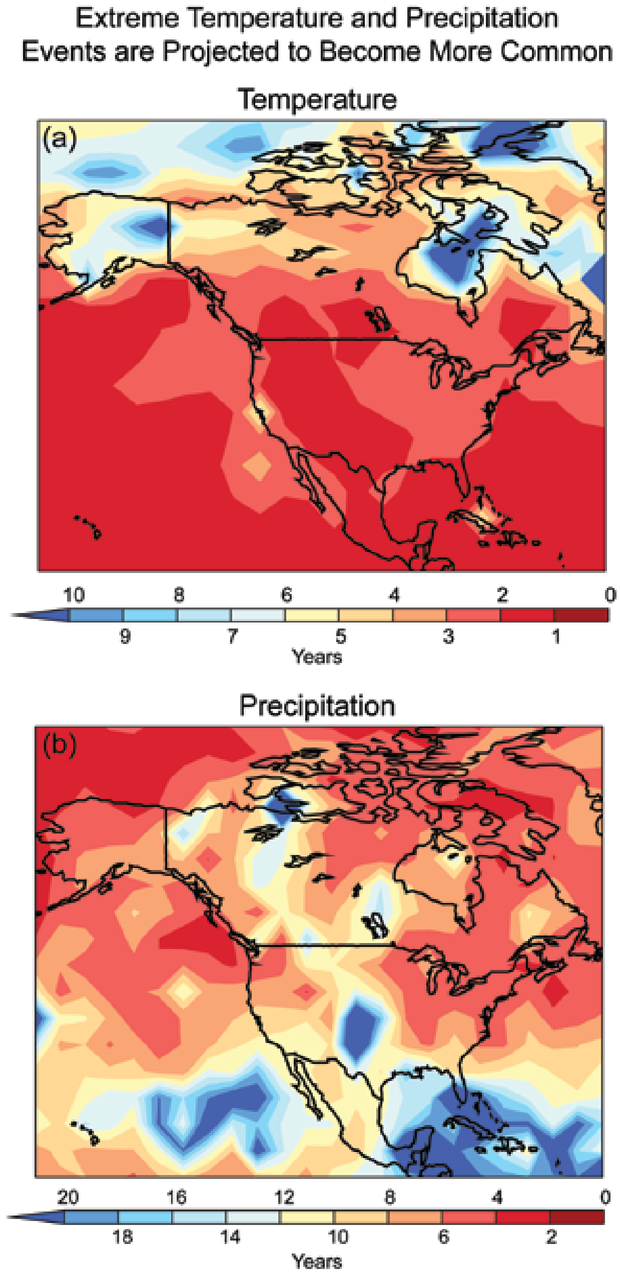


Figure 3.5 Simulations for 2090-2099 indicating how currently rare extremes (a 1-in-20-year event) are projected to become more commonplace. a) A day so hot that it is currently experienced once every 20 years would occur every other year or more by the end of the century. b) Daily total precipitation events that occur on average every 20 years in the present climate would, for example, occur once every 4-6 years for Northeast North America. These results are based on a multi-model ensemble of global climate models.

The "Heat Index", a measure of the apparent temperature felt by humans that includes moisture influences, was projected in a model study from the Geophysical Fluid Dynamics Laboratory to increase substantially more than the air temperature in a warming climate in many regions (Delworth *et al.*, 1999). The regions most prone to this effect included humid regions of the tropics and summer hemisphere extratropics, including the Southeast U.S. and Caribbean. A multi-model ensemble showed that simulated heat waves increase during the latter part of the 20th century, and are projected to increase globally and over most regions including North America (Tebaldi *et al.,* 2006), though different model parameters can influence the range in the magnitude of this response (Clark *et al.,* 2006).

Warm episodes in ocean temperatures can stress marine ecosystems, causing impacts such as coral bleaching (*e.g.*, Liu *et al*., 2006; Chapter 1, Box 1.4, this report). Key factors appear to be clear skies, low winds, and neap tides occurring near annual maximum temperatures since they promote heating with little vertical mixing of warm waters with cooler, deeper layers (Strong *et al*., 2006). At present, widespread bleaching episodes do not appear to be related to variability such as ENSO cycles (Arzayus and Skirving, 2004) or PDO (Strong *et al*., 2006), though the strong 1997-98 El Niño did produce sufficient warming to cause substantial coral bleaching (Hoegh-Guldberg, 1999, 2005; Wilkinson, 2000). The 2005 Caribbean coral bleaching event has been linked to warm ocean temperatures that appear to have been partially due to long-term warming associated with anthropogenic forcing and not a manifestation of unforced climate variability alone (Donner *et al*., 2007). Warming trends in the ocean increase the potential for temperatures to exceed thresholds for mass coral bleaching, and thus may greatly increase the frequency of bleaching events in the future, depending on the ability of corals and their symbiotic algae to adapt to increasing water temperatures (see Donner *et al*., 2007 and references therein).

A decrease in diurnal temperature range in most regions in a future warmer climate was reported in Cubasch *et al*. (2001) and is substantiated by more recent studies (*e.g.*, Stone and Weaver, 2002), which are assessed in the 2007 IPCC report (Meehl *et al*., 2007a; Christensen *et al*., 2007). However, noteworthy departures from this tendency have been found in the western portion of the United States, particularly the Southwest, where increased diurnal temperature ranges occur in several regional (*e.g.*, Bell *et al*., 2004; Leung *et al*., 2004) and global (Christensen *et al*., 2007) climate-change simulations. Increased diurnal temperature range often occurs in areas that experience drying in the summer.

3.3.2 Frost

As the mean climate warms, the number of frost days is expected to decrease (Cubasch *et al*., 2001). Meehl *et al*. (2004) have shown that there would indeed be decreases in frost days in a future warmer climate in the extratropics, particularly along the northwest coast of North America, with the pattern of the decreases dictated by the changes in atmospheric circulation from the increase in GHGs. Results from a multi-model ensemble show simulated and observed decreases in frost days for the 20th century continuing into the 21st century over North America and most other regions (Meehl *et al*., 2007a, Figure 3.1b). By the end of the 21st century, the number of frost days averaged over North America is projected to decrease by about one month in the three future scenarios considered here.

In both the models and the observations, the number of frost days decreased over the 20th century (Figure 3.1b). This decrease is generally related to warming climate, although the pattern of the warming and pattern of the frost-days changes (Figure 3.2) are not well correlated. The decrease in the number of frost days per year is biggest in the Rockies and along the west coast of North America. The projected pattern of change in 21st century frost days is similar to the 20th century pattern, but much larger in magnitude. In some places, by 2100, the number of frost days is projected to decrease by more than two months.

These changes would have a large impact on biological activity (See Chapter 1 for more discussion). An example of a positive impact is that there would be an increase in growing season length, directly related to the decrease in frost days per year. A negative example is that fruit trees would suffer because they need a certain number of frost periods per winter season to set their buds, and in some places, this threshold would no longer be met. Note also that changes in wetness and CO_2 content of the air would also affect biological responses.

3.3.3 Growing Season Length

A quantity related to frost days in many mid- and high latitude areas, particularly in the Northern Hemisphere, is growing season length as defined by Frich *et al*. (2002), and this has been projected to increase in a future climate in most areas (Tebaldi *et al.,* 2006). This result is also shown in a multi-model ensemble where the simulated increase in growing season length in the 20th century continues into the 21st century over North America and most other

By 2100, the number of frost days averaged across North America is projected to decrease by one month, with decreases of more than two months in some places. These changes would have a large impact on biological activity.

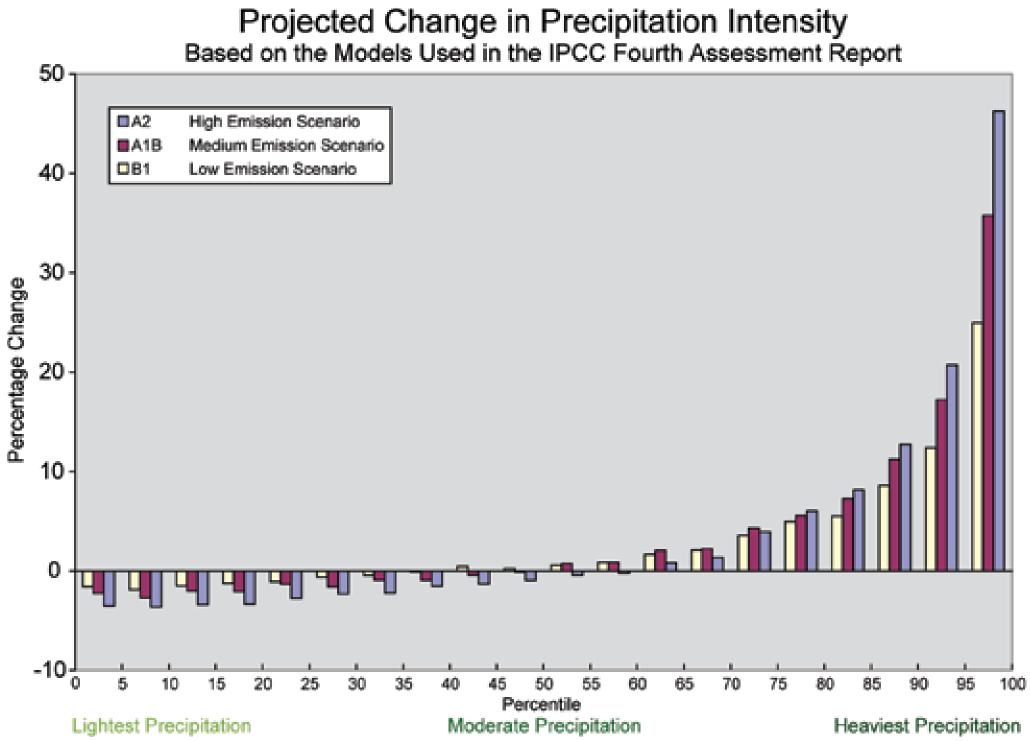
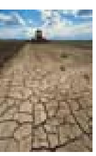


Figure 3.6 Projected changes in the intensity of precipitation, displayed in 5% increments, based on a suite of models and three emission scenarios. As shown here, the lightest precipitation is projected to decrease, while the heaviest will increase, continuing the observed trend. The higher emission scenarios yield larger changes. Figure courtesy of Michael Wehner.



regions (Meehl *et al*., 2007a, Figure 3.1c). The growing season length has increased by about one week over the 20th century when averaged over all of North America in the models and observations. By the end of the 21st century, the growing season is on average more than two weeks longer than present day. (For more discussion on the reasons these changes are important, see Chapter 1 this report.)

3.3.4 Snow Cover and Sea Ice

Warming generally leads to reduced snow and ice cover (Meehl *et al*., 2007a). Reduction in perennial sea ice may be large enough to yield a summertime, ice-free Arctic Ocean in this century (Arzel *et al*., 2006; Zhang and Walsh, 2006). Summer Arctic Ocean ice also may undergo substantial, decadal-scale abrupt changes rather than smooth retreat (Holland *et al*., 2006). The warming may also produce substantial reduction in the duration of seasonal ice in lakes across Canada and the U.S. (Hodgkins *et al*., 2002; Gao and Stefan, 2004; Williams *et al*., 2004; Morris *et al*., 2005) and in rivers (Hodgkins *et al*., 2003; Huntington *et al*., 2003). Reduced sea ice in particular may produce more strong storms over the ocean (Section 3.3.10). Reduced lake ice may alter the occurrence of heavy lake-effect snowfall (Section 3.3.8).

The annual cycle of snow cover and river runoff may be substantially altered in western U.S. basins (Miller *et al*., 2003; Leung *et al*., 2004). The water available from spring snowmelt runoff will likely decrease, affecting water-resource management and exacerbating the impacts of droughts.

The water available from spring snowmelt runoff will likely decrease, affecting water-resource management and exacerbating the impacts of droughts.

3.3.5 Precipitation

Climate-model projections continue to confirm the conclusion that in a future climate warmed by increasing GHGs, precipitation intensity (*i.e.*, precipitation amount per event) is projected to increase over most regions (Wilby and Wigley, 2002; Kharin and Zwiers, 2005; Meehl *et al.*, 2005; Barnett *et al.*, 2006) and the increase of precipitation extremes is greater than changes in mean precipitation (Figure 3.6; Kharin and Zwiers, 2005). Currently, rare precipitation events could become more commonplace in North America (Wehner, 2005; Kharin *et al*., 2007). For example, by the middle of the 21st century, in simulations of the SRES A1B scenario, the recurrence period for the current 20-year extreme in daily total precipitation reduces to between 12 and 15 years over much of North America (Kharin, *et al*., 2007). By the end of the century (Figure 3.5b), the expected average reoccurrence time may further reduce to every six to eight years (Wehner, 2005; Kharin, *et al.,* 2007). Note the area of little change in expected average reoccurrence time in the central United States in Figure 3.5b.

As discussed in section 3.2.3 of this chapter and in Hegerl *et al*. (2007), the substantial increase in precipitation extremes is related to the fact that the energy budget of the atmosphere constrains increases of large-scale mean precipitation, but extreme precipitation responds to increases in moisture content and thus the nonlinearities involved with the Clausius-Clapeyron relationship and the zero lower bound on precipitation rate. This behavior means that for a given increase in temperature, increases in extreme precipitation are relatively larger than the mean precipitation increase (*e.g*., Allen and Ingram, 2002), so long as the character of the regional circulation does not change substantially (Pall *et al*., 2007). Additionally, timescale can play a role whereby increases in the frequency of seasonal mean rainfall extremes can be greater than the increases in the frequency of daily extremes (Barnett *et al.,* 2006).

The increase in mean and extreme precipitation in various regions has been attributed to contributions from both dynamic (circulation) and thermodynamic (moisture content of the air) processes associated with global warming (Emori and Brown, 2005), although the precipitation mean and variability changes are largely due to the thermodynamic changes over most of North America. Changes in circulation also contribute to the pattern of precipitation intensity changes over Northwest and Northeast North America (Meehl *et al.,* 2005). Kharin and Zwiers (2005) showed that changes to both the location and scale of the extreme value distribution produced increases of precipitation extremes substantially greater than increases of annual mean precipitation. An increase in the scale parameter from the gamma distribution represents an increase in precipitation intensity, and various regions such as the Northern Hemisphere land areas in winter showed particularly high values of increased scale parameter (Semenov and Bengtsson, 2002; Watterson and Dix, 2003). Time slice simulations with a higher resolution model (at approximately 1°) show similar results using changes in the gamma distribution, namely increased extremes of the hydrological cycle (Voss *et al.,* 2002).

3.3.6 Flooding and Dry Days

Changes in precipitation extremes have a large impact on both flooding and the number of precipitation-free days. The discussion of both is combined because their changes are related, despite the fact that this seems counterintuitive.

A number of studies have noted that increased rainfall intensity may imply increased flooding. McCabe *et al*. (2001) and Watterson (2005) showed there was an increase in extreme rainfall intensity in extratropical surface lows, particularly over Northern Hemisphere land. However, analyses of climate changes due to increased GHGs gives mixed results, with increased or decreased risk of flooding depending on the model analyzed (Arora and Boer, 2001; Milly *et al*., 2002; Voss *et al*., 2002).

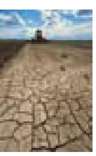
Intense and heavy rainfall events with high runoff amounts are projected to be interspersed with longer relatively dry periods, increasing the risk of both very dry conditions and flooding.

Global and North American averaged time series of the Frich *et al*. (2002) indices in the multi-model analysis of Tebaldi *et al*. (2006) show simulated increases in heavy precipitation during the 20th century continuing through the 21st century (Meehl *et al*., 2007a; Figure 3.1d), along with a somewhat weaker and less consistent trend for increasing dry periods between rainfall events for all scenarios (Meehl *et al*., 2007a). Part of the reason for these results is that precipitation intensity increases almost everywhere, but particularly at mid and high latitudes, where mean precipitation increases (Meehl *et al.,* 2005).

There are regions of increased runs of dry days between precipitation events in the subtropics and lower midlatitudes, but a decreased number of consecutive dry days at higher midlatitudes and high latitudes where mean precipitation increases. Since there are areas of both increases and decreases of consecutive dry days between precipitation events in the multi-model average, the global mean trends are smaller and less consistent across models. Consistency of response in a perturbed physics ensemble with one model shows only limited areas of increased frequency of wet days in July, and a larger range of changes of precipitation extremes relative to the control ensemble mean in contrast to the more consistent response of temperature extremes (discussed above), indicating a less consistent response for preciptitation extremes in general compared to temperature extremes (Barnett *et al.,* 2006).

Projections indicating reduced cool season precipitation across the Southwest U.S. and northwest Mexico are consistent with an observed recent shift to shorter and weaker winter rainy seasons.

Associated with the risk of drying is a projected increase in the chance of intense precipitation and flooding. Though somewhat counter-intuitive, this is because precipitation is projected to be concentrated into more intense events, with longer periods of little precipitation in between. Therefore, intense and heavy episodic rainfall events with high runoff amounts are interspersed with longer relatively dry periods with increased evapotranspiration, particularly in the subtropics (Frei *et al.,* 1998; Allen and Ingram, 2002; Palmer and Räisänen, 2002; Christensen and Christensen, 2003; Beniston, 2004; Christensen and Christensen, 2004; Pal *et al.,* 2004; Meehl *et al.,* 2005). However, increases in the frequency of dry days do not necessarily mean a decrease in the frequency of extreme high rainfall events depending on the threshold used to define such events (Barnett *et al.,* 2006). Another aspect of these changes has been related to the mean changes of precipitation, with wet extremes becoming more severe in many areas where mean precipitation increases, and dry extremes becoming more severe where the mean precipitation decreases (Kharin and Zwiers, 2005; Meehl *et al.,* 2005; Räisänen, 2005; Barnett *et al.,* 2006). However, analysis of a 53-member perturbed-physics ensemble indicates that the change in the frequency of extreme precipitation at an individual location can be difficult to estimate definitively due to model parameterization uncertainty (Barnett *et al.,* 2006).



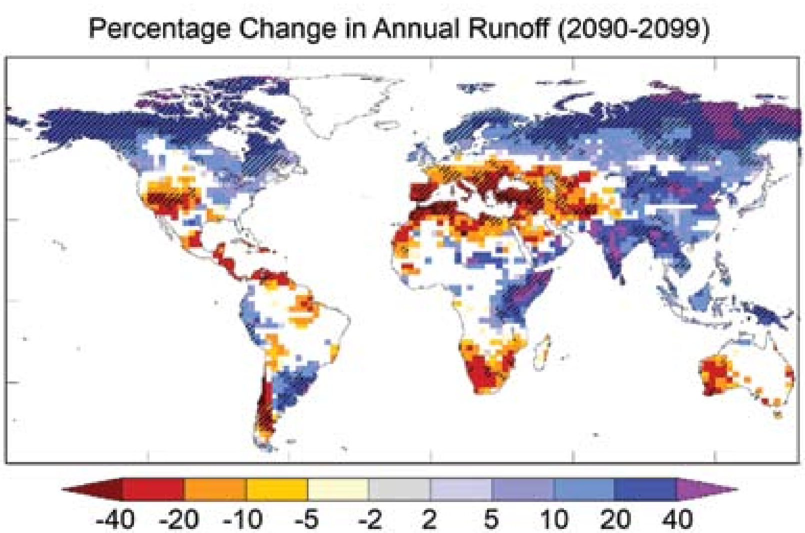


Figure 3.7 Change in annual runoff (%) for the period 2090-2099, relative to 1980-1999. Values are obtained from the median in a multi-model dataset that used the A1B emission scenario. White areas indicate where less than 66% of the models agree in the sign of change, and stippled areas indicate where more than 90% of the models agree in the sign of change. Derived from the analysis of Milly *et al.* (2005).

3.3.7 Drought

A long-standing result (*e.g.*, Manabe *et al*., 1981) from global coupled models noted in Cubasch *et al.* (2001) has been a projected increase of summer drying in the midlatitudes in a future warmer climate, with an associated increased likelihood of drought. The more recent generation of models continues to show this behavior (Burke *et al.,* 2006; Meehl *et al.,* 2006, 2007a; Rowell and Jones, 2006). For example, Wang (2005) analyzed 15 recent AOGCMs to show that in a future warmer climate, the models simulate summer dryness in most parts of the northern subtropics and midlatitudes, but there is a large range in the amplitude of summer dryness across models. Hayhoe *et al.* (2007) found, in an ensemble of AOGCMs, an increased frequency of droughts lasting a month or longer in the northeastern U.S. Droughts associated with summer drying could result in regional vegetation die-offs (Breshears *et al.,* 2005) and contribute to an increase in the percentage of land area experiencing drought at any one time. For example, extreme drought increases from 1% of present day land area (by definition) to 30% by the end of the century in the Hadley Centre AOGCM's A2 scenario (Burke *et al.,* 2006). Drier soil conditions can also contribute to more severe heat waves as discussed above (Brabson *et al.,* 2005).

A recent analysis of Milly *et al.* (2005) shows that several AOGCMs project greatly reduced annual water availability over the Southwest United States, the Caribbean, and in parts of Mexico in the future (Figure 3.7). In the historical context, this area is subject to very severe and long lasting droughts (Cook *et al*., 2004). The tree-ring record indicates that the late 20th century was a time of greater-than-average water availability. However, the consensus of most climate-model projections is for a reduction of cool season precipitation across the U.S. Southwest and northwest Mexico (Christensen *et al*., 2007). This is consistent with a recent 10-year shift to shorter and weaker winter rainy seasons and an observed northward shift in northwest Pacific winter storm tracks (Yin, 2005). Reduced cool season precipitation promotes drier summer conditions by reducing the amount of soil water available for evapotranspiration in summer.

The model projections of reduced water availability over the Southwest United States and Mexico needs further study. The uncertainty associated with these projections is related to the ability of models to simulate the precipitation distribution and variability in the present climate and to correctly project the response to future changes. For example, the uncertainty associated with the ENSO response to climate change (Zelle *et al*., 2005; Meehl *et al*., 2007a) also impacts the projections of future water availability in the Southwest United States and northern Mexico (*e.g.*, Meehl *et al*., 2007c). Changes in water availability accompanied by changes in seasonal wind patterns, such as Santa Ana winds, could also affect the occurrence of wildfires in the western United States (*e.g.*, Miller and Schlegel, 2006). See Chapter 1 for more discussion on the importance of drought.

3.3.8 Snowfall

Extreme snowfall events could change as a result of both precipitation and temperature change. Although reductions in North American snow depth and areal coverage have been projected (Frei and Gong, 2005; Bell and Sloan, 2006; Déry and Wood, 2006), there appears to be little analysis of changes in extreme snowfall. An assessment of possible future changes in heavy lake-effect snowstorms (Kunkel *et al*., 2002) from the Great Lakes found that surface air temperature increases are likely to be the dominant factor. They examined simulations from two different climate models and found that changes in the other factors favorable for heavy snow events were relatively small. In the snowbelts south of Lakes Ontario, Erie, and Michigan, warming decreases the frequency of temperatures in the range of -10°C to 0°C

that is favorable for heavy lake-effect snowfall. Thus, decreases in event frequency are likely in these areas. However, in the northern, colder snowbelts of the Great Lakes, such as the Upper Peninsula of Michigan, moderate increases in temperature have minor impacts on the frequency of favorable temperatures because in the present climate temperatures are often too cold for very heavy snow; warming makes these days more favorable, balancing the loss of other days that become too warm. Thus, the future frequency of heavy events may change little in the northern snowbelts of lake-effects regions.

Extreme snowfall events could change as a result of both precipitation and temperature change.

Increased temperature suggests that heavy snow events downwind of the Great Lakes will begin later in the season. Also, increased temperature with concomitant increased atmospheric moisture implies that in central and northern Canada, Alaska, and other places cold enough to snow (*e.g.*, high mountains), the intensity of heavy snow events may increase.

3.3.9 Tropical Cyclones (Tropical Storms and Hurricanes)

3.3.9.1 Introduction

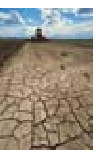
In response to future anthropogenic climate warming, tropical cyclones could potentially change in a number of important ways, including frequency, intensity, size, duration, tracks, area of genesis or occurrence, precipitation, and storm surge characteristics.

Overarching sources of uncertainty in future projections of hurricanes include uncertainties in future emission scenarios for climatically important radiative forcings, global-scale climate sensitivity to these forcings and the limited capacity of climate models to adequately simulate intense tropical cyclones. The vulnerability to

The high sensitivity of tropical storm and hurricane activity in the Atlantic basin to modest environmental variations suggests the possibility of strong sensitivity of hurricane activity to human-caused climate change.

storm surge flooding from future hurricanes will very likely increase, in part due to continuing global sea level rise associated with anthropogenic warming, modulated by local sea level changes due to other factors such as local land elevation changes and regionally varying sea level rise patterns. These related topics are covered in more detail in CCSP Synthesis and Assessment Products 2-1, 3-2, and 4-1, and the IPCC Fourth Assessment Report chapters on climate sensitivity, future emission scenarios, and sea level rise. An additional assessment of the state of understanding of tropical cyclones and climate change as of 2006 was prepared by the tropical cyclone community (WMO, 2006; section 3.2.4 of this CCSP document). This CCSP document summarizes some of the earlier findings but also highlights new publications since these reports.

Future projections of hurricanes will depend upon not only global mean climate considerations, but also on regional-scale projections of a number of aspects of climate that can potentially affect tropical cyclone behavior. These include:



- The local potential intensity (Emanuel 2005; 2006, Holland 1997), which depends on SSTs, atmospheric temperature and moisture profiles, and near-surface ocean temperature stratification;
- Influences of vertical wind shear, large-scale vorticity, and other circulation features (Gray, 1968, 1984; Goldenberg *et al.*, 2001; Bell and Chelliah, 2006); and,
- The characteristics of precursor disturbances such as easterly waves and their interaction with the environment (Dunn, 1940, Frank and Clark, 1980, Pasch *et al.*, 1998, Thorncroft and Hodges, 2001).

Details of future projections in regions remote from the tropical cyclone basin in question may also be important. For example, El Niño fluctuations in the Pacific influence Atlantic basin hurricane activity (Chapter 2 this report, Section 3.2 of this chapter). West African monsoon activity has been correlated with Atlantic hurricane activity (Gray, 1990), as have African dust outbreaks (Evan *et al.*, 2006). Zhang and Delworth (2006) show how a warming of the northern tropical Atlantic SST relative to the southern tropical Atlantic produces atmospheric circulation features, such as reduced vertical wind shear of the mean wind field, that are correlated with low-frequency variations in major hurricane activity (Goldenberg *et al.*, 2001).

The high sensitivity of tropical storm and hurricane activity in the Atlantic basin to modest environmental variations suggests the possibility of strong sensitivity of hurricane activity to anthropogenic climate change, though the nature of such changes remains to be determined. Confidence in any future projections of anthropogenic influence on Atlantic hurricanes will depend on the reliability of future projections of the local thermodynamic state (*e.g.*, potential intensity) as well as circulation changes driven by both local and remote influences, as described above. Projected effects of global warming on El Niño remain uncertain (Timmermann, 1999; Zelle *et al.*, 2005; Meehl *et al.*, 2007a). There is climate model-based evidence that the time-mean climate late in the 21st century will be characterized by higher tropical-cyclone potential intensity in most tropical-cyclone regions, and also tend toward having a decreased east-west overturning circulation in the Pacific sector in the 21st century, with likely consequences for vertical wind shear and other characteristics in the tropical Atlantic (Vecchi and Soden, 2007).

Even assuming that the climate factors discussed above can be projected accurately, additional uncertainties in hurricane future projections arise from uncertainties in understanding and modeling the response of hurricanes to changing environmental conditions. This is exacerbated by projections that the large-scale conditions for some factors, such as decadal means and seasonal extremes of SSTs, will be well outside the range of historically experienced values. This raises questions of the validity of statistical models trained in the present day climate (Ryan *et al.*, 1992; Royer *et al.*, 1998); thus, the emphasis here is placed on physical models and inferences as opposed to statistical methods and extrapolation. Thus, we consider projections based on global and regional nested modeling frameworks as well as more idealized modeling or theoretical frameworks developed specifically for hurricanes. The idealized approaches include potential intensity theories as well as empirical indices which attempt to relate tropical cyclone frequency to large-scale environmental conditions. Global and regional nested models simulate the development and life cycle of tropical cyclone-like phenomena that are typically much weaker and with a larger spatial scale than observed tropical cyclones. These model storms are identified and tracked using automated storm tracking algorithms, which typically differ in detail between studies, but include both intensity and "warm-core" criteria which must be satisfied. Models used for existing studies vary in horizontal resolution, with the low-resolution models having a grid spacing of about 300 km, medium resolution with grid spacing of about 120 km, and high resolution with grid spacing of 20-50 km.

3.3.9.2 Tropical Cyclone Intensity

Henderson-Sellers *et al.* (1998), in an assessment of tropical cyclones and climate change, concluded that the warming resulting from a doubling of CO_2 would cause the potential intensity of tropical cyclones to remain the same or increase by 10 to 20%. (Their estimate was given in terms of central pressure fall; all other references to intensity in this section will refer to maximum surface winds, except where specifically noted otherwise.) They also noted limitations of the potential intensity theories, such as sea spray influences and ocean interactions.

Further studies using a high resolution hurricane prediction model for case studies or idealized experiments under boundary conditions provided from high CO_2 conditions (Knutson *et al.*, 1998; Knutson and Tuleya, 1999, 2004, 2008) have provided additional model-based evidence to support these theoretical assessments. For a CO_2-induced tropical SST warming of 1.75°C, they found a 14% increase in central pressure fall (Figure 3.8) and a 6% increase in maximum surface wind or a maximum wind speed sensitivity of about 4% per degree Celsius (Knutson and Tuleya, 2008). For the pressure fall sensitivity, they reported that their model result (+14%) was intermediate between that of two potential intensity theories (+8% for Emanuel's MPI and +16% for Holland's MPI) applied to the same large scale environments. In a related study, Knutson *et al.* (2001) demonstrated that inclusion of an interactive ocean in their idealized hurricane model did not significantly affect the percentage increase in hurricane intensity associated with CO_2-induced large-scale SST warming. Caveats to these idealized studies are the simplified climate forcing (CO_2 only versus a mixture of forcings in the real world) and neglect of potentially important factors such as vertical wind shear and changes in tropical cyclone distribution.

Global climate model experiments have historically been performed at resolutions which precluded the simulation of realistic hurricane intensities (*e.g.*, major hurricanes). To date, the highest resolution tropical cyclone/climate change experiment published is that of Oouchi *et al.* (2006). Under present climate conditions, they simulated tropical cyclones with central pressures as low as about 935 hPa and surface wind speeds as high as about 53 m per second Oouchi *et al.* report a 14% increase in the annual maximum tropical cyclone intensity globally, and a 20% increase in the Atlantic, both in response to a greenhouse-warming experiment with global SSTs increasing by about 2.5°C. A

There is climate model-based evidence that the average climate late in the 21st century will be characterized by higher tropical-cyclone potential intensity in most tropical-cyclone regions.

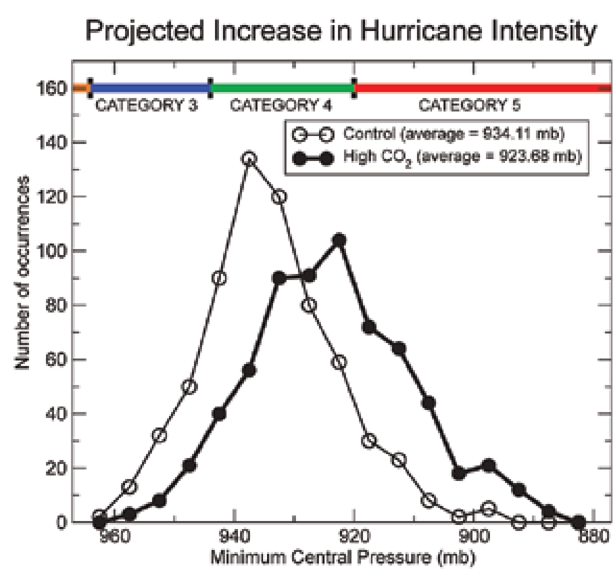
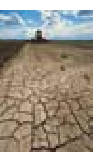


Figure 3.8 Frequency histograms of hurricane intensities in terms of central pressure (mb) aggregated across all idealized hurricane experiments in the Knutson and Tuleya (2004) study. The light curve shows the histogram from the experiments with present-day conditions, while the dark curve is for high CO_2 conditions (after an 80-year warming trend in a +1% per year CO_2 experiment). The results indicate that hurricanes in a CO_2-warmed climate will have significantly higher intensities (lower central pressures) than hurricanes in the present climate.



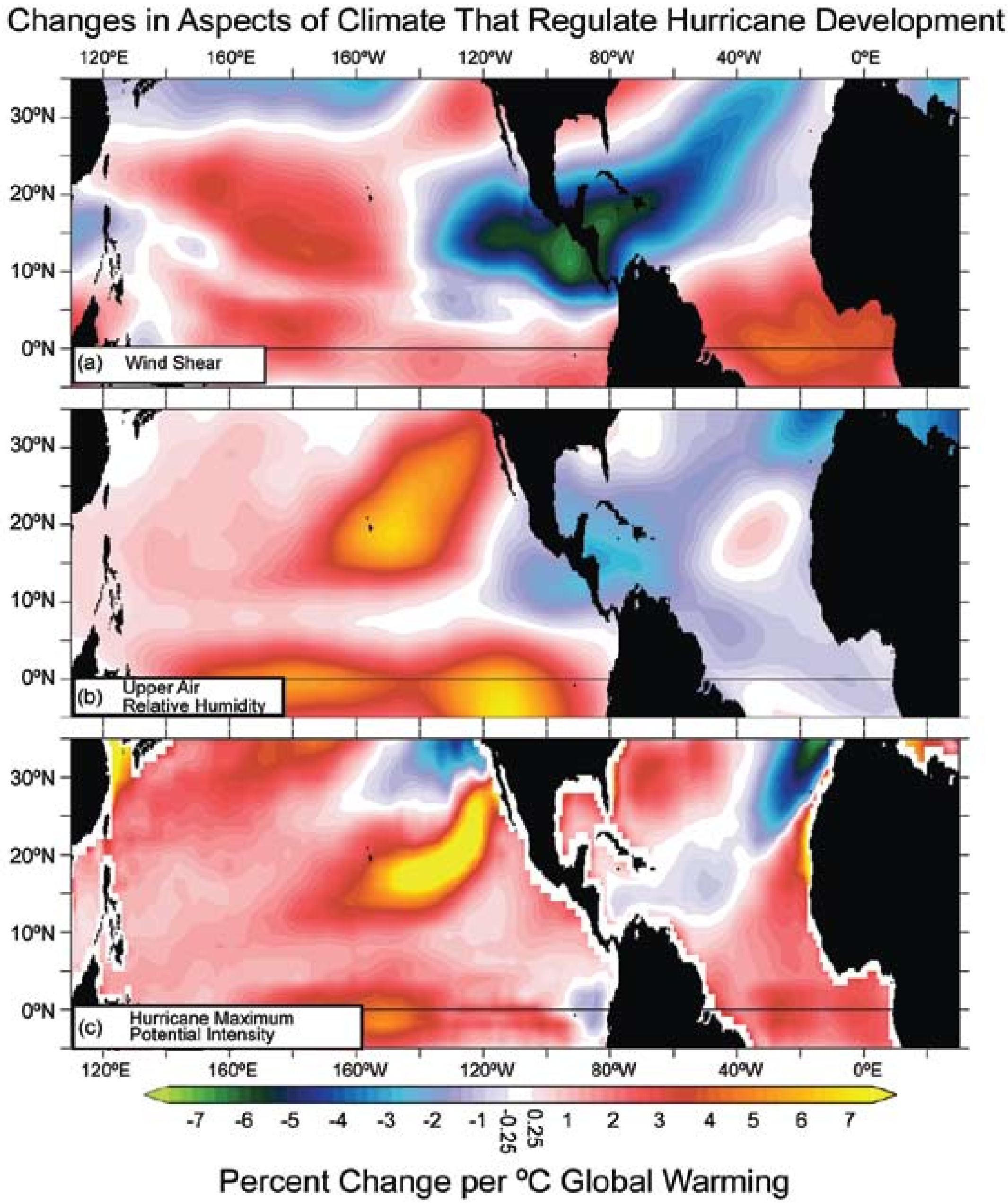


Figure 3.9 Percent changes in June-November ensemble mean a) vertical wind shear (multiplied by -1), b) mid-tropospheric relative humidity, and c) maximum potential intensity of tropical cyclones for the period 2081-2100 minus the period 2001-2021 for an ensemble of 18 GCMs, available in the IPCC AR4 archive, using the A1B scenario. The percentage changes are normalized by the global surface air temperature increase projected by the models. For the wind shear (a), blue areas denote regions with projected increases in vertical wind shear, a factor that is detrimental for hurricane development. Adapted from Vecchi and Soden (2007).

notable aspect of their results is the finding that the occurrence rate of the most intense storms increased despite a large reduction in the global frequency of tropical cyclones. Statistically significant intensity increases in their study were limited to two of six basins (North Atlantic and South Indian Ocean). As will be discussed in the next section on frequency projections, a caveat for the Oouchi *et al.* (2006) results for the Atlantic basin is the relatively short sample periods they used for their downscaling experiments. Bengtsson *et al.* (2007) also find a slightly reduced tropical cyclone frequency in the Atlantic coupled with an increase in the intensities (measured in terms of relative vorticity) of the most intense storms. The latter finding only became apparent at relatively high model resolution (at approximately 30-40 km grid).

Other studies using comparatively lower resolution models have reported tropical-cyclone intensity results. However, the simulated response of intensity to changes in climate in lower resolution models may not be reliable as they have not been able to simulate the marked difference in achievable tropical-cyclone intensities for different SST levels (*e.g.*, Yoshimura *et al.*, 2006) as documented for observed tropical cyclones (DeMaria and Kaplan, 1994; Whitney and Hobgood, 1997; Baik and Paek, 1998). Given this important caveat, the lower resolution model results for intensity are mixed: Tsutsui (2002) and McDonald *et al.* (2005) report intensity increases under warmer climate conditions, while Sugi *et al.* (2002), Bengtsson *et al.* (2006), and Hasegawa and Emori (2005; western North Pacific only), and Chauvin *et al.* (2006; North Atlantic only) found either no increase or a decrease of intensity.

Vecchi and Soden (2007) present maps of projected late 21st century changes in Emanuel's potential intensity, vertical wind shear, vorticity, and mid-tropospheric relative humidity as obtained from the latest (IPCC, 2007) climate models (Figure 3.9). While their results indicate an increase in potential intensity in most tropical cyclone regions, the Atlantic basin in particular displays a mixture with about two-thirds of the area showing increases and about one-third slight decreases. In some regions, they also found a clear tendency for increased vertical wind shear and reduced mid-tropospheric relative humidity – factors that are detrimental for tropical cyclone development. In the Gulf of Mexico and closer to the U.S. and Mexican coasts, the potential intensity generally increases. The net effect of these composite changes remains to be modeled in detail, although existing global modeling studies (Oouchi *et al.*, 2006; Bengtsson *et al.*, 2007) suggest increases in the intensities and frequencies of the strongest storms. An area average of the Vecchi and Soden (2007) 18 model composite MPI changes (for the region 90°W-60°W, 18°N-35°N) yields a negligible wind speed sensitivity of about 1%/°C (G. Vecchi, personal communication, 2007). This region is north of the Caribbean and includes regions of the Gulf of Mexico and along the U.S. East Coast that are most relevant to U.S. and Mexican landfalls. It is noted that the potential intensity technique used by Vecchi and Soden (Emanuel MPI) was found to be the least sensitive of three estimation techniques in the multi-model study of Knutson and Tuleya (2004). In the Eastern Pacific, the potential intensity is projected to increase across the entire basin, although the vertical wind shear increases may counteract this to some extent.

Increased vertical wind shear and reduced mid-tropospheric relative humidity are factors that are detrimental for tropical cyclone development.

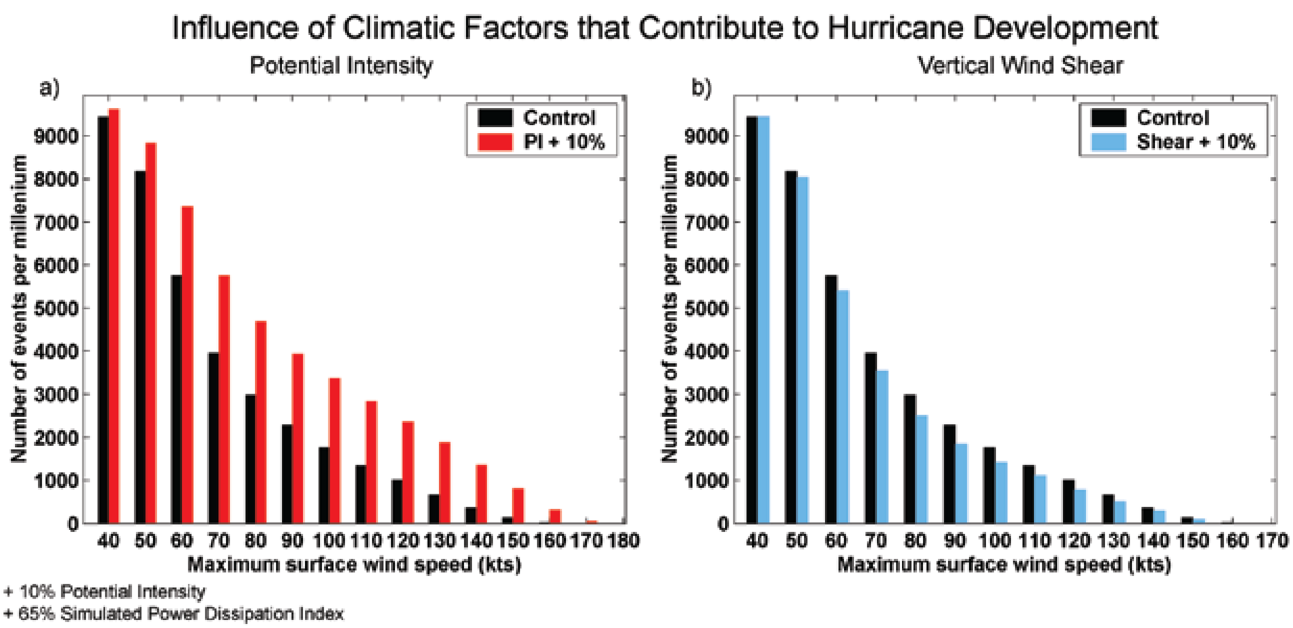
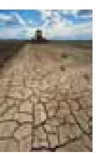


Figure 3.10 Number of events per 1000 years with peak wind speeds exceeding the value on the x-axis. Results obtained by running a simple coupled hurricane intensity prediction model over a set of 3000 synthetic storm tracks for the North Atlantic. The grey bars depict storms for present day climate conditions. The black bars depict storms for similar conditions except that the potential intensity (a) or vertical wind shear (b) of the environment is increased everywhere by 10%. From Emanuel (2006).

A more recent idealized calculation by Emanuel *et al*. (2006) finds that artificially increasing the modeled potential intensity by 10% leads to a marked increase in the occurrence rate of relatively intense hurricanes (Figure 3.10a), and to a 65% increase in the PDI. Increasing vertical wind shear by 10% leads to a much smaller decrease in the occurrence rate of relatively intense hurricanes (Figure 3.10b) and a 12% reduction in the PDI. This suggests that increased potential intensity in a CO_2-warmed climate implies a much larger percentage change in potential destructiveness of storms from wind damage than the percentage change in wind speed itself. Emanuel (1987; 2005) estimated a wind speed sensitivity of his MPI to greenhouse gas-induced warming of about 5% per °C; based on one climate model.

Models indicate increasing intensity and frequency of the strongest hurricanes and typhoons in a CO_2-warmed climate.

The statistical analysis of Jagger and Elsner (2006) provides some support for the notion of more intense storms occurring with higher global temperatures, based on observational analysis. However, it is not yet clear if the empirical relationship they identified is specifically related to anthropogenic influences on global temperature.



In summary, theory and high-resolution idealized models indicate increasing intensity and frequency of the strongest hurricanes and typhoons in a CO_2-warmed climate. Parts of the Atlantic basin may have small decreases in the upper limit intensity, according to one multi-model study of theoretical potential intensity. Expected changes in tropical cyclone intensity and their confidence are therefore assessed as follows: in the Atlantic and North Pacific basins, some increase of maximum surface wind speeds of the strongest hurricanes and typhoons is likely. We estimate the likely range for the intensity increase (in terms of maximum surface winds) to be about 1 to 8% per °C tropical sea surface warming over most tropical cyclone regions. This range encompasses the broad range of available credible estimates, from the relatively low 1.3% per °C area average estimate by Vecchi (personal communication, 2007) of Vecchi and Soden (2007) to the higher estimate (5% per °C) of Emanuel (1987, 2005), and includes some additional subjective margin of error in this range. The ensemble sensitivity estimate from the dynamical hurricane modeling study of Knutson and Tuleya (2004) of 3.7% per °C is near the middle of the above range. Furthermore, the available evidence suggests that maximum intensities may decrease in some regions, particularly in parts of the Atlantic basin, even though sea surfaces are expected to warm in all regions.

This assessment assumes that there is no change in geographical distribution of the storms (*i.e.*, the storms move over the same locations, but with a generally warmer climate). On the other hand, there is evidence (Holland and Webster, 2007) that changes in distribution (*e.g.*, tropical-cyclone development occurring more equatorward, or poleward of present day) have historically been associated with large changes in the proportion of major hurricanes. It is uncertain how such distributions will change in the future (see below), but such changes potentially could strongly modify the projections reported here.

3.3.9.3 Tropical Cyclone Frequency and Area of Genesis

In contrast to the case for tropical-cyclone intensity, the existing theoretical frameworks for relating tropical-cyclone frequency to global climate change are relatively less well-developed. Gray (1979) developed empirical relationships that model the geographical variation of tropical-cyclone genesis in the present climate relatively well, but several investigators have cautioned against the use of these relationships in a climate change context (Ryan *et al*., 1992; Royer *et al*., 1998). Royer *et al*. proposed a modified form of the Gray relationships based on a measure of convective rainfall as opposed to SST or oceanic heat content, but this alternative has not been widely tested. They showed that tropical-cyclone frequency results for a future climate scenario depended strongly on whether the modified or unmodified genesis parameter approach was used. More recently, Emanuel and Nolan (2004) and Nolan *et al*. (2006) have developed a new empirical scheme designed to be more appropriate for climate change application (see also Camargo *et al*., 2006), but tropical-cyclone frequency/climate change scenarios with this framework have not been published to date.

Vecchi and Soden (2007) have assessed the different components of the Emanuel and Nolan (2004) scheme using outputs from the IPCC AR4 models. Their results suggest that a decrease in tropical cyclone frequency may occur over some parts of the Atlantic basin associated with a SW-NE oriented band of less favorable conditions for tropical cyclogenesis and intensification, including enhanced vertical wind shear, reduced mid-tropospheric relative humidity, and slight decrease in potential intensity. The enhanced vertical shear feature (present in about 14 of 18 models in the Caribbean region) also extends into the main cyclogenesis region of the Eastern Pacific basin. Physically, this projection is related to the weakening of the east-west oriented Walker Circulation in the Pacific region, similar to that occurring during El Niño events. During El Niño conditions in the present-day climate, hurricane activity is reduced, as occurred, for example, in the latter part of the 2006 season. While this projection may appear at odds with observational evidence for an increase in Atlantic tropical cyclone counts during the past century (Holland and Webster, 2007; Vecchi and Knutson, 2008), there is evidence that this has occurred in conjunction with a regional decreasing trend in storm occurrence and formation rates in the western part of the Caribbean and Gulf of Mexico (Vecchi and Knutson, 2008; Holland, 2007). Earlier, Knutson and Tuleya (2004) had examined the vertical wind shear of the zonal wind component for a key region of the tropical Atlantic basin using nine different coupled models from the CMIP2+ project. Their analysis showed a slight preference for increased vertical shear under high CO_2 conditions if all of the models are considered, and a somewhat greater preference for increased shear if only the six models with the most realistic present-day simulation of shear in the basin are considered. Note that these studies are based on different sets of models, and that a more idealized future forcing scenario was used in the earlier Knutson and Tuleya study.

Alternative approaches to the empirical analysis of large-scale fields are the global and regional climate simulations, in which the occurrence of model tropical cyclones can be tracked. Beginning with the early studies of Broccoli and Manabe (1990), Haarsma *et al*. (1993), and Bengtsson *et al*. (1996), a number of investigators have shown that global models can generate tropical cyclone-like disturbances in roughly the correct geographical locations with roughly the correct seasonal timing. The annual occurrence rate of these systems can be quite model dependent (Camargo *et al*., 2005), and is apparently sensitive to various aspects of model physics (*e.g.*, Vitart *et al*., 2001).

The notion of using global models to simulate the climate change response of tropical cyclone counts is given some support by several studies showing that such models can successfully simulate certain aspects of interannual to interdecadal variability of tropical-cyclone occurrence seen in the real world (Vitart *et al*., 1997; Camargo *et al*., 2005; Vitart and Anderson, 2001). A recent regional model dynamical downscaling study (Knutson *et al*., 2007) with an 18 km grid model and a more idealized modeling approach (Emanuel *et al*., 2008) both indicate that the increase in hurricane activity in the Atlantic from 1980-2005 can be reproduced in a model using specified SSTs and large-scale historical atmospheric information from reanalyses.

Since tropical cyclones are relatively rare events and can exhibit large interannual to interdecadal variability, large sample sizes (*i.e.*, many seasons) are typically required to test the significance of any changes in a model simulation against the model's "natural variability."

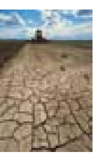
The most recent future projection results obtained from medium and high resolution (120 km-20 km) GCMs are summarized in Table 3.2. Among these models, those with higher resolution indicate a consistent signal of fewer tropical cyclones globally in a warmer climate, while two lower resolution models find essentially no change. There are, however, regional variations in the sign of the changes, and these vary substantially between models (Table 3.2). For the North Atlantic in particular, more tropical cyclones are projected in some models, despite a large reduction globally (Sugi *et al*., 2002; Oouchi *et al*., 2006), while fewer Atlantic tropical cyclones are projected by other models (*e.g.*, McDonald *et al*., 2005; Bengtsson *et al*., 2007). It is not clear at present how the Sugi *et al*. (2002) and Oouchi *et al*. (2006) results for

While there is recent observational evidence for an increase in the number of tropical storms and hurricanes in the Atlantic, a confident assessment of future storm frequency cannot be made at this time.

Table 3.2 Summary of tropical cyclone frequency, expressed as a percent of present day levels, as simulated by several climate GCMs under global warming conditions.

Reference	Model	Resolution	Experiment				
				Global	North Atlantic	NW Pacific	NE Pacific
Sugi *et al.* 2002	JMA time slice	T106 L21 (~120km)	10y $1xCO_2$, $2xCO_2$	*66*	**161**	*34*	33
Tsutsui 2002	NCAR CCM2	T42 L18	10y $1xCO_2$ $2xCO_2$ from 115y CO_2 1% pa	102	86	111	91
McDonald *et al.* 2005	HadAM3 time slice	N144 L30 (~100km)	15y IS95a 1979-1994 2082-2097	*94*	*75*	*70*	**180**
Hasegawa and Emori 2005	CCSR/NIES/ FRCGC time slice	T106 L56 (~120km)	5x20y at $1xCO_2$ 7x20y at $2xCO_2$			96	
Yoshimura *et al.* 2006	JMA time slice	T106 L21 (~120km)	10y $1xCO_2$, $2xCO_2$	*85*			
Bengtsson *et al.* 2006	ECHAM5-OM	T63 L31 1.5° L40	A1B 3 members 30y 20C and 21C	94			
Oouchi *et al.* 2006	MRI/JMA time slice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	*70*	**134**	*62*	*66*
Chauvin *et al.* 2006	ARPEGE-Climate time slice	Stretched non-uniform grid (~50 km)	10y CNRM SRES-B2: Hadley SRES-A2:		**118** *75*		
Bengtsson *et al.* 2007	ECHAM5 time slice	up to T319 (down to ~30-40 km grid)	20yr, A1B scenario	---	87	72	107

Bold = significantly **more** tropical cyclones in the future simulation
Italic = significantly *fewer* tropical cyclones in the future simulation
Plain text = not significant or significance level not tested



the Atlantic reconciles with the tendency for increased vertical wind shear projected for parts of that basin by most recent models (Vecchi and Soden, 2007). For example, Oouchi *et al.* (2006) do not analyze how Atlantic vertical wind shear changed in their warming experiment. However, their results suggest that a future increase in tropical cyclone frequency in the Atlantic is at least plausible based on current models. Chauvin *et al.* (2006) and Emanuel *et al.* (2008) find, in multi-model experiments, that the sign of the changes in tropical cyclone frequency in the North Atlantic basin depends on the climate model used. All of the results cited here should be treated with some caution, as it is not always clear that these changes are greater than the model's natural variability, or that the natural variability or the tropical-cyclone genesis process are being properly simulated in the models, particularly for the Atlantic basin. For example, Oouchi *et al.* (2006) sample relatively short periods (20 years) from a single pair of experiments to examine greenhouse gas-induced changes, yet internal multidecadal variability in the Atlantic in their model conceivably could produce changes in tropical-cyclone-relevant fields (such as wind shear) between two 20-year periods that are larger than those for the radiative perturbation they are focusing on in their study.

From the above summarized results, it is not clear that current models provide a confident assessment of even the sign of change of tropical cyclone frequency in the Atlantic, East Pacific, or Northwest Pacific basins. From an observational perspective, recent studies (Chapter 2 this report) report that there has been a long term increase in Atlantic tropical-cyclone counts since the late 1800s, although the magnitude, and in some cases, statistical significance of the trend depends on adjustments for missing storms early in the record.

Based on the above available information, we assess that it is unknown how late 21st century tropical cyclone frequency in the Atlantic and North Pacific basins will change compared to the historical period (approximately 1950-2006).

3.3.9.4 Tropical Cyclone Precipitation

The notion that tropical cyclone precipitation rates could increase in a warmer climate is based on the hypothesis that moisture convergence into tropical cyclones will be enhanced by the increased column integrated water vapor – with the increased water vapor being extremely likely to accompany a warming of tropical SSTs. The increased moisture convergence would then be expected to lead to enhanced precipitation rates. This mechanism has been discussed in the context of extreme precipitation in general by Trenberth (1999), Allen and Ingram (2002), and Emori and Brown (2005). In contrast to the near-storm or storm core precipitation rate, accumulated rainfall at a locality along the storm's path is strongly dependent upon the speed of the storm, and there is little guidance at present on whether any change in this factor is likely in a future warmed climate.

An enhanced near-storm tropical rainfall rate for high CO_2 conditions has been simulated, for example, by Knutson and Tuleya (2004, 2008) based on an idealized version of the GFDL hurricane model. The latter study reported an increase of 21.6% for a 1.75˚C tropical SST warming (Figure 3.11), or about 12% per degree Celsius SST increase. Using a global model, Hasegawa and Emori (2005) found an increase in tropical-cyclone-related precipitation in a warmer climate in the western North Pacific basin, despite a decrease in tropical-cyclone intensity there in their model. Chauvin *et al.* (2006) found a similar result in the North Atlantic in their model, and Yoshimura *et al.* (2006) found a similar result on a global domain. There are issues with all of these modeling studies as they are, of course, low resolution, and thus generally depend on parameterization of much of the rainfall within the grid box. Further, there is a tendency towards tropical cyclone rainfall simulations that have a high bias in core rainfall rates (*e.g.,* Marchok *et al*., 2007). Nevertheless, the consistent result of an increased rainfall with greenhouse warming over a number of models, together with the theoretical expectations that this will occur, lends credibility to there being a real trend.

Based on the modeling studies to date, the relatively straightforward proposed physical mechanism, and the observed increases in extremely heavy rainfall in the United States (although not established observationally for hurricane-related rainfall [Groismann *et al*., 2004]), it is likely that hurricane related rainfall (per storm) will increase in this century. Note that if the frequency of tropical cyclones decreases, the total rainfall from tropical cyclones may decrease. The expected general magnitude of the change for storm core rainfall rates is about +6% to +18% per degree Celsius increase in tropical SST.

> It is likely that hurricane related rainfall (per storm) will increase in this century.

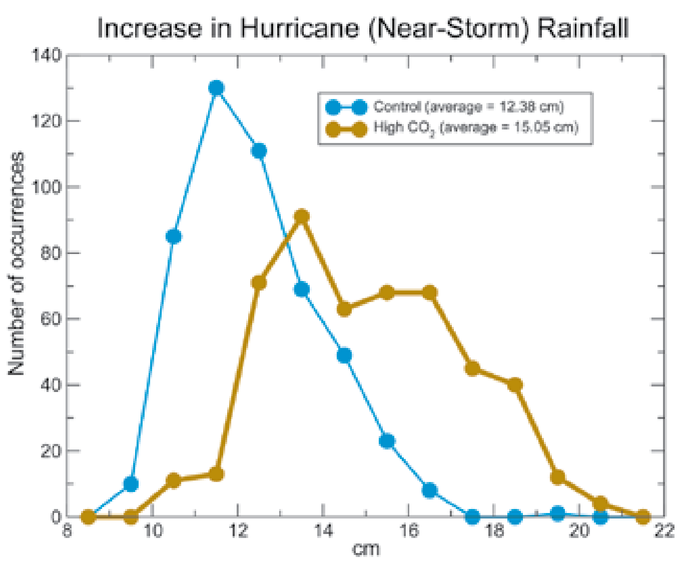


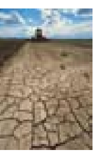
Figure 3.11 As in Figure 3.8, but for near-hurricane precipitation, estimated as the average precipitation rate for the 102 model grid points (32,700 km^2 area) with highest accumulated rainfall over the last 6 hours of the 5-day idealized hurricane experiments in Knutson and Tuleya (2004). The results indicate that hurricanes in a CO_2-warmed climate will have substantially higher core rainfall rates than those in the present climate. From Knutson and Tuleya (2008).

3.3.9.5 Tropical Cyclone Size, Duration, Track, Storm Surge, and Regions of Occurrence

In this section, other possible impacts of greenhouse gas induced climate warming on tropical cyclones are briefly assessed. The assessment is highly preliminary, and the discussion for these relatively brief, owing to the lack of detailed studies on these possible impacts at this time.

Storm surge levels are likely to increase due to projected sea level rise.

Wu and Wang (2004) explored the issue of tropical cyclone track changes in a climate change context. Based on experiments derived from one climate model, they found some evidence for inferred track changes in the Northwest Pacific, although the pattern of changes was fairly complex.



Concerning storm duration, using an idealized hurricane simulation approach in which the potential intensity of a large sample of Atlantic basin storms with synthetically generated storm tracks was artificially increased by 10%, Emanuel (2006) found that the average storm lifetime of all storms increased by only 3%, whereas the average duration at hurricane intensity for those storms that attained hurricane intensity increased by 15%. However, in the Atlantic and Northeast Pacific, future changes in duration are quite uncertain, owing to the uncertainties in formation locations and potential circulation changes mentioned previously.

Few studies have attempted to assess possible future changes in hurricane size. Knutson and Tuleya (1999) noted that the radius of hurricane-force winds increased a few percent in their experiments in which the intensities also increased a few percent.

Changes in tropical cyclone activity may be particularly apparent near the wings of the present climatological distributions. For example, locations near the periphery of current genesis regions may experience relatively large fractional changes in activity.

Storm surge depends on many factors, including storm intensity, size and track, local bathymetry, and the structure of coastal features such as wetlands and river inlets. Unknowns in storm frequency, tracks, size, and future changes to coastal features lead to considerable uncertainty in assessing storm surge changes. However, the high confidence of there being future sea level rise, as well as the likely increase of intensity of the strongest hurricanes, leads to an assessment that storm surge levels are likely to increase, though the degree of projected increase has not been adequately studied.

3.3.9.6 Reconciliation of Future Projections and Past Variations

In this section, we comment on reconciling the future projections discussed above with the past-observed variations in tropical cyclone activity. A confident assessment of human influence on hurricanes will require further studies with models and observations, with emphasis on how human activity has contributed to the observed changes in hurricane activity through its influence on factors such as historical SSTs, wind shear, and vertical stability.

No published model study has directly simulated a substantial century-scale rise in Atlantic tropical cyclone counts similar to those reported for the observations (*e.g.*, Chapter 2). In fact, the 20th century behavior in tropical cyclone frequency has not yet been documented for existing models. One exception is Bengtsson *et al.* (2007) who simulate little change in tropical cyclone frequencies comparing the late 1800s and late 1900s. A recent modeling study (Knutson *et al.*, 2007) indicates that the increase in hurricane activity in the Atlantic from 1980-2005 can be reproduced using a high-resolution nested regional model downscaling approach. However, the various changes in the large-scale atmospheric and SST forcings used to drive their regional model were prescribed from observations. Concerning future projections, the multi-model consensus of increased vertical wind shear in the IPCC AR4 models (Vecchi and Soden, 2007) further implies that it would be difficult to reconcile significant long-term increasing trends in tropical cyclone counts with existing models. If in further studies a significant anthropogenic signal were detected in observed tropical cyclone activity and confidently attributed to increasing GHGs, then this would imply that a future increase in tropical cyclone frequency in the Atlantic would be much more likely than assessed here.

3.3.10 Extratropical Storms

Scientists have used a variety of methods for diagnosing extratropical storms in GCM projections of future climate. These include sea-level pressure (Lambert and Fyfe, 2006), strong surface winds (Fischer-Bruns *et al.*, 2005), lower atmosphere vorticity (Bengtsson *et al.*, 2006), and significant wave heights (Wang *et al.*, 2004; Caires *et al.*, 2006). Consequently, there are no consistent definitions used to diagnose extreme extratropical storms. Some analyses do not, for example, determine events in extreme percentiles, but rather consider storms that deepen below a threshold sea-level pressure (*e.g.*, Lambert and Fyfe, 2006), though such thresholds may effectively select the most extreme percentiles.

Wave heights of course indicate strong storms only over oceans, but the strongest extratropical storms typically occur in ocean storm tracks, so all three methods focus on similar regions. Ocean storms in the North Atlantic and North Pacific are relevant for this study because they affect coastal areas and shipping to and from North America. GCMs projecting climate change can supply sea-level pressure and surface winds, but they typically do not compute significant wave heights. Rather, empirical relationships (Wang *et al.*, 2004; Caires *et al.*, 2006) using sea-level pressure anomalies and gradients provide estimates of significant wave heights.

Despite the variety of diagnoses, some consistent changes emerge in analyses of extratropical storms under anthropogenic greenhouse warming. Projections of future climate indicate strong storms will be more frequent (Figure 3.12; Wang *et al.*, 2004; Fischer-Bruns *et al.*, 2005; Bengtsson *et al.*, 2006; Caires *et al.*, 2006; Lambert and Fyfe, 2006; Pinto *et al.*, 2007), though the overall number of storms may decrease. These changes are consistent with observed trends over the last half of the 20th century (Paciorek *et al.*, 2002). More frequent strong storms may reduce the frequency of all

Projections of future climate indicate strong non-tropical storms will be more frequent, though the overall number of storms may decrease, consistent with observed trends over the last 50 years.

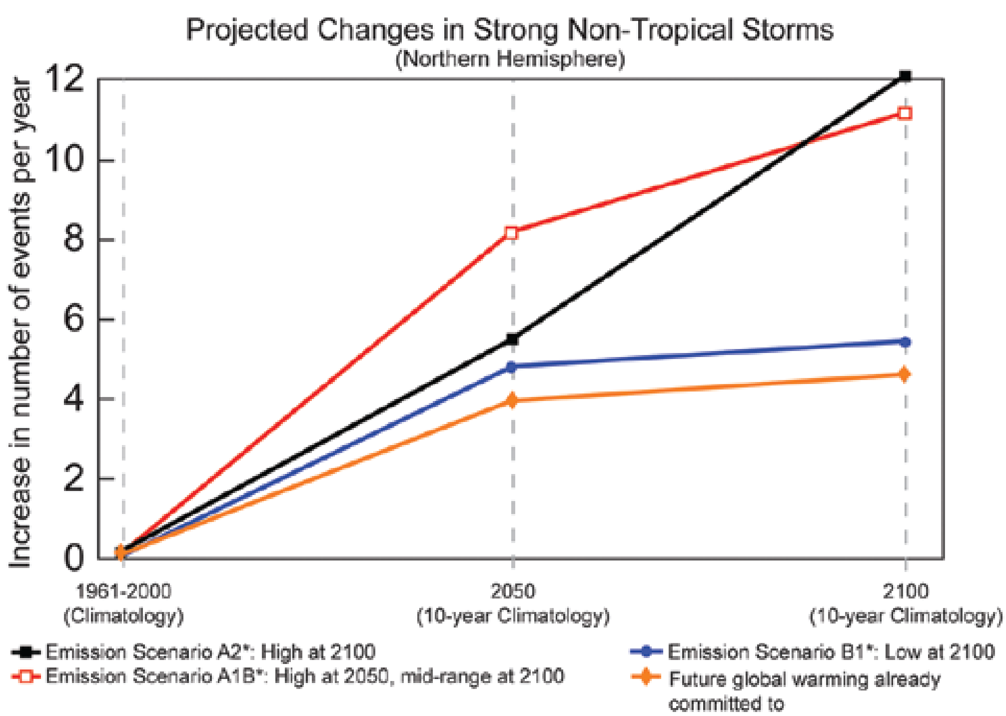
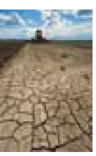


Figure 3.12 The projected change in intense low pressure systems (strong storms) during the cold season for the Northern Hemisphere for various emission scenarios* (adapted from Lambert and Fyfe; 2006). Storms counted have central pressures less than 970 mb and occur poleward of 30°N during the 120-day season starting November 15. Adapted from Lambert and Fyfe (2006).

extratropical storms by increasing the stability of the atmosphere (Lambert and Fyfe 2006). Analyses of strong winds (Fischer-Bruns *et al*., 2005, Pinto *et al*., 2007), lower atmosphere vorticity (Bengtsson *et al*., 2006), and significant wave heights (Wang *et al*., 2004; Caires *et al*., 2006) from single models suggest increased storm strength in the northeast Atlantic, but this increase is not apparent in an analysis using output from multiple GCMs (Lambert and Fyfe, 2006). Differences may be due to the focus on cold season behavior in the wind and wave analyses, whereas Lambert and Fyfe's (2006) analysis includes the entire year.

The retreat of sea ice together with changing sea levels will likely increase the exposure of arctic coastlines to damaging waves and extreme erosion produced by strong storms, continuing an observed trend of increasing coastal erosion in arctic Alaska.



The warming projected for the 21st century is largest in the high latitudes due to a poleward retreat of snow and ice resulting in enhanced warming (Manabe and Stouffer 1980; Meehl *et al*., 2007a). Projected seasonal changes in sea ice extent show summertime ice area declining much more rapidly than wintertime ice area, and that sea ice thins largest where it is initially the thickest, which is consistent with observed sea ice thinning in the late 20th century (Meehl *et al*., 2007a). Increased storm strength in the northeast Atlantic found by some may be linked to the poleward retreat of arctic ice (Fischer-Bruns *et al*., 2005) and a tendency toward less frequent blocking and more frequent positive phase of the NAM (Pinto *et al*., 2007), though further analysis is needed to diagnose physical associations with ice line, atmospheric temperature, and pressure structures and storm behavior. Whether or not storm strength increases, the retreat of sea ice together with changing sea levels will likely increase the exposure of arctic coastlines to damaging waves and extreme erosion produced by strong storms (Lynch *et al*., 2004; Brunner *et al*., 2004; Cassano *et al*., 2006), continuing an observed trend of increasing coastal erosion in arctic Alaska (Mars and Houseknecht, 2007). Rising sea levels, of course, may expose all coastlines to more extreme wave heights (*e.g.*, Cayan *et al*., 2008).

3.3.11 Convective Storms

Conclusions about possible changes in convective precipitating storms and associated severe-weather hazards under elevated greenhouse gas concentrations have remained elusive. Perhaps the most important reason for this is the mesoscale (10s of km) and smaller dynamics that control behavior of these storms, particularly the initiation of storms. Del Genio *et al*. (2007), Marsh *et al*. (2007) and Trapp *et al*. (2007) have evaluated changes in the frequency of environments that are favorable for severe thunderstorms in GCM simulations of greenhouse-enhanced climates. In all three cases, increases in the frequency of environments favorable to severe thunderstorms are seen, but the absence of the mesoscale details in the models means that the results are preliminary. Nevertheless, the approach and the use of nested models within the GCMs show promise for yielding estimates of changes in extreme convective storms.