Chapter 3 How Well Do We Understand the Causes of Observed Changes in Extremes, and What Are the Projected Future Changes?

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KEY FINDINGS

Observed Changes

Changes in some weather and climate extremes are attributable to human-induced changes in 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 increased water holding capacity of the atmosphere in a warmer climate and observed increases in water vapor over the oceans.

- It is likely that human activities have caused a discernable increase in sea surface temperatures in the hurricane formation region of the tropical Atlantic Ocean over the past 100 years. The balance of evidence suggests that human activity has caused a discernable increase in tropical storm/hurricane and major hurricane frequency in the North Atlantic.

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.
- According to theory and models for North Atlantic and North Pacific hurricanes and typhoons (both basin-wide and land-falling):
  – Hurricane/typhoon core rainfall rates will likely increase by about 6 to 18% per degree Celsius tropical sea surface warming.
  – It is likely that surface wind speeds of the strongest hurricanes/typhoons will increase by about 2 to 10% per degree Celsius tropical sea surface warming.

– Frequency changes are too uncertain for confident projections.

– The spatial distribution of hurricanes/typhoons will likely change.

– Due to projected sea level rise, the potential for storm surge damage will very likely increase.

- 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 ENSO cycles, as well as the mechanisms of extremes themselves (e.g., processes producing heavy precipitation). In other words, processes creating an environment conducive to extreme behavior and processes of the extreme behavior itself. This includes not only the extreme events but also the factors governing their timing and location.

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. Understanding physical mechanisms serves a further purpose for projected climate changes. Because the verification time for climate-change projections can be 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 physical realism of changes in extremes. While physical consistency of simulations with observed behavior is not sufficient evidence for accurate projection, it is necessary.

3.2 What Are the Physical Mechanisms of Observed Changes in Extremes?

3.2.1 Detection and Attribution of Anthropogenic 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, solar radiation or frequency of volcanoes. 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.

3.2.1.1 Detection and Attribution of Anthropogenic Changes in Mean Climate That Affect Climate Extremes

This section discusses the present understanding on 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 (Katz and Brown 1992). Expected changes in temperature extremes are largely but not entirely due to changes in seasonal mean temperatures. Some differences between the two 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 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 interpreting changes in extremes, although more difficult to interpret (Groisman et al., 1999). Relevant information about mean temperature changes appeared 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 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 volcano 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, IDAG 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). For example, in Alaska warming has been large but high levels of internal variability lead to an overlap of naturally forced and all-forcing simulations even at the end of the 20th century (Wang 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 envelop 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 1901to 1940 and cooling from 1940 to 1979 may have been a consequence on 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 US 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 US climate extremes index for the late twentieth 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 and lead to a small increase in global mean precipitation. More important, the increase in water holding capacity of the atmosphere is expected to affect more strongly 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 of this document, Trenberth et al. 2007). In addition, greenhouse gas increases are also expected to cause enhanced 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 integrations including both natural and anthropogenic forcings is significantly correlated with that observed (Allen and Ingram, 2002; Gillett et al., 2004b; 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 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 wetting north of 50N and drying between 0-30N, and this together with agreement on moistening south of the equator provides support for the detection of a global anthropogenic influence.

3.2.1.2 Detection and Attribution of Other 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 El Niño Southern Oscillation (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 risk of extreme temperature (Thompson and Wallace 2002, Kenyon and Hegerl 2007), 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, 2006) and Wang et al. (2007) 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 extremes related to circulation changes may therefore be affected. The change in sea level pressure largely manifests itself through an intensification of the Northern and Southern Annular Modes with reduced pressure above both poles and equatorward displacement of mass. However, apart from these modes, 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 enhanced 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 of this report). There have been multi-decadal 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. 2007).

Decadal variability in the North Pacific is characterised 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 Pacific Decadal Oscillation (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, 2007), 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, Zwiers and Yu 2007).

The Northern Annular Mode (NAM) is an approximately zonally symmetric mode of variability in the Northern Hemisphere (Thompson and Wallace, 1998, Chapter 1 of this report), and the North Atlantic Oscillation (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., 2003a). Several studies have shown this trend to be inconsistent with simulated internal variability (Osborn et al., 1999; Gillett et al., 2000; Gillett et al., 2002b; 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., 2002b, Osborn, 2004, Gillet 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 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, 2007), 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, there has been a widespread reduction in the number of frost days in mid-latitude regions in recent decades, an increase in the number of warm extremes, particularly warm nights, and a reduction in the number of cold extremes, such as cold nights.

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 HadCM3 model, 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 underestimated 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 (Fig. 3.1a,b,c). There is also good agreement between the observed and ensemble mean simulated spatial pattern of change in frost days (Fig.3.2a,b) over the latter half of the 20th century. Note that the observational estimate has a much greater degree of temporal (Fig. 3.1) and spatial (Fig. 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 with human and natural forcings approximate well the observed changes, but when driven with natural forcings only cannot reproduce the observed changes, indicating a human 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 (Fig. 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 methodology has not yet been applied to North American extremes, though Hoerling et al. (2007) have used the method to conclude that the very hot 2006 in the United States was primarily due to human influences.

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 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 vapour 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.

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 precipiation 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 et al. 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 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; Fig. 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 (Fig. 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 runoff in the latter decades of the 20th century in part to suppression of transpiration due to 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 the both the Northern and Southern hemispheres since the 1950's (Trenberth et al., 2006). 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.

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., 2003; Seager et al., 2005), indicating the importance of sea-surface temperatures in determining North American drought (see also, for example, Hoerling and Kumar, 2003). Specifically, Schubert et al. (2003) 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 1930's drought. Only the Seager et al. (2005) model simulates the 1950's drought over North America, indicating that more modelling 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 the 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 Development Criteria and Mechanisms

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 ^{o}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, 1998). Some skill has been demonstrated in applying it to re-analysis 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 Clarke 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 Nino 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 Clarke 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 eastwards (Holland, 1995), though development can occur almost anywhere (e.g. Lander 1994). 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 Nino phase (Chan 1985, Lander 1994, 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 1999, 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 1995), 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 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.

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 US 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 subject to vigorous community debate. Chief amongst 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 put together by the attendees at a World Meteorological Society Workshop on Tropical Cyclones held in November 2006 (WMO 2006, Knutson et al 2006b). Of direct relevance in the WMO statement are the following:

- Though there is evidence both for and against the existence of a detectable anthropogenic signal in the tropical cyclone climate record to date, no firm conclusion can be made on this point.
- It is likely that some increase in tropical cyclone intensity and rainfall will occur if the climate continues to warm. Model studies and theory project a 3-5% increase in wind speed per degree increase of tropical sea surface temperatures.
- No individual tropical cyclone can be directly attributed to climate change.
- Some studies of the observational record conclude that the reported global increase in tropical cyclone activity is questionable owing to data problems, since tropical cyclone monitoring has improved continuously.
- There is an observed multi-decadal variability of Atlantic hurricanes whose causes, whether natural, anthropogenic or a combination, are currently being debated. This variability makes detecting any long-term trends in tropical cyclone activity difficult.
- Current theories and computer models predict an increase in wind speed and rainfall of tropical cyclones in a warmer climate.
- Recent climate model simulations project a decrease or no change in global tropical cyclone numbers in a warmer climate, although there is low confidence in this projection.

We note that these were consensus views, and no attempt was made to assign likely probabilities to the possible outcomes. The International Panel for Climate Change (IPCC) arrived at similar findings, but also focused on the observed changes in the North Atlantic (IPCC 2007):

- There is observational evidence for an increase of intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases of tropical sea surface temperatures.
- There are also suggestions of increased intense tropical cyclone activity in some other regions where concerns over data quality are greater.
- Multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity.
- There is no clear trend in the annual global numbers of tropical cyclones.

The IPCC also made the following probability assessments on intense tropical cyclone activity:

- Likely that increases have occurred in some regions since 1970;
- More likely than not a human contribution to the observed trend;
- Likely that there will be future trends in tropical cyclone intensity and heavy precipitation associated with ongoing increases of tropical SSTs;
- Less confidence in projections of a global decrease in the numbers of tropical cyclones.

Emanuel (2005) and Webster et al. (2005) showed a clear increase in the more intense Northwest Pacific cyclones (as shown by 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. On the other hand there are also 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.

One area where there is consensus is on tropical cyclone rainfall. WMO (2007) and IPCC (2007) concur on there being a likely increase in heavy rainfall associated with tropical cyclones, though the actual level of increase is not clear.

The remainder of the attribution section on tropical cyclones concentrates on attribution in 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 cyclones, 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 around 1 to 7% for the observed 0.5 to 0.7^{o}C trend in tropical North Atlantic SSTs (Henderson-Sellers et al 1998, Knutson et al 1998; 2001; Knutson and Tuleya 2004; 2007).

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 (2005a; 2007a) examined a Power Dissipation Index (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 Power Dissipation Index (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 multi-decadal 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.

While there is a close statistical relationship between low frequency variations of tropical cyclone activity (e.g., the PDI and storm frequency) and SSTs (Ch. 2), this almost certainly arises from a combination of factors, including joint relationships to other atmospheric process that effect cyclone development, such as vertical windshear (Shapiro 1982, Kossin and Vitmer 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, Ch. 2).

Low-frequency variations in Atlantic tropical cyclone activity have previously been attributed to a natural variability in Atlantic SSTs associated with the Atlantic Multi-decadal 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 multi-decadal 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, it is also likely that a discernable warming trend, due to greenhouse gases, has occurred, especially over the past 30-40 years. For example, Santer et al. (2006; see also Gillett et al. 2007) 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 NW Pacific tropical cyclogenesis region (Santer et al. 2006, Gillett et al. 2007; 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^{o}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 likely that increased greenhouse gases have caused a discernible increase in SSTs both the North Atlantic and the NW Pacific tropical storm basins over the past 100 yrs and also for the period since about 1950.

Chapter 2 also concludes that it is likely that there has been an increase in tropical storm/hurricane and major hurricane frequency in the North Atlantic over the past century or so, a time during which tropical Atlantic SSTs also increased. Ongoing efforts to reconstruct a complete record of Atlantic tropical cyclone counts back to 1900 or the late 1800s find evidence (in several analyses) for a statistically significant increasing trend since 1900. The evidence is much less compelling for significant positive trends beginning in the late 1800s, although there is increasing uncertainty in the data as one proceeds further back in time. There has not been a significant trend in U.S. landfalling activity since the late 1880s as the overall impacts of the increasing trend in North Atlantic tropical cyclones appear to have been to some extent ameliorated by concomitant shifts into eastern North Atlantic developments, which are less likely to directly affect US coastal regions.

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 increase 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. We therefore must rely on statistical analyses and expert judgement to make attribution assessments. Further discussion of these issues is contained in section 3.3.9.6 (Reconciliation of Future Projections and Past Variations).

The strong relationship with SST—and particularly the large increase in both tropical cyclone activity (PDI) and SST since 1970, along with the observed increases in tropical storm/hurricane and major hurricane frequency and SSTs over the past century or so—provides evidence in support of a discernible impact of anthropogenic forcing on Atlantic tropical cyclone activity. Although there is evidence both for and against this interpretation (e.g., lack of trend in U.S. landfalling hurricanes), the balance of evidence now suggests that human activity has caused a discernible increase in tropical storm, hurricane and major hurricane frequency. It is more difficult to judge whether anthropogenic forcing will cause further increases in activity as the climate continues to warm, since the precise physical reasons for the relationship have not been fully elucidated. It is noted that relevant anthropogenic forcing includes increasing greenhouse gases, as well as changes in aerosol forcing, and possibly decreasing stratospheric ozone and other factors associated with cooling upper atmospheric (~100mb) temperatures in recent decades (Emanuel 2007a).

This assessment is consistent with the IPCC (2007) conclusion that it is more likely than not that there has been a human contribution to the observed increase in intense tropical cyclone activity. It is further supported by several recent related studies, including Trenberth and Shea (2006), Mann and Emanuel (2006), Santer et al (2006), Elsner (2006), Emanuel (2007a), Gillett et al. (2007), Kossin and Vitmer (2007), Vitmer and Kossin (2007), Vecchi and Knutson (2007), and Holland and Webster (2007a).

3.2.4.3.3 Storm lifetime, Track and Extratropical Transition

There has been insufficient work done on the changes, or otherwise, in these important aspects of tropical cyclones to arrive at any firm conclusions.

3.2.5 Extratropical Storms

Chapter 2 documents changes in strong extratropical storms during the twentieth century, especially for 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 North Atlantic Oscillation (e.g., Lozano and Swail, 2002, Caires and Sterl 2005) or the related Northern Annular Mode (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, 2006; Wang et al 2007), which would have influenced storm activity. There is also some evidence that anthropogenic forcing has affected related variables such as geostrophic wind energy and significant wave height (Wang et al 2007) during the latter half of the 20th century, although as with sea-level pressure change, the model simulated response to forcing is not as large as observed. On the other hand, the WASA Group (1998), using long records of station data, suggest that observed changes in storminess in Northern Europe 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).

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 North Atlantic Oscillation has been recognized (e.g., Neu, 1984; WASA, 1998; Gulev and Grignorieva, 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 Grignorieva, 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. However, Wang et al. (2007) indicate that anthropogenically forced circulation change may have been an important factor in changes of significant wave heights.

A definite control 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 (MEI), showing that while the greatest increase 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 since the amount of moisture in the atmosphere is likely to rise much faster as a consequence of rising temperatures than the total precipitation, this should lead to an increase in the intensity of storms, offset by decreases in duration or frequency of events. Environmental conditions that are most likely associated with severe and tornadic thunderstorms have been derived from reanalysis data (Brooks et al. 2003b). Brooks and Dotzek (2007) 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 m s^{-1}, and/or a tornado of F2 or greater intensity) for the area east of the Rocky Mountains in the US 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 in the broader global context.

3.3.1 Temperature

The IPCC Third Assessment Report concluded there was a very likely risk of increased 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). An ensemble of more recent global simulations projects marked increase in the frequency of very warm daily-temperature minima (Fig. 3.1a). Kharin and Zwiers (2005) show in a single model that future increases in temperature extremes follow increases in mean temperature over most of the world including North America. They 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. They also show that summertime warm temperature extremes increase in regions where the soil dries due to a smaller fraction of surface energy used for evaporation. Furthermore, that study showed that in most instances warm-extreme changes are similar in magnitude to the increases in daily maximum temperature, but cold extremes shift to warmer temperatures faster than daily minimum temperatures, though this result is less consistent when model parameters are varied in a perturbed physics ensemble where there are increased daily temperature maxima for nearly the whole land surface. However, the range in magnitude of increases was substantial indicating a sensitivity to model formulations (Clark et al., 2006).

Events that are rare could become more commonplace. Recent studies using both individual models (Kharin and Zwiers, 2005) and an ensemble of models (Wehner 2006, 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 (Fig. 3.5a), the average reoccurrence time may further reduce to every other year or less (Wehner, 2006).

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) analysed 7 AOGCMs run with the A1B scenario, and defined a cold air outbreak as 2 or more consecutive days when the daily temperatures were at least 2 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 NH 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 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 risk 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). The "Heat Index", a measure of the apparent temperature felt by humans that includes moisture influences, was projected in a GFDL model study 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). 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 Pacific Decadal Oscillation (Strong et al. 2006). 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 symbionts 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 US (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 are expected to decrease (Cubasch et al. 2001). Meehl et al (2004a) 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, Fig. 3.1b). By then end of the 21st century, the number of frost days averaged over North America has decreased by about 1 month in the 3 future scenarios considered here.

In both the models and the observations, the number of frost days is decreasing over the 20th century (Fig. 3.1b). This decrease is generally related to warming climate, although the pattern of the warming and pattern of the frost-days changes (Fig. 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 21st century frost day pattern of change is similar to the 20th century pattern, just much larger in magnitude. In some places by 2100, the number of frost days decrease by more than 2 months.

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

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 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 regions (Meehl et al. 2007a, Fig. 3.1c). The growing season length has increased by about 1 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 2 weeks longer than present day. (For more discussion on the reasons these changes are important, see chapter 1)

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 by the end of the 21st 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), affecting water-resource management and potentially exacerbating the impacts of droughts.

3.3.5 Precipitation

Climate models continue to confirm the earlier results 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., 2005a; Barnett et al., 2006), and the increase of precipitation extremes is greater than changes in mean precipitation (Kharin and Zwiers, 2005). Rare events precipitation events could become more commonplace in North America (Wehner, 2006, Kharin et al. 2007). 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 total precipitation reduces to between 12 and 15 years over much of North America (Kharin, et al 2007). By the end of the century (Fig. 3.5b), the expected average reoccurrence time may further reduce to every six to eight years (Wehner, 2006, Kharin, et al 2007). Note the area of little change in expected average reoccurrence time in the central United States in Fig. 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. This behavior means that for a given increase in temperature, increases in extreme precipitation can be 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 of 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., 2005a). 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 (~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 the 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, in spite of the apparent contradiction.

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 from increased greenhouse gases 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).

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, Fig. 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., 2005a).

There are regions of increased runs of dry days between precipitation events in the subtropics and lower midlatitudes, but a decreased number of consectutive 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).

Associated with the risk of drying is a projected increase in 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., 2005a). 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., 2005a; Räisänen, 2005a; 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).

3.3.7 Drought

A long-standing result 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 risk of drought. The more recent generation of models continues to show this behavior (Burke et al., 2006; Meehl et al., 2006b, 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 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 US and northern Mexico in the future (Fig. 3.6). 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 normal water availability. However, the consensus of most climate models is for a reduction of cool season precipitation across the 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 US and Mexico in the future 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 predict 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 southwest US and northern Mexico (e.g., Meehl and Tebaldi 2007). 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 Laurentian Great Lakes found that surface air temperature increases are likely to be the dominant factor. They examined simulations from 2 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.

Increased temperature suggests that heavy snow events downwind of the Great Lakes will begin later in the season, and on most lakes end earlier. 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 Storms

3.3.9.1 Introduction

In response to future anthropogenic climate warming (IPCC 2001) 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 storm surge flooding from future hurricanes will very likely be enhanced to some degree 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 other CCSP Synthesis and Assessment Products 2-1, 3-2, and 4-1, or IPCC Fourth Assessment Report chapters on climate sensitivity, future emission scenarios, and sea level rise. An assessment of the state of understading of tropical cyclones and climate change as of 2006 has been prepared by the tropical cyclone community (IWTC VI, 2006; section 3.2.4 of this document). Although not published in the literature as yet, the full summary statement and condensed summary are available online at http://www.wmo.ch/web/arep/arep-home.html.

Future projections of hurricanes will depend upon not only on 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 2005a; 2006a, Holland 1997), which depends on sea surface temperatures, 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 Clarke 1980, Pasch et al 1998, Thorncroft and Hodges 2001).

Details of future projections in regions remote from the tropical storm basin in question may also be important. For example, El Nino fluctuations in the Pacific influence Atlantic basin hurricane activity (Chapter 2, Section 3.2 of this chapter). West African monsoon activity has been correlated with Atlantic hurricane activity (Gray 1990), as have African dust outbreaks (Evans 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 storm-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; 2007) have provided additional model-based evidence to support these theoretical assessments. For a CO_2-induced tropical SST warming of 1.75C, they found a 14% increase in central pressure fall (Fig. 3.7) and a 6% increase in maximum surface wind or a maximum wind speed sensitivity of about 4% per degree Celsius (Knutson and Tuleya 2007). 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/sec. 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 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). Bengtsson et al. (2007) also find a slightly reduced tropical storm 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 relative high model resolution (~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 AR4, 2007) climate models (Fig. 3.8). 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 storm 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 modelled in detail, although existing global modelling studies (Oouchi et al. 2006; Bengtsson et al. 2007) suggest increases in the intensities and frequencies of the strongest storms. In the Eastern Pacific, the potential intensity is predicted to increase across the entire basin, although the vertical wind shear increases may counteract this to some extent.

A more recent idealized calculation by Emanuel et al. (2006) finds that artificially increasing the modelled potential intensity by 10% leads to a marked increase in the occurrence rate of relatively intense hurricanes (Fig. 3.9a), 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 (Fig. 3.9b) 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.

In summary, theory and high-resolution idealized models indicate increasing intensity and frequency of the strongest hurricanes/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 is 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 change (in terms of maximum surface winds) to be +2% to +10% per degree Celsius tropical sea surface warming over most tropical storm regions. This range is based on our subjective judgement that the likely range is from about half to twice the sensitivity found in current hurricane models and theory. Furthermore, the balance of 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 2007a) 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 Nino events. During El Nino 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 storm counts during the past century (Holland and Webster 2007a; Vecchi and Knutson 2007), 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 2007; 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 CO2 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 storm-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; Carmargo et al. 2005; Vitart and Anderson 2001). A recent regional model dynamical downscaling study (Knutson et al. 2007) with an18 km grid model, and a more idealized modelling approach (Emanuel et al. 2007) 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 storms are relatively rare events and can exhibit large interannual to interdecadal variability, large samples 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, the higher resolution ones 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 storms 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 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) did 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. (2007) 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 these 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.

From the above summarized results, it is not clear that current models provide a confident assessment of even the sign of change of tropical storm frequency in the Atlantic, East Pacific, or Northwest Pacific basins. From an observational perspective, recent studies (Chapter 2) 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 (~1950-2006).

3.3.9.4 Tropical Cyclone Precipitation

The notion the 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 like 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 CO2 conditions has been simulated, for example, by Knutson and Tuleya (2004, 2007) 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 (Fig. 3.10), 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 modelling studies as they are of course 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 U.S. (although not established observationally for hurricane-related rainfall (Groismann et al. 2004)) we assess the projections that hurricane related rainfall (per storm) will increase in the 21st century as likely. 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 sea surface temperature.

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.

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 NW 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 (2006b) 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 NE 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.

An important question for regions along the periphery of tropical cyclone basins is whether regions with have never or only infrequently experienced tropical cyclones in recorded history may experience them more frequently in the future owing to climate change. Little guidance is available at present on this important question.

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 the potential for storm surge damage (per hurricane) is very likely to increase.

In summary, tropical cyclone size, duration, track and regions of occurrence are important questions that need to be addressed. However, based on available published work and previous assessments, it is unknown how these will change in the future (IWTC-VI 2006). Storm surge damage (per hurricane) is likely to rise.

3.3.9.6 Reconciliation of Future Projections and Past Variations

In this section, we attempt to reconcile the future projections discussed above with the past observed variations in TC activity. The balance of evidence suggests that human activity has caused a discernible increase in tropical storm/hurricane and major hurricane frequency in the North Atlantic. U.S. landfalling hurricane frequency has not increased. However, it is more difficult to judge whether anthropogenic forcing will cause further increases in basin-wide activity as the climate continues to warm, since the precise physical reasons for the observed increases have not been fully elucidated. It is noted that relevant anthropogenic forcing includes increasing greenhouse gases, as well as changes in aerosol forcing, and possibly decreasing stratospheric ozone and other factors associated with cooling upper atmospheric (~100mb) temperatures in recent decades (Emanuel 2007a). 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.

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., Ch. 2). In fact the 20th century behavior in TC frequency has not yet been documented for existing models. One exception is Bengtsson et al. (2007) who simulate little change in tropical storm frequencies comparing the late 1800s and late 1900s. Given the future regional climate projections arising from the models, including the multi-model consensus increase of vertical wind shear in the IPCC AR4 models (Vecchi and Soden 2007), the substantial variability among existing models of such projected characteristics as Atlantic vertical wind shear and the differing mixtures of climate forcings that may be relevant in the two periods, we anticipate that it would be difficult to confidently extrapolate the strong increasing trend in 20th century storm counts using future consensus projections available from existing models. Nonetheless, a significant trend (or anthropogenic signal, whether trend-like or not) detected in observed tropical cyclone activity and attributed to increasing greenhouse gases could imply that a future increase in tropical cyclone frequency in the Atlantic is 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 (Fig. 3.11; 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 twentieth century (Paciorek et al. 2002). More frequent strong storms may reduce the frequency of all 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 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 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 (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 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 Northern Annular mode (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 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., 2007).

3.3.11 Convective Storms

Conclusions about possible changes in convective precipitating storms (CPSs) 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. 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 both 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.

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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

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

Reference	Model	Resolution	Experiment	Global	N Atlantic	NW Pacific	NE Pacific
Sugi et al. 2002	JMA timeslice	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 timeslice	N144 L30 (~100km)	15y IS95a 1979-1994 2082-2097	*94*	*75*	*70*	**180**
Hasegawa and Emori 2005	CCSR/NIES /FRCGC timeslice	T106 L56 (~120km)	5x20y at 1xCO_2 7x20y at 2xCO_2			96	
Yoshimura et al. 2006	JMA timeslice	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 timeslice	TL959 L60 (~20km)	10y A1B 1982-1993	*70*	**134**	*62*	*66*

			2080-2099				
Chauvin et al. 2006	ARPEGE-Climat 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 storms in the future simulation

Italic = significantly *fewer* tropical storms in the future simulation

Plain text = not significant or significance level not tested

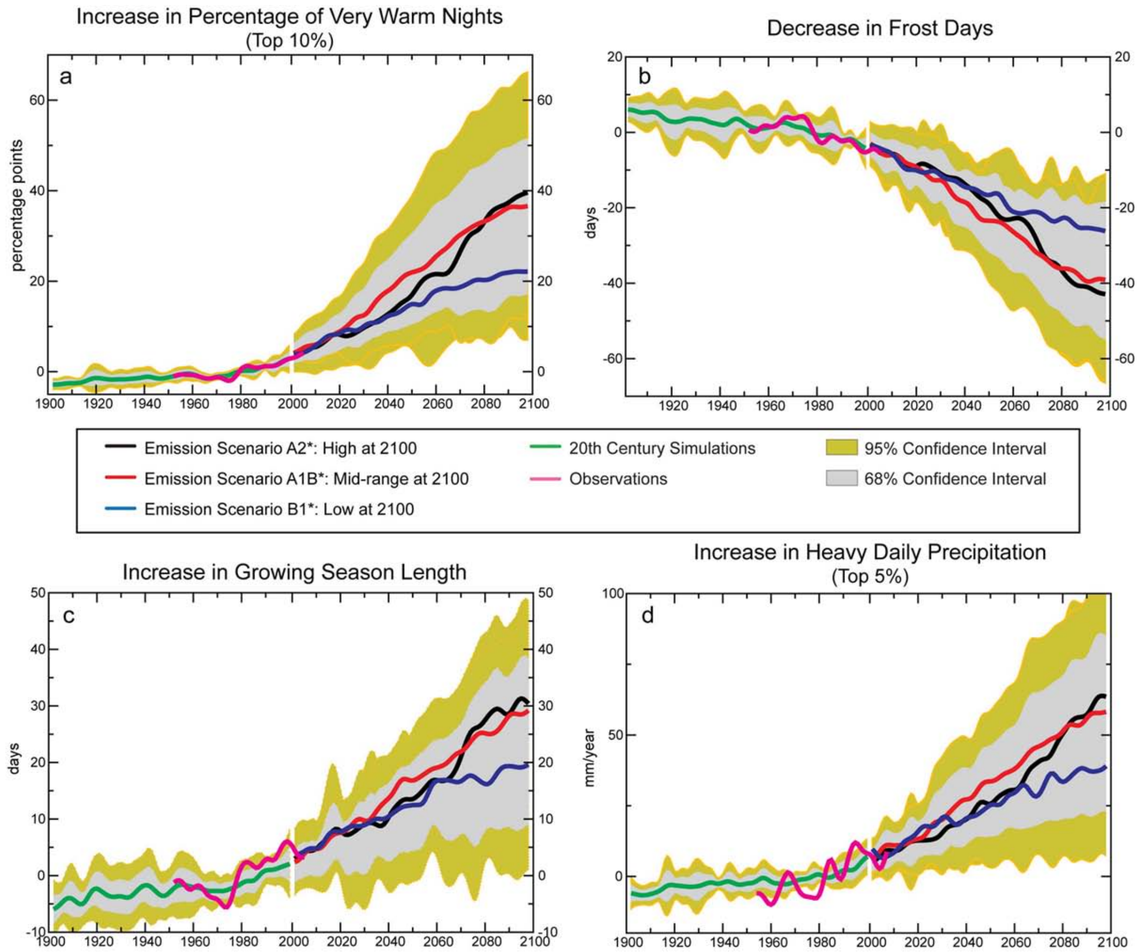

Figure 3.1 Indices (Frich et al. ,2002) averaged over North America for model simulations and observations for the 20th and 21st centuries showing changes relative to 1961-1990 in the a) percentage of days in a year for which daily low temperature is in the top 10% of warm nights for the period 1961-1990, 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 1-σ and 2-σ bounds 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. (2007).

*3 future emission scenarios from the IPCC Special Report on Emissions Scenarios:
B1 blue line: emissions increase very slowly for a few more decades, then level off and decline
A2 black line: emissions continue to increase rapidly and steadily throughout this century
A1B red line: emissions increase rapidly until 2050 and then decline.
There are more details on these emission scenarios in the glossary.

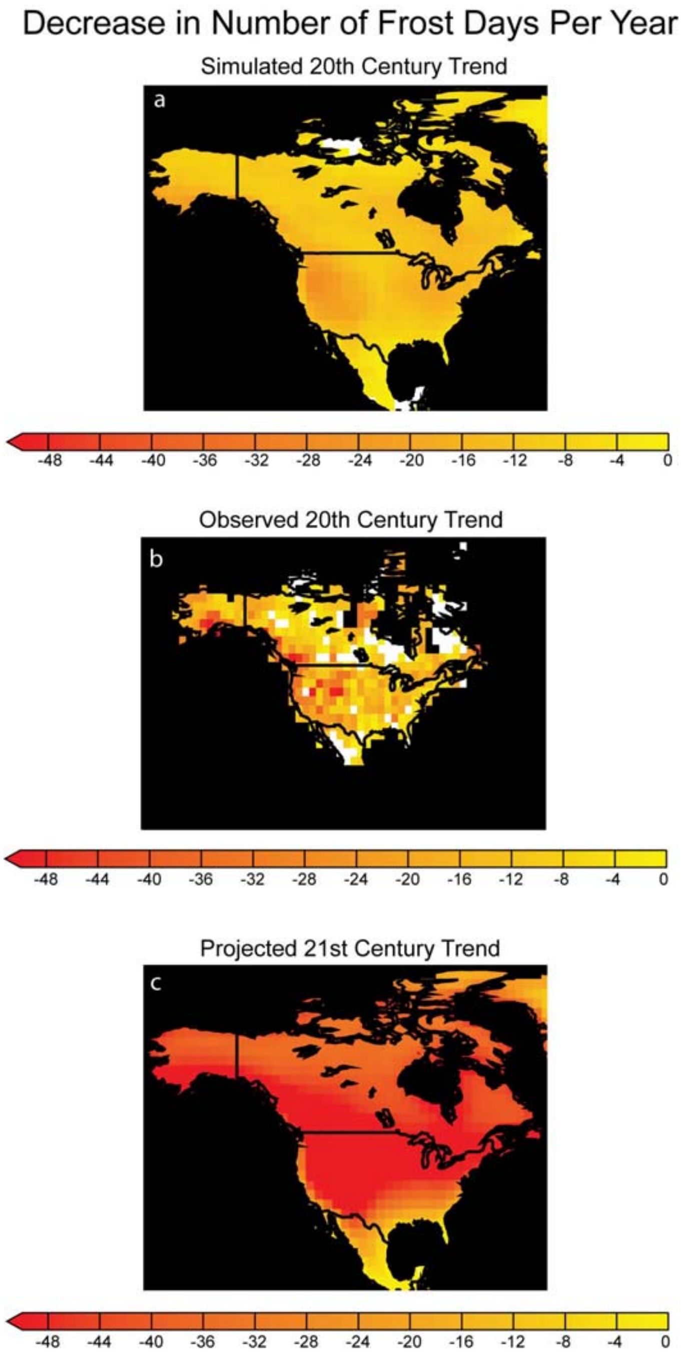

Figure 3.2 Indices (Frich et al., 2002) for frost days over North America for model simulations and observations: a) 20th century trend for model ensemble, b) Observed 20th century trend and c) 21st century trend for emission scenario A2 from model ensemble. The model plots are obtained from the CMIP-3 multi-model data set at PCMDI and the observations are from Peterson et al. (2007).

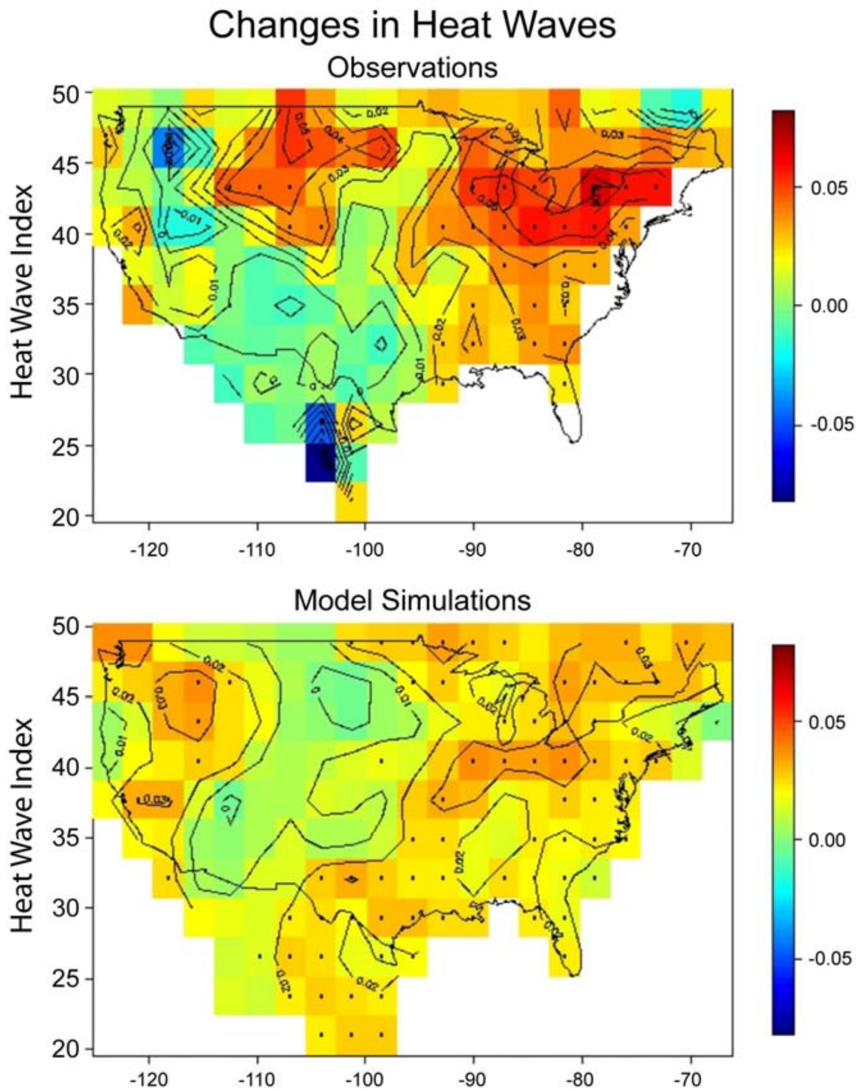

Figure 3.3 Trends in the Karl-Knight heat-wave index (Karl and Knight, 1997) for 1961-1990 in observations (top panel) and in an ensemble of climate simulations by the Parallel Climate Model (bottom panel). Dots mark trends that are significant at the 95% level.

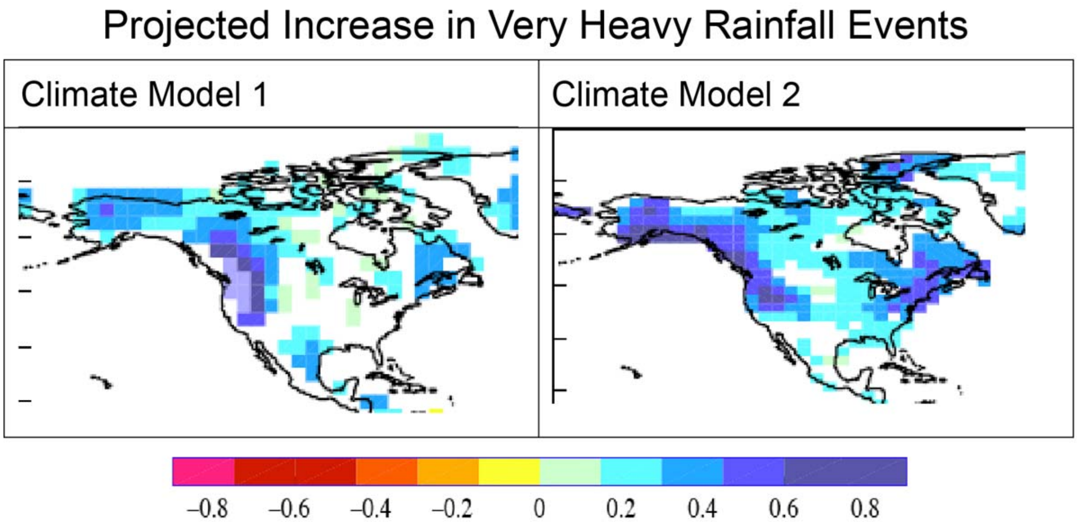

Figure 3.4 Comparison between regions with disproportionate trends in the number of exceedances of the heaviest rainfall events (99.7th percentile) in two climate models at the time of CO2 doubling. See figure 2.8 for areas of N. America which show observed increases in very heavy rainfall Model 1 is the CGCM2 and model 2 is the HadCM3. After Groisman et al. (2005).

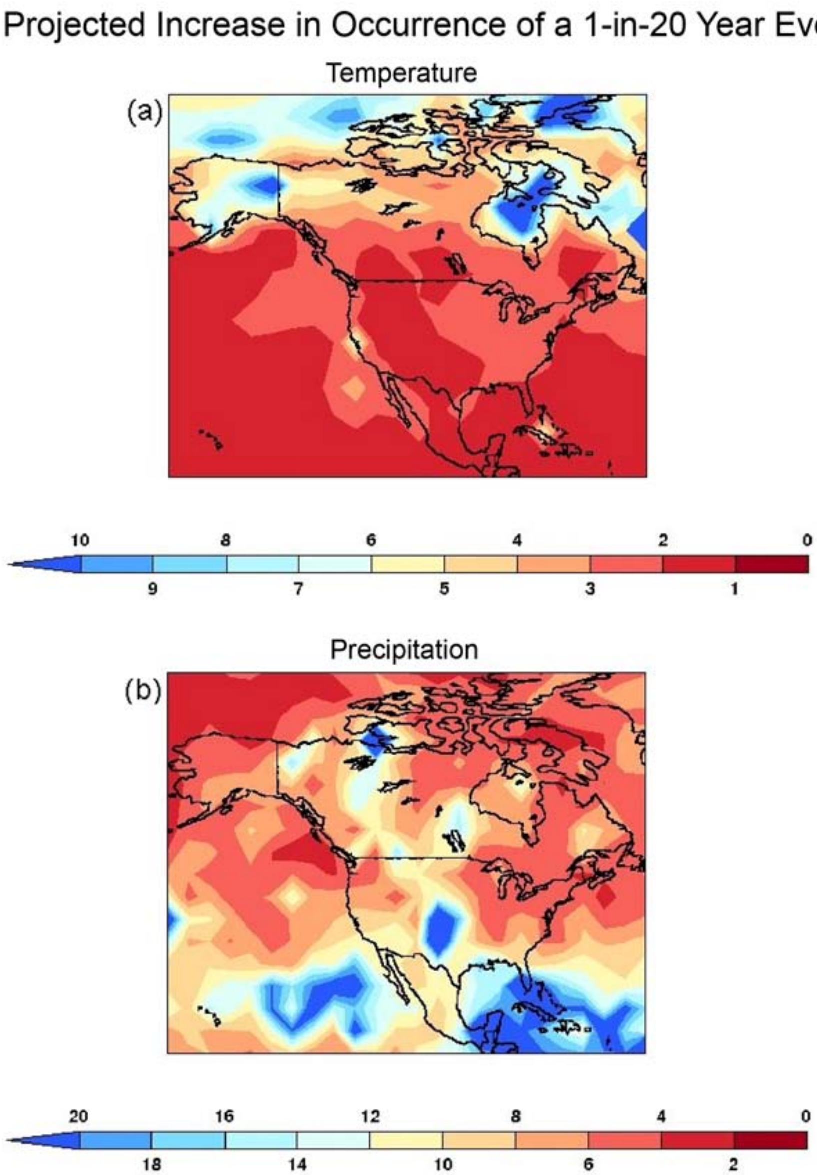

Figure 3.5 Simulations for 2090-2099 indicating how currently rare extremes (a 1-in-20-year event) are projected to become more commonplace. a) Temperature - a day so hot that it is currently experienced once every 20 years would occur every other year or more by the end of the century, (b) daily total precipitation events that occur on average every 20 years in the present climate would, for example, occur once in every 4-6 years for N.E. North America. These results are based on a multi-model ensemble of global climate models simulating the midrange A1B emission scenario*. (from Wehner 2005). [units: years].

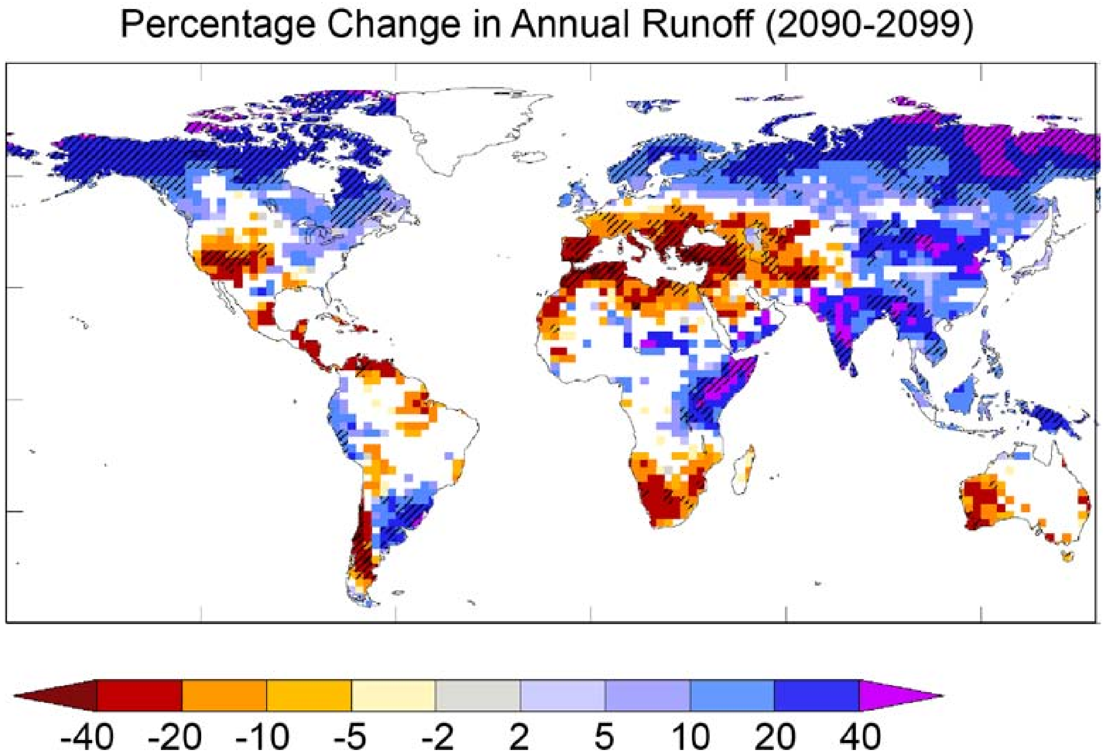

Figure 3.6 Change in annual runoff (%) for the period 2090-2099, relative to 1980-1999. Values are obtained from the median in a multi-model dataset that used the A1B emission scenario. White areas are where less than 66% of the models agree in the sign of change and stippled areas are where more than 90% models agree in the sign of change. [Derived from the analysis of Milly et al. (2005)]

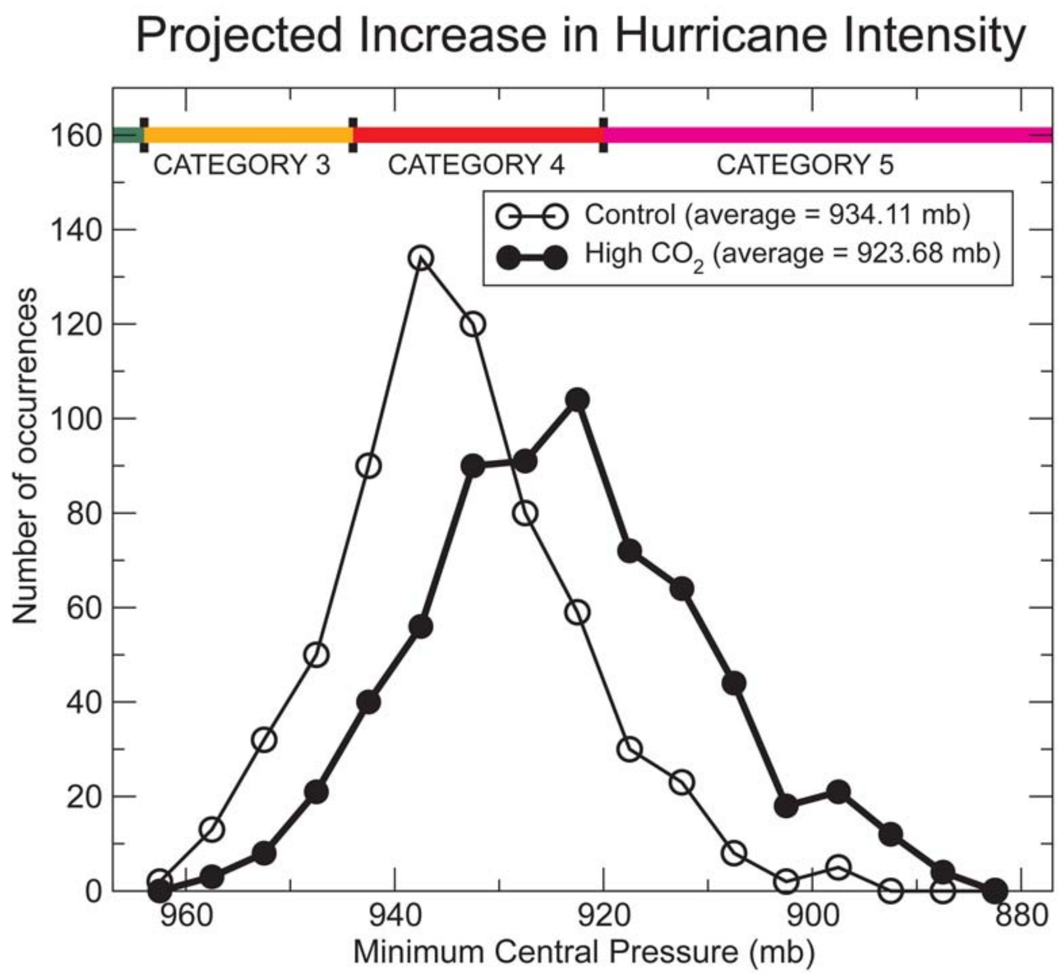

Figure 3.7 Frequency histograms of hurricane intensities in terms of central pressure (mb) aggregated across all idealized hurricane experiments in the Knutson and Tuleya (2004) study. The light curve shows the histogram from the experiments with present-day conditions, while the dark curve is for high CO_2 conditions (after an 80 yr warming trend in a +1%/yr 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.

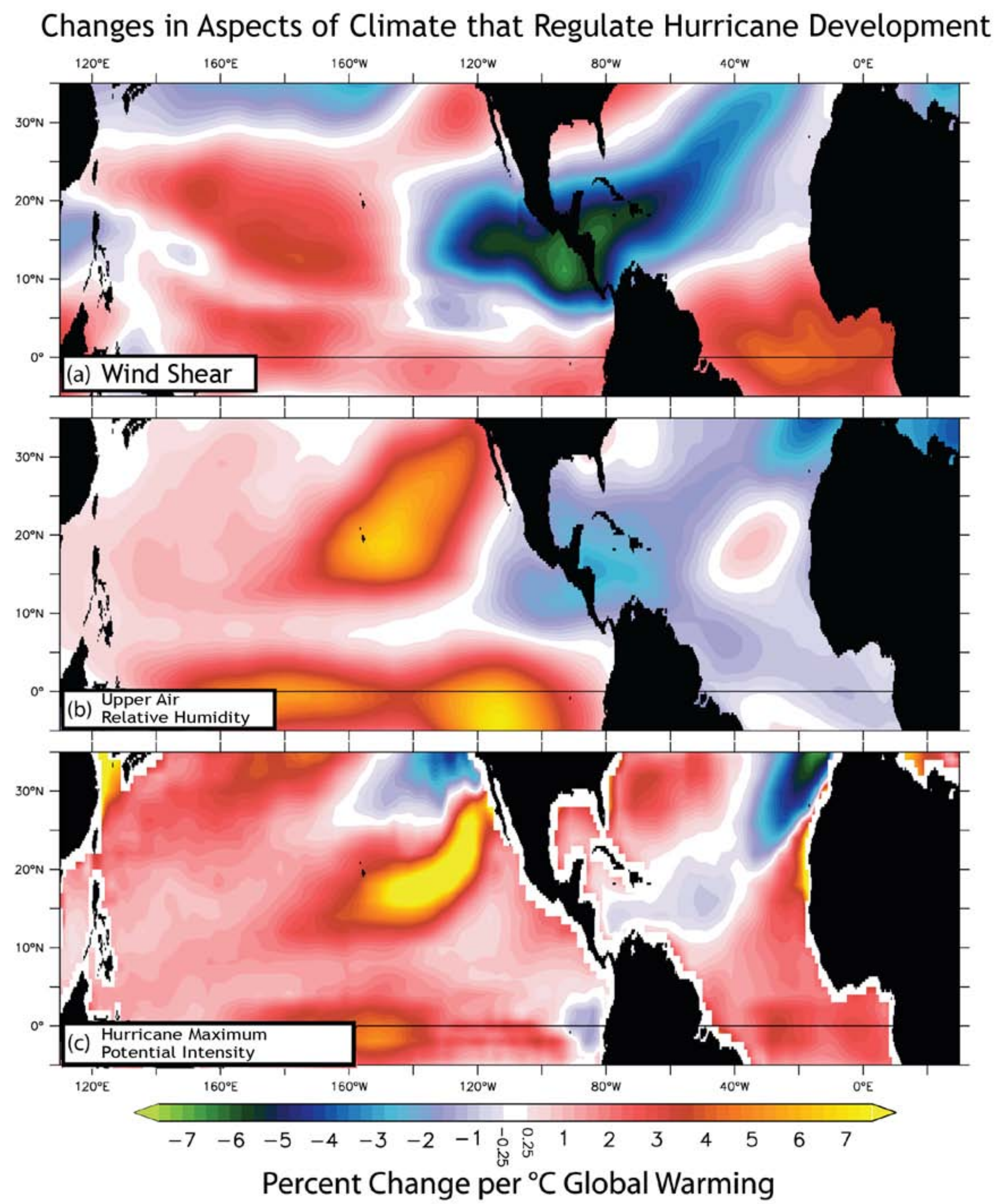

Figure 3.8 Percent changes in June-November ensemble mean a) vertical wind shear, b) mid-tropospheric relative humidity, and c) maximum potential intensity of tropical cyclones for the period 2081-2100 minus the period 2001-2021 for an ensemble of 18

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. From Vecchi and Soden (2007).

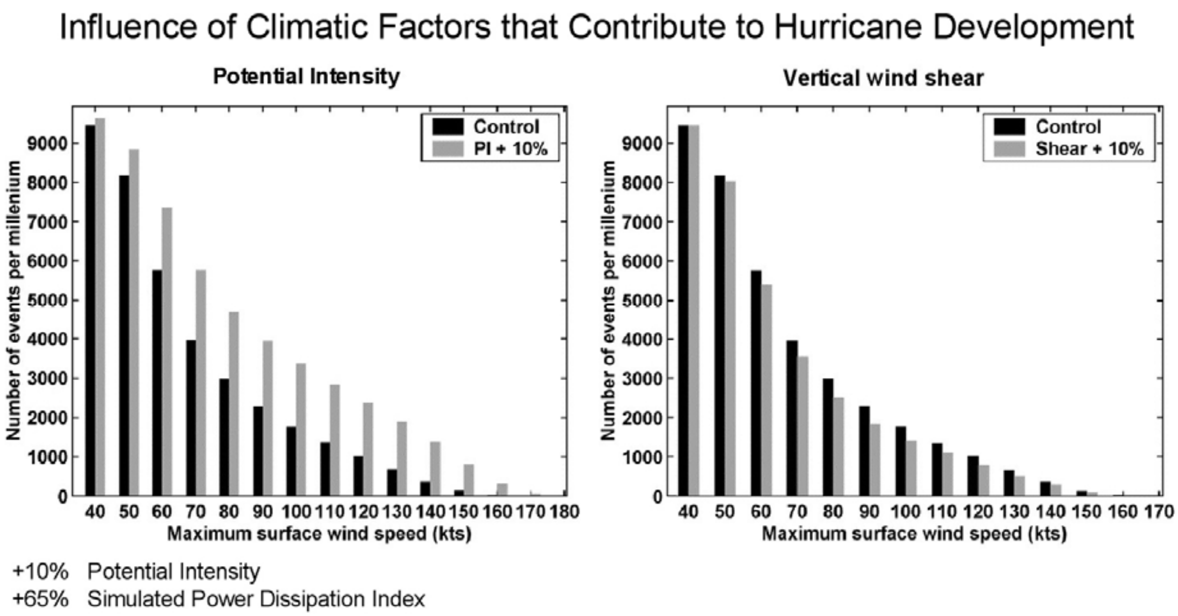

Figure 3.9 Number of events per 1000 yrs with peak wind speeds exceeding the value on the x-axis. Results obtained by running a simple coupled hurricane intensity prediction model over a set of 3000 synthetic storm tracks for the North Atlantic. The grey bars depict storms for present day climate conditions. 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).

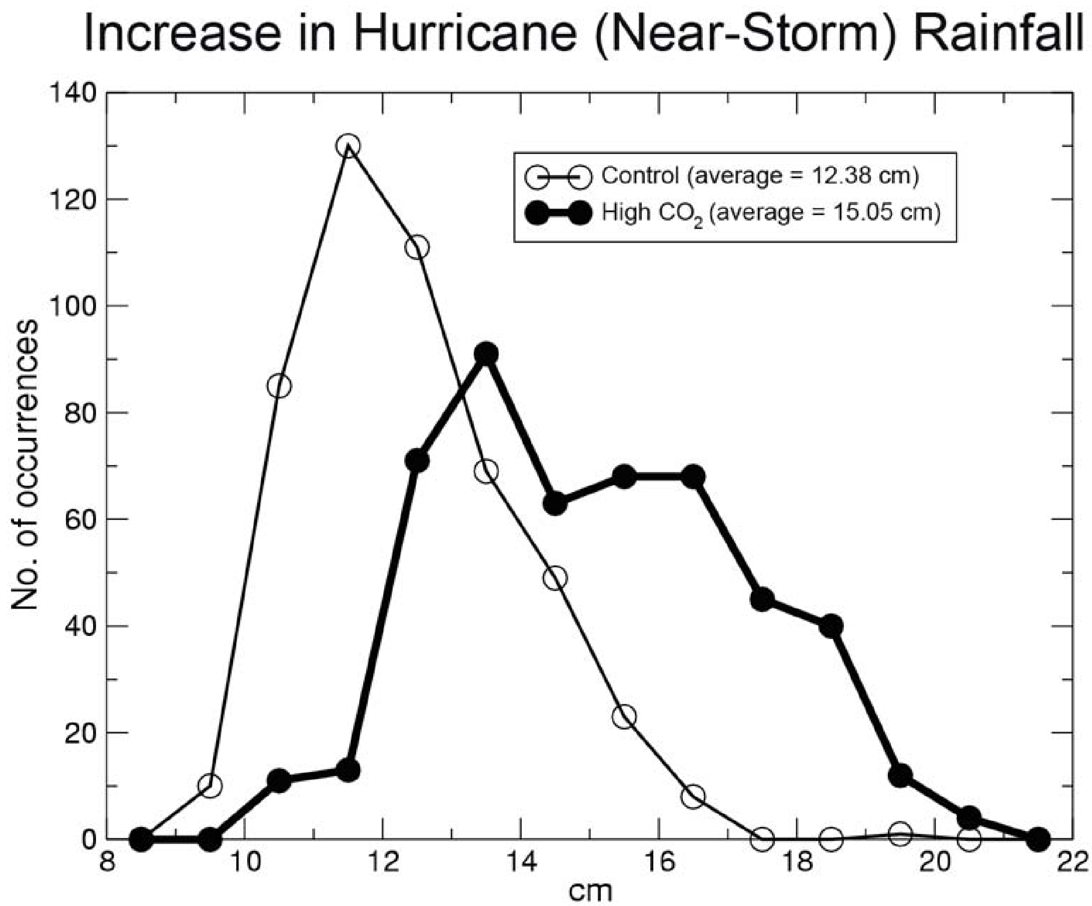

Figure 3.10 As in Fig. 3.7, but for near-hurricane precipitation, estimated as the average precipitation rate for the 102 model grid points (32,700 km^2 area) with highest accumulated rainfall over the last 6 hours of the 5-day idealized hurricane experiments in Knutson and Tuleya (2004). The results indicate that hurricanes in a CO2-warmed climate will have substantially higher core rainfall rates than those in the present climate. (From Knutson and Tuleya, 2007).

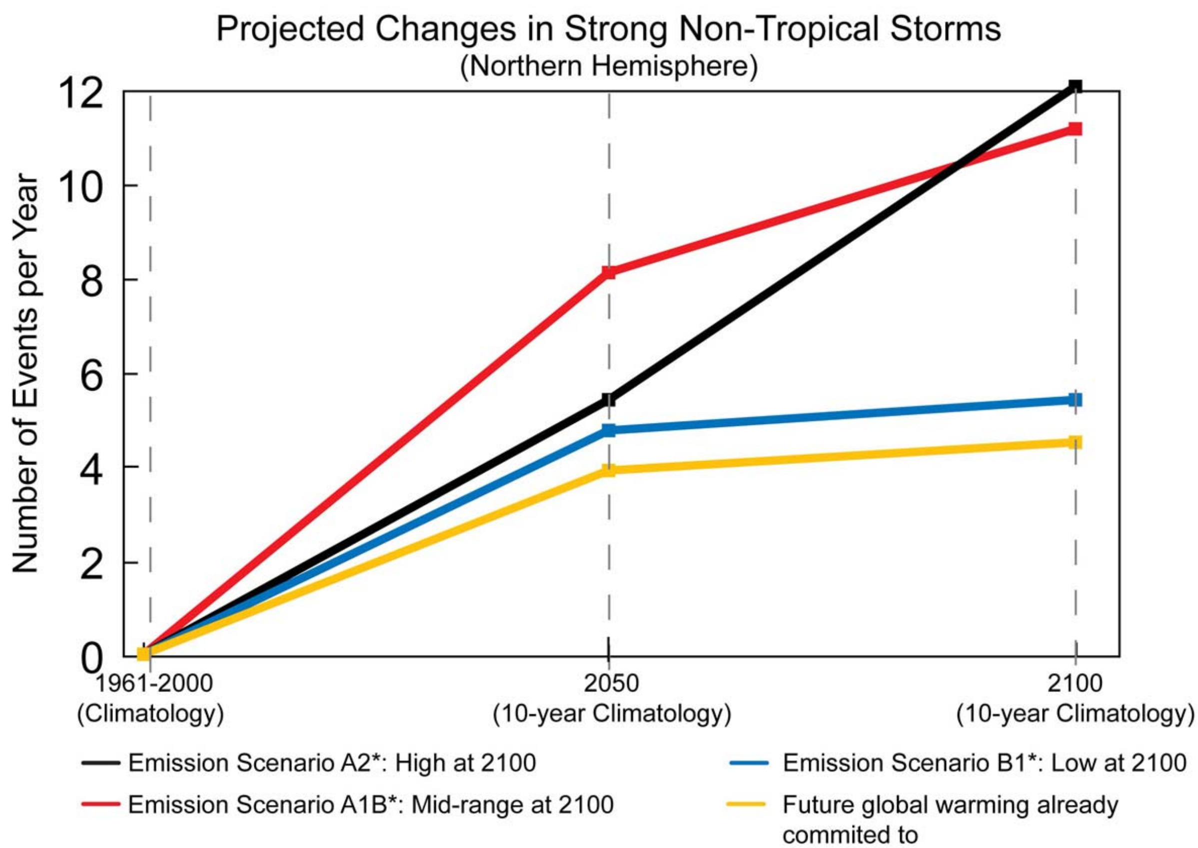

Figure 3.11 The projected change in intense low pressure systems (strong storms) during the cold season for the Northern Hemisphere for various emission scenarios* (adapted from Lambert and Fyfe; 2006). Storms counted have central pressures less than 970 mb and occur poleward of 30˚N during 120-day season starting November 15. Adapted from Lambert and Fyfe (2006).