

# Trends in Extreme Weather and Climate Events: Issues Related to Modeling Extremes in Projections of Future Climate Change\*



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## ABSTRACT

Projections of statistical aspects of weather and climate extremes can be derived from climate models representing possible future climate states. Some of the recent models have reproduced results previously reported in the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report, such as a greater frequency of extreme warm days and lower frequency of extreme cold days associated with a warmer mean climate, a decrease in diurnal temperature range associated with higher nighttime temperatures, increased precipitation intensity, midcontinent summer drying, decreasing daily variability of surface temperature in winter, and increasing variability of northern midlatitude summer surface temperatures. This reconfirmation of previous results gives an increased confidence in the credibility of the models, though agreement among models does not guarantee those changes will occur. New results since the IPCC Second Assessment Report indicate a possible increase of extreme heat stress events in a warmer climate, an increase of cooling degree days and decrease in heating degree days, an increase of precipitation extremes such that there is a decrease in return periods for 20-yr extreme precipitation events, and more detailed analyses of possible changes in 20-yr return values for extreme maximum and minimum temperatures. Additionally, recent studies are now addressing interannual and synoptic time and space scale processes that affect weather and climate extremes, such as tropical cyclones, El Niño effects, and extratropical storms. However, current climate models are not yet in agreement with respect to possible future changes in such features.

## 1. Introduction

As part of the series of papers in this issue looking at various aspects of weather and climate extremes, the purpose of this paper is to summarize the state of our

knowledge of possible future changes in the statistical aspects of weather and climate extremes. A definition and conceptual discussion of such extremes is given in the introductory paper in this series (Meehl et al. 2000). Possible future changes of weather and climate extremes are derived by comparing climate model simulations of naturally occurring climate variability to future simulated climate states with atmospheric constituents affected by human activity (e.g., increased greenhouse gases, sulfate aerosols, etc.). We will delineate recent model studies that have reconfirmed results reported in the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (Houghton et al. 1996), and identify new results that have emerged since the publication of that report.

The focus of earlier climate model studies of global warming was mainly on changes in mean climate (e.g., Houghton et al. 1990). It has been only since the early 1990s that climate models have started to be analyzed to study possible changes of future weather and

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climate extremes (Houghton et al. 1996). The last several years have seen even more of these types of studies as the models have improved enough to at least begin to look at such higher-order features in more detail. This is a product of the rapid development of climate modeling capabilities over the past 10 years, in concert with increased computer resources. The current generation of global coupled climate models have improved resolution (grid points typically every 2.5° of latitude and longitude), more detailed and accurate land surface simulation schemes, and dynamical sea ice formulations. Some have even higher resolution in the ocean near the equator (leading to improved simulations of El Niño). These changes are coupled with improved techniques to study climate changes and climate processes at smaller regional scales from general circulation model (GCM) results through either embedding high-resolution regional models (with grid points every 50 km or so) in the global models or statistical downscaling techniques. Consequently, possible future changes of extreme climate and weather events in these models are a current focus of the IPCC Third Assessment Report, which is slated to be published in early 2001.

Though the models have improved over time, they still have limitations in terms of spatial resolution, simulation errors, and parameterizations that must represent processes that cannot yet be included explicitly in the models, particularly dealing with clouds and precipitation. Thus we have varying degrees of confidence in many of the quantitative aspects of the model simulations. However, the models are able to qualitatively reproduce many of the features of the observed climate system not only in terms of means but also naturally occurring variability (Tett et al. 1997). Coupled models appear to be producing increasingly realistic simulations of the climate changes that already have been observed in the twentieth century. For example, a recent global climate model study finds that greenhouse gases, sulfate aerosols, and solar variability may have all played important roles in twentieth century climate change (Tett et al. 1999). Paleoclimate simulations with the same models used for projecting future climate changes indicate that many of the features of past climates also can be simulated (Gates et al. 1996). Thus we have increasing confidence that today's climate models can provide plausible first-order projections of changes that could occur in a future climate altered by human activity.

Since the publication of the IPCC Second Assessment Report in early 1996, subsequent modeling stud-

ies have reproduced a number of the model results reported in that report. For example, an increase in mean temperatures leads to more extreme high temperatures and less extreme low temperatures. Nighttime low temperatures in many regions increase more than daytime highs, thus reducing the diurnal temperature range. Decreased daily variability of temperature in winter and increased variability in summer in Northern Hemisphere midlatitude areas significantly modify changes in extremes. Increased moisture content in many regions contributes to increased precipitation intensity. There is a general drying of the mid-continental areas during summer with increased chance of drought, and this is ascribed to a combination of increased temperature and evaporation along with decreased precipitation.

This paper is organized to address possible changes of extremes phenomenologically. In subsequent sections we will note the more recent studies that reproduce the previous results, and will identify new results regarding possible future changes of weather and climate extremes in a warmer climate.

## 2. Temperature

One of the earlier results pertaining to changes of temperature extremes was that higher mean temperatures increase the probability of extreme warm days and decrease the probability of extreme cold days (e.g., listed as a "probable projection" by Mahlman 1997) unless a compensating decrease in standard deviation or skewness occurs. This result has been reconfirmed by more recent studies. For example, a high-resolution regional model over southeastern Australia nested in a global model run under a transient enhanced greenhouse scenario shows that the frequency of minimum temperatures below freezing was roughly halved when the mean minimum temperature increased by nearly 2°C (Hennessy et al. 1998). Increases in minimum temperature have appeared consistently in a number of different climate models and also are associated with an observed decrease in diurnal temperature range in some areas (Karl and Knight 1998).

New aspects of temperature extreme changes have been explored with more detailed statistical analyses of climate model experiments. For example, the pattern of change in return values of 20-yr extreme temperature events from an equilibrium simulation for doubled CO<sub>2</sub> with a global atmospheric model coupled to a nondynamic slab ocean shows moderate increases

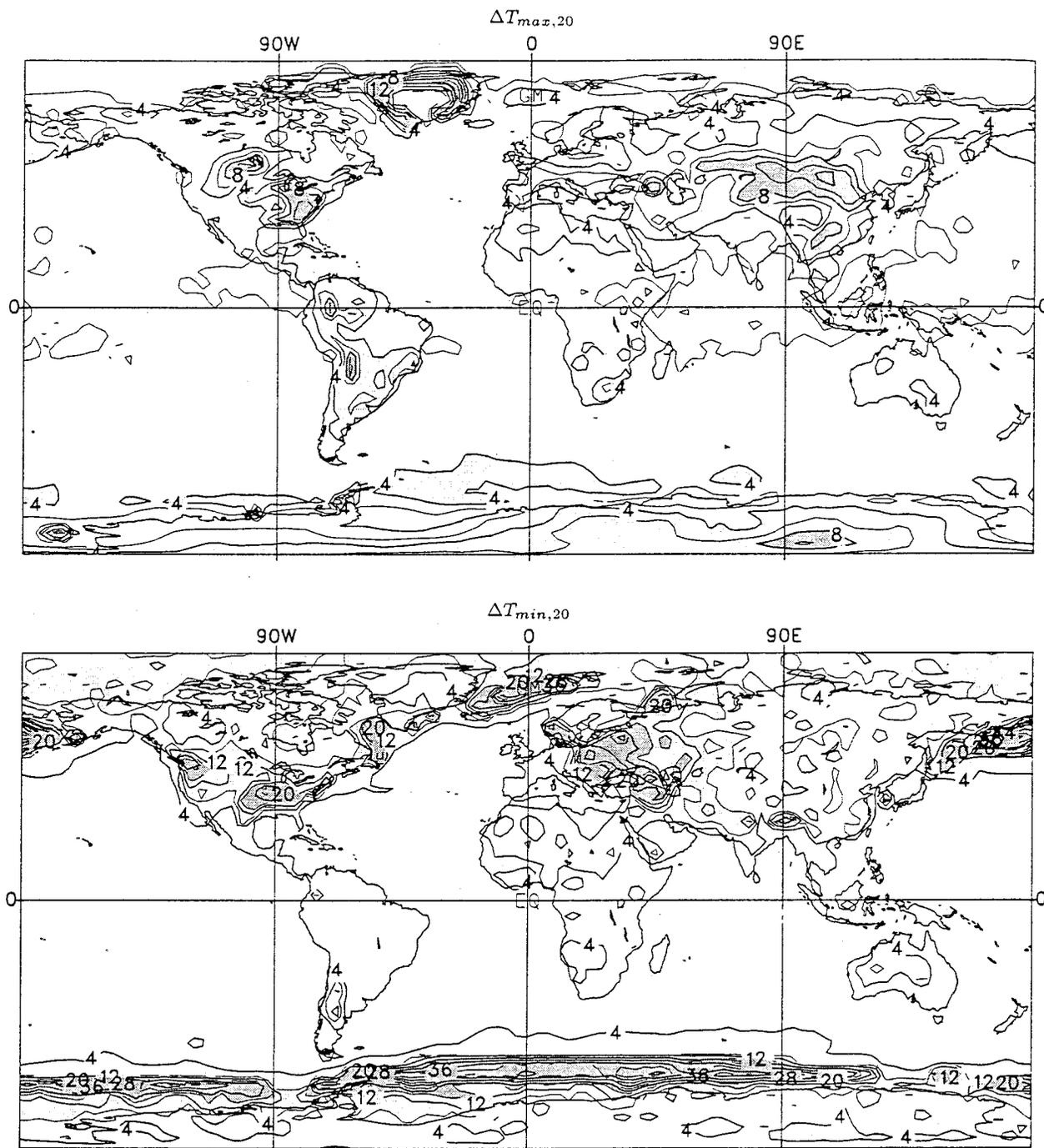


FIG. 1. The change in 20-yr return values for extreme daily maximum (upper panel) and minimum (lower panel) surface air temperature (or screen temperature) for the equilibrium response to a doubling of  $\text{CO}_2$  in a global atmospheric model coupled to a slab ocean (from Zwiers and Kharin 1998). Contour interval is  $2^\circ\text{C}$  in top panel and  $4^\circ\text{C}$  in lower panel. Light (dark) shading indicates regions in which the 20-yr return value has increased by at least  $4^\circ\text{C}$  ( $8^\circ\text{C}$ ) for maxima, and at least  $8^\circ\text{C}$  ( $16^\circ\text{C}$ ) for minima.

over oceans and larger increases over landmasses (Fig. 1; Zwiers and Kharin 1998). The greatest change in the 20-yr return values of daily maximum temperature (Fig. 1a) is found in central and southeast North America, central and southeast Asia, and tropical Af-

rica where there is a decrease in soil moisture content. Large extreme temperature increases also are seen over the dry surface of north Africa. In contrast, the west coast of North America is affected by increased precipitation resulting in moister soil and more moder-

ate increases in extreme temperature. There are small areas of decrease in the Labrador Sea and Southern Ocean that are associated with changes in ocean circulation.

The changes in the return values of daily minimum temperature (Fig. 1b) are larger than those of daily maximum temperature over land areas and high-latitude oceans where snow and ice retreat. Somewhat larger changes are found over landmasses and the Arctic, while smaller increases in extreme minimum temperatures occur at the margins of the polar oceans. Thus, there is some asymmetry between the change in the extremes of minimum and maximum temperature (with a bigger increase for minima than maxima). This has to do with the change in the nature of the contact between atmosphere and the surface (e.g., minima increase sharply where ice and snow cover have retreated exposing either ocean or land; maxima increase more where the land surface has dried).

Increased temperature variance adds to the probability of extreme high-temperature events over and above simply what could be expected from increases of mean alone. Simulations suggest that both mean and variance are likely to change with a changed climate, and the relative contribution of the mean and variance changes depends on how much each moment changes. Earlier studies showed increased variance of daily temperature in summer in northern midcontinental areas in regional model experiments (Mearns et al. 1995), in global models (Gregory and Mitchell 1995), and also in the more recent global model noted previously in Fig. 1 (Zwiers and Kharin 1998).

The change in the mean is usually larger than the change in variance for most climate change simulations. This was the case in the Australian example cited above. However, the change in variance provides important further modifications. For example, a recent regional climate change experiment shows that the change in the mean may increase the probability of extreme warm days in Iowa by an order of magnitude; accounting for the change in variance further increases the probability (Giorgi et al. 1998).

Another recent model study shows an increase of about 5°C in a July mean "heat index" (a measure that includes both the effects of temperature and moisture) over the southeastern United States by the year 2050 (Delworth et al. 1999). An upward trend in the frequency of extreme heat stress events over the eastern United States has been reported in the observations (Gaffen and Ross 1998). Changes in the heating and cooling degree days are another likely extreme temperature-related effect of future greenhouse warming.

For example, a recent analysis of these measures in one global climate model shows a decrease in heating degree days for Canada and an increase in cooling degree days in the southwest United States in a future climate with increased greenhouse gases (Zwiers and Kharin 1998).

Earlier climate models also projected decreased variability of daily temperature in winter in northern temperate midcontinental regions (Mearns et al. 1995; Gregory and Mitchell 1995). Such a decrease would further reduce cold extremes, as noted previously, which are primarily reduced by the increased mean of the daily minimum temperature.

### 3. Precipitation

Increased precipitation intensity (albeit with certain regional variations) in a future climate with increased greenhouse gases was one of the earliest model results regarding precipitation extremes, and remains a consistent result with improved, more detailed models (Kothavala 1997; Hennessy et al. 1997; Durman et al. 2000, unpublished manuscript). There are also some indications from observations that such changes of precipitation intensity are already being seen in some regions (Karl and Knight 1998). There have been questions regarding the relatively coarse spatial scale resolution in climate models being able to represent essentially mesoscale and smaller precipitation processes. However, the globally averaged increase in moisture capacity of a warmer atmosphere is physically consistent with increases in precipitation and, potentially, with increases of precipitation rate in some regions.

It has been recognized recently that changes in precipitation intensity could have a geographical dependence. For example, Bhaskharan and Mitchell (1998) note that range of precipitation intensity over the south Asian monsoon region broadens in a future climate experiment with increased greenhouse gases, with decreases prevalent in the west and increases more widespread in the east. Increases in extreme precipitation events recently have been projected in nested regional models over Australia (Hennessy et al. 1998) and the United States (Giorgi et al. 1998), and in a high-resolution nested hurricane model over the northwest tropical Pacific (Knutson and Tuleya 1999). In a recent global model simulation with doubled CO<sub>2</sub>, precipitation extremes increase more than the mean (the mean increase is 4%; 20-yr extreme precipitation

event return values increase 11%) with a consequent decrease in return period for the 20-yr extreme precipitation events almost everywhere (e.g., to 10 years over North America; Zwiers and Kharin 1998).

Earlier modeling studies indicated increased year-to-year seasonal precipitation variability for the Indian monsoon in a warmer climate (Meehl and Washington 1993). This result also has been noted in more recent studies (Kitoh et al. 1997). Although changes in future mean Indian monsoon strength depend on the details of the forcing scenario and model, a change in interannual variability has implications for increasing the likelihood of drought and flood during the monsoon season. There are also implications for tropical cyclone activity in the Asia–Pacific region.

Another long-standing model result regarding drought (a general drying of the midcontinental areas during summer with increasing CO<sub>2</sub>) has been reproduced with the latest generation of global coupled climate models (Haywood et al. 1997; Wetherald and Manabe 1999). This increased chance of drought during summer generally is attributed to a combination of increased temperature and evaporation along with decreased precipitation. To more quantitatively address this problem, a recent global climate model with increased CO<sub>2</sub> was analyzed to show large increases in frequency of low summer precipitation, the probability of dry soil, and the occurrence of long dry spells (Gregory et al. 1997). The latter was ascribed to the reduction of rainfall events in the model rather than to decreases in mean precipitation.

#### 4. Extratropical storms

Storms have severe impacts associated with extremes of temperature, precipitation, wind, and waves. However, because of limitations in previous generations of global climate models, until recently there have been few studies of future changes in the frequency, location, and strength of extratropical storms. With the improved recent generation of global climate models, such studies are now becoming more credible, but results are still mixed. An analysis of an ensemble of four future climate change experiments in a global coupled model with increased CO<sub>2</sub> and sulfate aerosols showed a decrease in the total number of Northern Hemisphere storms, but an increase in the number of the most intense storms (Fig. 2; Carnell and Senior 1998). This is consistent with results found in the Southern Hemisphere for midlatitude cyclones off the

east coast of Australia (Katzfey and McInnes 1996). A storm track analysis of a GCM with doubled CO<sub>2</sub> indicates a northeastward shift of storm frequency in the North Atlantic, with little change in storm intensities (Schubert et al. 1998), though another study found a reduction of intensity (Beersma et al. 1997), and still another found an increase (Lunkeit et al. 1996). An increase in upper-air storm track activity (with implied increases in extremes associated with the greater number of storms) over the east Atlantic and western Europe with rising greenhouse gas forcing has been related to a change in the North Atlantic oscillation (Ulbrich and Christoph 1999). Longer time series from models have made the statistics more robust (e.g., Carnell and Senior 1998). High-resolution models may improve the simulation in the control runs, but the length of experiments may be too short for indications of significant changes (e.g., Beersma et al. 1997). Consequently, several studies have tried to look in more detail at mechanisms. For example, Christoph et al. (1997) identify a midwinter suppression of the North Pacific storm track in present-day climate, which they attribute to very strong upper-level winds at that time of year. Then in a 3xCO<sub>2</sub> climate model experiment, they note that very intense upper-level winds occur more often, thus producing a more pronounced midwinter suppression of the Pacific storm track.

As can be seen, there are now a growing number of studies addressing possible changes in storm activity, but there is little agreement as yet between the models concerning the possible future behavior of storms in a warmer climate.

#### 5. El Niño–Southern Oscillation (ENSO)

ENSO is associated with strong year-to-year climate variations in many parts of the world. Several aspects could affect future climate extremes: Will the long-term mean Pacific climate shift toward a more El Niño–like or La Niña–like regime? Will El Niño variability (the amplitude and/or the frequency of temperature swings in equatorial Pacific) increase or decrease? How will El Niño’s impact on weather in the Pacific basin and other parts of the world change?

Current global climate models are able to simulate a number of aspects of El Niño–like phenomena (Meehl and Arblaster 1998; Timmermann et al. 1999; Collins 2000). Results from several earlier global climate model studies indicated that as global temperatures rise due to increased greenhouse gases, the mean

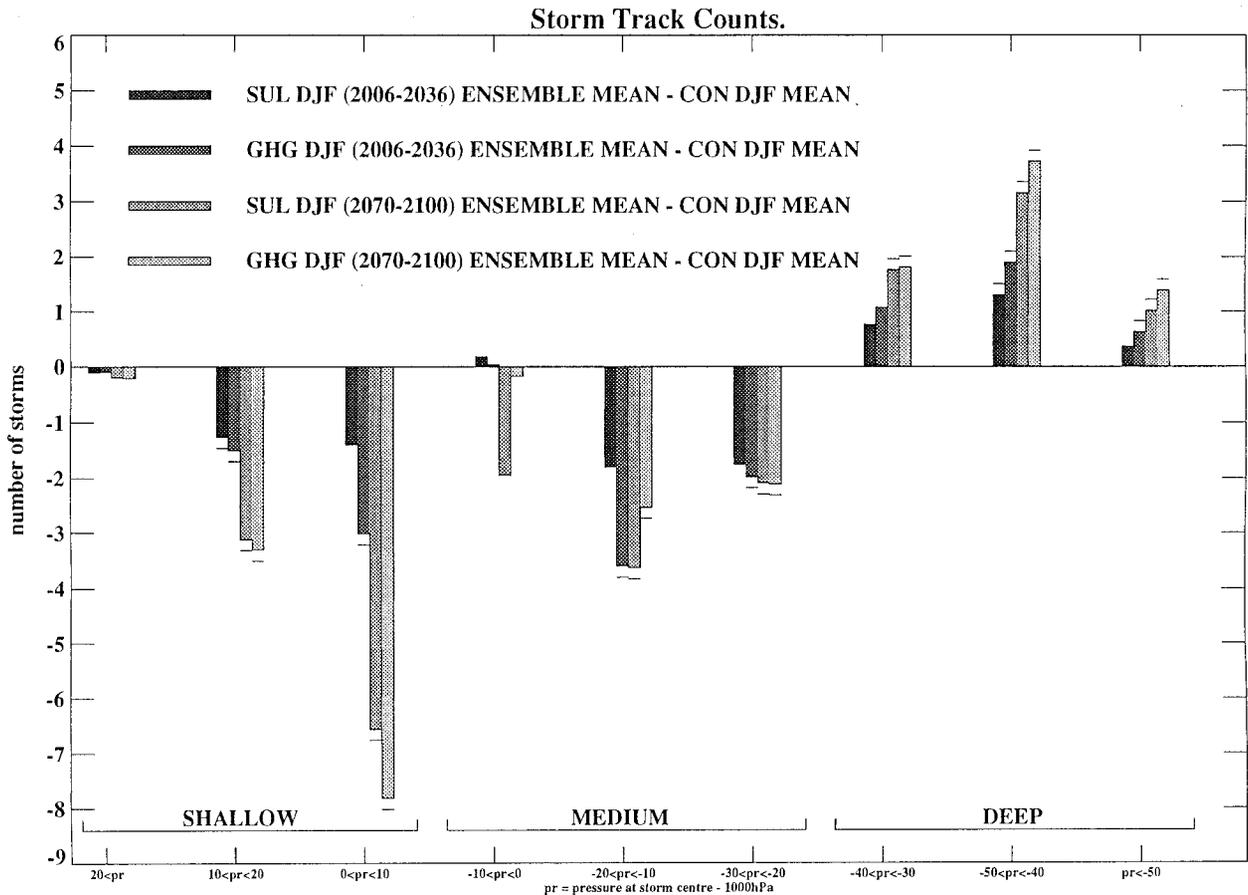


FIG. 2. Changes in the number of Northern Hemisphere storm tracks per 90-day northern winter season [December–January–February (DJF)] for two time periods in the future in a set of global climate change experiments. Dark shading (first peak from left of each group): DJF (2006–36), ensemble mean of a greenhouse gas plus sulfate aerosol experiment (SUL) minus a control (CON) experiment. Medium dark shading (second from left): DJF (2006–36) ensemble mean of a greenhouse gas increase only experiment (GHG) minus CON. Medium light shading (third from left): DJF (2070–2100) ensemble mean of SUL minus CON. Light shading (fourth from left): DJF (2070–2100) ensemble mean of GHG (2070–2100) minus CON. Horizontal bars at the end of the peaks show changes that are significant at the 1% level. Note that the number of shallow and medium storm tracks decreases in the future climate change experiments, while the number of deep storm tracks increases in this particular model (Carnell and Senior 1998).

Pacific climate will tend to more resemble an El Niño-like state with greater relative surface warming in the equatorial eastern Pacific than the west (Meehl and Washington 1996; Knutson and Manabe 1995). More recent studies also have shown this result (Knutson and Manabe 1998; Timmermann et al. 1999). It has been shown this conclusion could be dependent on the model representation of cloud feedbacks in comparing a global coupled model with an El Niño-like response to one with uniform warming across the tropical Pacific (Meehl et al. 2000). Additionally, though one model shows a La Niña-like response (Noda et al. 1999), another shows an initial La Niña-like pattern that eventually transitions to an El Niño-like pattern due to subducted warmed extratropical water that penetrates through the subtropics into the

Tropics (Cai and Whetton 1999, manuscript submitted to *Geophys. Res. Letts.*).

Concerning El Niño's effects on weather, it previously has been shown that a warmer base state would result in future El Niño-related seasonal precipitation swings that are more extreme (Meehl et al. 1993). Thus, areas in the tropical Pacific and Indian Ocean regions that are anomalously wet during El Niño could become wetter, and anomalously dry areas would become drier during future El Niño events. These changes in extremes in dry spells have been noted more recently to have serious consequences, for example, for water resources on small Pacific islands (Meehl 1996).

Previous attempts to address the question of future changes in El Niño SST variability using climate

models indicated little change or a modest reduction in amplitude of future El Niño events (e.g., Knutson et al. 1997). However, two recent studies using somewhat higher resolution models predict a somewhat greater amplitude of future El Niño/La Niña events due to a strengthening of the equatorial Pacific thermocline (Timmermann et al. 1999; Collins 2000). Recent studies also have indicated that El Niño-like SST patterns can apparently occur at a variety of timescales ranging from interannual to interdecadal (Zhang et al. 1997; Lau and Weng 1999) in addition to possible El Niño-like changes to the mean climate in response to external forcings such as increased CO<sub>2</sub> (see discussion above). Making conclusions about “changes” in future El Niño events is complicated by these factors. Additionally, since substantial internally generated variability of El Niño statistics on multidecadal to century timescales occurs in observations (Allan et al. 1996) and in long unforced climate model simulations (Knutson et al. 1997), the attribution of past and future changes in El Niño amplitude and frequency to specific causes may be quite difficult.

Although there are now better El Niño simulations in global coupled climate models, further model improvements are needed to simulate a more realistic Pacific climatology and seasonal cycle as well as more realistic El Niño variability. Such improvements will be necessary to gain further confidence in climate model projections.

## 6. Tropical cyclones

Greenhouse gas-induced climate warming potentially could affect tropical cyclones in a number of ways, including their intensity, frequency of occurrence, geographical distribution, and storm tracks. Concerning future changes in tropical cyclone frequency, no consensus has emerged yet among global models, although two recent studies of this issue employing relatively high-resolution global climate models (approximately 1°) both indicate a decrease in tropical storm frequency in a CO<sub>2</sub>-warmed climate (Bengtsson et al. 1996; Yoshimura et al. 1999). The merits of using current global climate models to project future changes in tropical storm frequency has been the subject of active debate (e.g., Henderson-Sellers et al. 1998).

Regarding tropical cyclone intensities, some of the global climate models suggest an increase of intensities with CO<sub>2</sub>-induced warming (Krishnamurti et al.

1998). However, the highest resolution global climate model experiment reported to date (Bengtsson et al. 1996) still has a resolution too coarse (1°) to simulate the most intense storms and/or realistically simulate structures such as the hurricane eye. Recent experiments with a nested high-resolution regional model (resolution of up to 1/6 degree or 18 km) indicate a 5%–11% increase in surface wind speeds and a 28% increase in near-storm precipitation, based on a comparison of strong north Pacific typhoons simulated under present day and high CO<sub>2</sub> conditions (Knutson et al. 1998; Knutson and Tuleya 1999). This simulated increase of wind speeds is similar to the increase in tropical cyclone upper-limit intensities predicted by theories based on thermodynamic considerations (Henderson-Sellers et al. 1998; Emanuel 1987). In other applications of regional embedded models, high-resolution experiments for the Australian region have shown similar increases in tropical cyclone intensity as well as possible poleward shifts in occurrence (Walsh and Ryan 1999). This approach, along with higher-resolution global model experiments, holds promise for better estimates of future tropical cyclone behavior.

Indices of tropical cyclone activity (Gray 1975) summarize the necessary large-scale conditions for tropical cyclone activity, even for coarse-resolution GCMs (Evans and Kempisty 1998; Royer et al. 1998). Climate change studies to date show a great sensitivity to the measure of convective activity chosen, with little change in the fields relating to dynamical organization. Additionally, since tropical storm activity in most basins is modulated by El Niño conditions in the tropical Pacific, projections of future regional changes in tropical storm frequencies may depend on accurate projections of future El Niño conditions, which is an area of uncertainty for climate models (as noted above).

## 7. Summary

Many of the model studies of weather and climate extremes in a future climate with increased greenhouse gases agree with intuitions from our understanding of how the climate system works. For example, a warming of the surface supplies more water vapor to the atmosphere, thus making more moisture available to storms. We would therefore expect an increase of intense precipitation and more rainfall from a given storm, both results seen in climate model simulations. Additionally, a number of changes in weather and cli-

mate extremes from climate models have been seen in observations in various parts of the world (decreased diurnal temperature range, warmer mean temperatures associated with increased very warm days and decreased very cold days, increased rainfall intensity, etc.). Though the climate models can simulate many aspects of climate variability and extremes, they still are characterized by systematic simulation errors and limitations in accurately simulating regional climate such that appropriate caveats must accompany any discussion of future changes in weather and climate extremes.

Recent studies have reproduced some of the previous results reported by the Intergovernmental Panel on Climate Change (Kattenberg et al. 1996) and this gives us increased confidence in their credibility (though agreement between models does not guarantee those changes will occur in the real climate system).

- 1) An increase in mean temperatures leads to more extreme high temperatures and less extreme low temperatures.
- 2) Nighttime low temperatures in many regions increase more than daytime highs, thus reducing the diurnal temperature range.
- 3) Decreased daily variability of temperature in winter and increased variability in summer in Northern Hemisphere midlatitude areas significantly modify changes in extremes.
- 4) Increased moisture content in many regions contributes to increased precipitation intensity.
- 5) Indian monsoon variability tends to increase, thus increasing the chances of extreme dry and wet monsoon seasons.
- 6) There is a general drying of the midcontinental areas during summer with increased chance of drought. This is ascribed to a combination of increased temperature and decreased precipitation.
- 7) Several global climate models indicate that the future mean Pacific climate base state could more resemble an El Niño-like state (i.e., a slackened west-east SST gradient with associated eastward shifts of precipitation), though that result remains model dependent. For such an El Niño-like climate change, future seasonal precipitation extremes associated with a given El Niño would be more intense due to the more El Niño-like mean base state.

Significant new results since the publication of the IPCC Second Assessment Report (Houghton et al. 1996) include the following:

- 1) Changes in temperature extremes noted above have been related to an increase in a heat index (leading to increased discomfort and stress on the human body), an increase in cooling degree days and decrease in heating degree days.
- 2) The greatest increase in the 20-yr return values of daily maximum temperature is found in central and southeast North America, central and southeast Asia, and tropical Africa where there is a decrease in soil moisture content, and also over the dry surface of north Africa. The west coast of North America is affected by increased precipitation resulting in moister soil and more moderate increases in extreme temperature. The increases in the return values of daily minimum temperature are larger than those of daily maximum temperature over land areas where snow and ice retreat.
- 3) Precipitation extremes increase more than the mean resulting in a decrease in return period for 20-yr extreme precipitation events almost everywhere (e.g., to 10 years over North America)

Additional aspects recently have been addressed in model studies, but remain unresolved at this time.

- 1) There is little agreement between the models concerning the possible future behavior of midlatitude storms, their intensity or frequency changes, or storm track changes. However, new studies have pioneered techniques to study such changes, and with improved models a more confident assessment may emerge.
- 2) Decadal and longer timescale variability complicate assessment of future changes in the amplitude and frequency of El Niño events, and assessment of such possible changes remains quite difficult, though recent studies suggest possible increased amplitude of future El Niño/La Niña events.
- 3) Studies of possible future changes in tropical cyclone frequency remain inconclusive, with two recent higher-resolution studies suggesting a less frequent occurrence of tropical storms in a future warmer climate. Other high-resolution modeling and theoretical studies suggest that the strongest tropical cyclones in a future warmer climate could be stronger than those in the present climate. If the base state in a future climate becomes more El Niño-like as predicted by some models, there could be accompanying shifts in the regional distribution of tropical cyclone activity such as those that occur in the present climate during El Niño

events. Progress has been made in studying changes in tropical cyclones with embedded regional high-resolution models, an approach that holds promise for better estimates of future tropical cyclone behavior.

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