Intermodel Comparisons of Precipitation Changes for the 21st Century Due to Greenhouse Gases and Sulfate Aerosols

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Section 1. Introduction

Significant changes in the composition of the global atmosphere have occurred since the start of the Industrial Revolution. The effect of these changes on the climate system is less certain. Over the last century, the average surface temperature has warmed noticeably. The concentrations of greenhouse gases (GHGs), which include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), ozone (O₃), and water vapor (H₂O), appear to be partly responsible for this warming. Through an enhanced greenhouse effect this warming could increase evaporation rates and add more water vapor to the atmosphere, which is itself a greenhouse gas. Anthropogenic activities have also increased the availability of sulfate emissions to the atmosphere, which provide a slight cooling effect to ameliorate greenhouse warming. Trends in GHGs are increasing, but future trends of sulfur emissions and their potential impact are less certain (Figure 1a,b,c,d).

In response to the need for regional information on climate impacts, the United States National Assessment of Potential Consequences of Climate Variability and Change (Dresler et al., 1998) was mandated to provide the information needed to increase our understanding of climate variability and improve our ability to cope with the consequences of future change. The
Intermodel Comparisons of Precipitation Changes for the 21st Century Due to Greenhouse Gases and Sulfate Aerosols

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ABSTRACT

Potential anomalies of precipitation patterns for the coterminous U.S. were obtained from the Canadian Centre for Climate Modeling and Analysis model (CGCM1) and the United Kingdom Hadley Centre for Climate Prediction model (HADCM2) using simulation scenarios of present (1961-1990) and future (2090-2099) climate. Both models simulated positive precipitation anomalies in the southwest for the summer and winter seasons. CGCM1 indicated drier conditions than present and HADCM2 revealed relatively moister conditions. Further evaluation of direct model output revealed that precipitation anomalies over southern California occurred because of the availability of water vapor due to potential increases of sea-surface temperatures (SSTs) and ocean-land moisture transport. Differences in precipitation anomaly patterns over the southeastern U.S. occurred because of the positioning of storm tracks along the eastern seaboard. The physical significance of precipitation anomalies in the southeast and southwest U.S. is the subject of this paper.

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overall goal of the National Assessment is to analyze and evaluate what is known about the potential consequences of climate variability in terms of pressures on the public, the environment, and the nation's economic resources.

There are three major components of the National Assessment, including the national synthesis, sectoral analyses, and regional analyses (Figure 2). There are 20 regional assessments that focus on the most significant issues at the regional level across the U.S. Sectoral analyses focus on issues that are natural in scope and related to the goods and services upon which the economy depends. The national synthesis integrates key findings from the regional and sectoral assessments and addresses questions related to overarching implications of the next 25 to 100 years. All three components link stakeholders, universities, government agencies, and non-government organizations in efforts to address concerns about climate variability.

The National Assessment is using several approaches to assess the consequences of various socioeconomic and climate scenarios for the U.S. The climate scenarios approach (Figure 3) includes applying historic trends and variations in the future, determining the limits of regional and sectoral
vulnerability in relation to plausible future climates, and using general
circulation models (GCMs) to provide a range of potential future climates.
In support of the National Assessment, this paper reports the physical
significance of GCM scenarios in terms of dynamic and thermodynamic
factors influencing the location and intensity of precipitation anomalies for
the 2090s. Throughout this paper, anomalies refer to changes between the
2090s (2090-2099) and the present (1961-1990) in the time-dependent
simulations.

Section 2. Methods

The two models used in this study are the first generation coupled
ocean-atmosphere GCM from the Canadian Centre for Climate Modeling
and Analyses and the second generation coupled ocean-atmosphere model
from the United Kingdom Hadley Centre for Climate Prediction (Table 1).
A description of the Canadian model (CGCM1) is given by Boer et al.,
(1984), McFarlane et al., (1992), and Flato et al., (1999). Johns et al.,
(1997) provides details of the Hadley model (HADCM2).

In a previous study Felzer and Heard (1999) analyzed GCM scenarios
for CGCM1 and HADCM2 in terms of atmospheric circulation and other
processes responsible for resulting hydrological patterns for the 2090s. We
reported positive precipitation anomalies for the summer and winter seasons in the southwestern U.S. for both models. In the southeastern U.S., differences in anomaly patterns occurred with CGCM1 showing less precipitation than present and HADCM2 showing relatively moister conditions. Based on our analyses of simulated precipitation anomalies, several cautionary points were issued about the significance of regional anomalies indicated by GCM simulations.

In this paper, we extend our previous work by evaluating regional precipitation patterns in the context of global changes. In determining the causative factors and significance of regional precipitation anomalies within GCMs, we selected a subset of variables within the model output, identified the potential for increased moisture in the atmosphere, and linked its transport to simulated precipitation anomalies. Although the GCMs showed notable changes between the present and future climate states, the robustness of specific precipitation anomalies was assessed through intermodel comparisons.

We first present regional precipitation and soil moisture anomalies during the summer and winter seasons for both CGCM1 and HADCM2 models North America (Figure 4a,b,c,d,e,f,g,h) and then explore the reasons
for the resulting patterns. Considering simulated precipitation anomalies, we
focused on the importance of dynamical and thermodynamical features to
understand the impact of convective and synoptic processes on total
precipitation anomalies. To understand the thermodynamics of GCMs, we
considered sea-surface temperature (SSTs) patterns as a measure for
precipitable water in the atmosphere. We also evaluated precipitation
changes within the global context of changes and determined how important
the anomalies were relative to the absolute change in precipitation values
over the continental U.S. The resulting anomaly patterns, which showed a
wide range of inconsistencies between models, enabled us to concentrate the
analyses on the southeastern U.S. and the North American west coast.

Section 3. Results

A. Winter 2090s

Total precipitation anomalies over a broad area are shown in Figure 5
for the winter and summer seasons of the 2090s. During winter both models
showed positive precipitation anomalies over the eastern Pacific that
extended inland over the North American Pacific coast (Figure 5a,b).
HADCM2 highlighted a connection between negative anomalies that
occurred in the western Pacific Ocean to those in the Atlantic Ocean.
CGCM1 also showed negative precipitation anomalies over the Pacific, but characterized a less pronounced connection between the two oceans.

One of the main features revealed by CGCM1 was the area of decreased precipitation extending from Mexico northeastward along the Atlantic seaboard. HADCM2 showed negative precipitation anomalies extending from the eastern equatorial Pacific to the Gulf of Mexico, however, indicated moister conditions from the eastern Gulf inland along the Atlantic coast. Downwind of North America both models showed areas of increased precipitation. Although there is some consistency in this area the region of decreased precipitation in HADCM2 was shifted further east over the Atlantic Ocean than CGCM1. For areas of positive precipitation anomalies along the equatorial Pacific Ocean both models agreed relatively well. HADCM2 characterized positive anomalies between the latitude bands of 10N and 10S from Australia to South America whereas CGCM1 showed positive anomalies in this region to extend southeastward beyond 30S.

Changes in SSTs, which were utilized as a measure of precipitable water in the atmosphere, served as an important indicator of thermodynamics within the respective models (Figure 6a,b). Both models showed overall increases in SSTs, with the most pronounced changes highlighted by an
elbow-shaped pattern connecting the west coasts of North and South America via the equatorial Pacific. Less pronounced increases of SSTs occurred in the northern Pacific Ocean and extended from Southeast Asia into the Gulf of Alaska, which corresponded well with increased patterns of total precipitation. One key characteristic of SST patterns was the northern elbow-shaped region and its correspondence to the extension of positive precipitation anomalies that occurred along the North American west coast. Both models characterized these features relatively well.

Convective and synoptic precipitation processes helped us understand the source of precipitation anomalies in terms of dynamic and thermodynamic influences. The importance of large-scale and localized precipitation processes was taken into account for the areas of interest (Figure 7a,b). Overall patterns of convective precipitation mirrored those of total precipitation considerably well along both coasts. For the southwest both large-scale and localized convection regimes contributed to resulting anomaly patterns of total precipitation. Convective precipitation dominated anomaly patterns over the Pacific Ocean whereas synoptic processes were more responsible for anomalies that occurred over land. In the southeast, where HADCM2 showed increased precipitation, convective patterns were
the most dominant. Over this region we found that synoptic processes contributed to resulting precipitation anomalies, however, their contribution was relatively less.

**B. Summer 2090s**

During summer, anomalies of total precipitation were less pronounced than during winter (Figure 8a,b). Both models showed positive precipitation anomalies over the North and South Pacific that extended slightly over the North American west coast. Along the equatorial Pacific Ocean the models agreed that positive precipitation anomalies extended southeastward toward the western coast of South America. CGCM1 showed a more extensive area of positive anomalies centered over the Pacific Northwest. HADCM2 indicated less precipitation over the same region from the Northwest Territory of Canada southward into the eastern equatorial Pacific.

A common feature revealed by both models was the area of decreased precipitation that extended southward along the Rocky Mountain Basin and eastward into the Atlantic Ocean via Central America. Along the Rocky Mountain Basin, CGCM1 showed more pronounced negative anomalies, which extended further southward than shown by HADCM2. HADCM2 also indicated a more expansive area of positive anomaly patterns extending
from the Great Plains eastward into the Atlantic. CGCM1 showed a small area of positive anomalies extending from the Great Lakes down into the Southern Plains with more pronounced negative anomalies extending from the Greater Mississippi River Basin eastward into the central Atlantic Ocean. For the interior U.S. the most pronounced differences occurred from the Great Plains eastward toward the Atlantic. CGCM1 simulated drier conditions than HADCM2 with the area of negative anomalies extending eastward from the Great Plains well into the Central Atlantic Ocean. HADCM2 indicated moister conditions east of the Rocky Mountain Basin extending well into the Atlantic Ocean.

SST anomaly patterns for both models indicated positive anomalies extending from eastern Asia across the Pacific into North America (Figure 9a,b). A major difference between the models involved land-surface temperature anomalies that were more extensive in one model than in the other. CGCM1 showed a more pronounced increase over a majority of the U.S. with a similar elbow-shaped pattern extending across the equatorial Pacific into South America as seen during winter. SST patterns from HADCM2 mirrored those of CGCM1 except that the pattern of more pronounced increases covered only the western third of the U.S. Also,
HADCM2 simulated only the forearm portion of the elbow-shaped pattern extending southwestward near the equator.

Anomaly patterns of convective and synoptic precipitation for HADCM2 are shown in Figure 10. Consistent with those for winter, convective patterns of precipitation corresponded very well with those of global precipitation. Over the North American west coast synoptic processes were responsible for the less pronounced anomalies over this region. In the southeast localized processes of convection dominated the increase in precipitation.

Section 4. Discussion

In addressing what may be responsible for simulated precipitation anomalies, factors such as positive SST anomalies and their effect on ocean-driven circulation were considered. The resulting precipitation anomaly patterns in both models, with negative precipitation anomalies over the western tropical Pacific Ocean and positive anomalies over the eastern Pacific and along the west coast of North America, more closely resembled the El Nino-like pattern described by Trenberth (1991). Assuming increases in SST anomalies correspond to local heating and the buildup of moisture
and energy, we asserted that these processes influenced atmospheric circulation and the occurrence of cyclonic activity.

As SSTs increased so did evaporation and the enhancement of localized convection. As seen over the ocean, total precipitation increases correlated well with SSTs over the Pacific Ocean as did localized convection processes. HADCM2 showed positive anomalies of total precipitation over much of the U.S. except for the Rocky Mountain Basin. Within this area convective patterns compared considerably well and dominated large-scale processes. The occurrence of positive precipitation anomalies in the southwest revealed that both convective and synoptic processes played important roles in the transport of moisture from the ocean to land. We also noticed that changes in convective precipitation corresponded well with those of total precipitation. Although a majority of inland precipitation fell in association with synoptic disturbances, the predominance of localized convective processes over the ocean highlighted the potential impact of enhanced SST patterns.

For large-scale precipitation anomalies associated with El Nino-like conditions during winter, Trenberth (1991) reported that wetter conditions should occur in the southern U.S. and extend eastward over the
Atlantic seaboard. HADCM2 simulated this feature, however, CGCM1 indicated an expansive area of negative precipitation anomalies along the eastern seaboard of the U.S. In the previous study Felzer and Heard (1999) found that the Atlantic storm track in CGCM1 was shifted further south and west than HADCM2. We concluded that the position of storm tracks and the availability of moisture from the Gulf of Mexico influenced the depiction of precipitation anomalies in that region.

Although SST anomaly patterns for both seasons agreed considerably well, increases in summer precipitation over the west coast of North America were relatively less and did not extend over such a wide area as in winter. Because of the El Nino-like pattern over the eastern Pacific Ocean most of the precipitation was convective, however large-scale processes dominated the precipitation anomaly pattern that extended inland from the eastern Pacific Ocean over the Rocky Mountains.

Over the southeastern U.S., CGCM1 indicated negative anomalies that extended northward along the eastern seaboard and HADCM2 showed wetter conditions. The pattern of large-scale precipitation associated with
El Nino indicated no change and raised questions about the accuracy of the models in simulating this global phenomenon and its effects on global precipitation anomalies.

**Section 5. Conclusions**

The U.S. national assessment is using general circulation model simulations of the 20th and 21st century to provide scenarios of climate change for specific regions within the U.S. In support of the national assessment, Felzer and Heard (1999) investigated how moisture transport contributed to hydrological changes during the 2090s in the terms of atmospheric circulation and other climate processes. In this paper, we determined the causative factors and significance of regional precipitation anomalies within GCMs by focusing on a subset of variables within the model output. While the GCMs show notable changes between the present and future climate, the robustness of precipitation anomalies of the southwest and southeast were assessed through intermodel comparisons.

Future GCM projections of precipitation for the 2090s generally showed pronounced increases in precipitation over the west coast of North America during both summer and winter (Figure 5). Based on this evidence we concluded that the El Nino-like state greatly influenced precipitation
anomaly patterns. As a result of enhanced SSTs more precipitable water was available to convective and synoptic processes in transporting moisture from the Pacific Ocean inland over the North American west coast. Further investigation determined that large-scale synoptic processes were more predominant for inland precipitation than localized convective processes, which were responsible for positive anomalies of precipitation over the ocean.

Inconsistencies in the representation of precipitation anomalies in the southeast raised questions about how climate variables were parameterized within the respective models. Further investigation of atmospheric circulation features (Felzer and Heard, 1999) suggested that differences in storm counts and the position of storm tracks were responsible for the inconsistencies between the models for during both seasons. Another factor may be how the respective land-surface model components parameterized soil moisture.

Initially our inquiries were based on the significance of model simulated future precipitation anomalies. The physical significance of these features suggest that although precipitation anomalies correspond very well with SST anomaly patterns, there exists uncertainty in how well these
models simulate El Nino phenomena and global teleconnections. In the future we plan to further determine the robustness of the simulated precipitation anomalies by performing pattern correlation analysis between model parameters and investigating the statistical significance of the respective model ensembles. In addition to these steps, we also plan to utilize results from the NCAR Climate System Model (CSM) and the DOE Parallel Climate Model (PCM) to complement the existing results for comparison.
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REFERENCES


FIGURE CAPTIONS

Figure 1: Concentration and equivalent radiative forcing scenarios for past and future CO$_2$ and SO$_4$ emissions. (a) CO$_2$ concentration; (b) Equivalent radiative forcing; (c) Sulfate aerosol concentration; (d) SO$_4$ radiative forcing.

Figure 2: U.S. National Assessment Structure.

Figure 3: U.S. National Assessment Climate Scenarios Approach.

Table 1: Physical characteristics of CGCM1 and HADCM2 general circulation models.

Figure 4: Precipitation ratios [future (2090-2099)/present (1961-1990)] and soil moisture deltas [future - present]. (a) December, January, February (DJF) precipitation from CGCM1; (b) DJF precipitation from HADCM2; (c) CGCM1 soil moisture; (d) HADCM2 DJF soil moisture; (e) June, July, August (JJA) precipitation from CGCM1; (f) HADCM2 JJA precipitation; (g) CGCM1 JJA soil moisture; (h) HADCM2 JJA soil moisture.

Figure 5: DJF total precipitation deltas [future – present]. (a) CGCM1; (b) HADCM2.

Figure 6: DJF skin temperature deltas. (a) CGCM1; (b) HADCM2.

Figure 7: DJF precipitation regimes from HADCM2. (a) Convective precipitation; (b) Synoptic precipitation.

Figure 8: JJA total precipitation deltas. (a) CGCM1; (b) HADCM2.

Figure 9: JJA skin temperature deltas. (a) CGCM1; (b) HADCM2.

Figure 10: JJA precipitation regime deltas from HADCM2. (a) Convective precipitation; (b) Synoptic precipitation.
NATIONAL ASSESSMENT STRUCTURE

NATIONAL SYNTHESIS

SECTORAL ANALYSES
Agriculture, Water, Human Health
Forest, Coastal Areas

REGIONAL ANALYSES
(e.g., Northeast, Southeast,
Great Plains, Northwest)
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Figure 5

Canadian CGCM1 (scenario: GHG-A)
Total Precipitation for DJF (2090-99) - (1961-1990)
(unit: mm/day x10)

(A)

Hadley HADCM2 (scenario: HCSSa1)
Total Precipitation for DJF (2090-99) - (1961-1990)
(unit: mm/day x10)

(B)
Figure 8

Canadian CGCM1 (scenario: GHG+A)
Total Precipitation for JJA (2090-99) - (1961-90)
(unit: mm/day x10)

(A)

Hadley HADCM2 (scenario: HCGS1)
Total Precipitation for JJA (2090-99) - (1961-90)
(unit: mm/day x10)

(B)
Figure 7
Canadian CGCM1 (scenario: GHG-A)
Skin Temp for JJA (2090-99) - (1961-90)
(degr C)

(A)

Hadley HADCM2 (scenario: HGSa1)
Skin Temp for JJA (2090-99) - (1961-90)
(unit: degr C)

(B)