The impact of sea surface temperature on the North American monsoon: A GCM study

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[1] The NCAR CCM3 was used to simulate the circulation and rainfall patterns of the North American monsoon system (NAMS). When forced with repeated annual cycles of climatological average sea surface temperatures (SSTs), the CCM3 significantly under-represents monsoon rainfall in the southwest United States while simulating excessive precipitation in the tropical eastern Pacific Ocean and the Caribbean Sea. However, when forced with the observed monthly average SSTs from 1979 to 1997, the CCM3 produces an improved simulation of monsoon rainfall in the southwestern U.S., as well as in the eastern tropical Pacific Ocean and the Caribbean Sea. Using the SSTs for 1983 in the Pacific and climatological SSTs elsewhere, the modeled circulation and rainfall distribution resembles that given with observed monthly average SSTs. The simulations are sensitive to the size of the domains over which the Pacific SST anomalies are imposed. Overall, these results suggest that the magnitude and size of winter- and springtime Pacific SST anomalies have a significant influence on summertime rainfall in the southwest U.S., and that these SSTs contribute to the NAMS precipitation climatology in extreme years more than in less extreme years. *INDEX TERMS:* 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3309 Climatology (1620); 3354 Precipitation (1854); 3319 General circulation; 1836 Hydrology: Hydrologic budget (1655). **Citation:** Yang, Z.-L., D. Gochis, W. J. Shuttleworth, and G.-Y. Niu, The impact of sea surface temperature on the North American monsoon: A GCM study, *Geophys. Res. Lett., 30*(2), 1033, doi:10.1029/2002GL015628, 2003.

1. Introduction

[2] The North American Monsoon System (NAMS) provides an important water resource to the arid/semi-arid southwest United States, and understanding the cause of variations in the strength of the NAMS potentially has profound social and economic implications [*Douglas et al.*, 1993; *Adams and Comrie*, 1997]. Recent observational studies have suggested that tropical and north Pacific sea surface temperatures (SSTs) correlate with the NAMS circulation and rainfall at the seasonal-to-interannual time scales [*Higgins et al.*, 1999; *Castro et al.*, 2001]. Because General Circulation Models (GCMs) potentially are important tools for understanding the physical mechanisms controlling the NAMS, it is important to test whether GCMs can reproduce these observed relationships.

[3] *Yang et al.* [2001] showed that, when forced with repeated annual cycles of climatologically average SSTs, the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3) significantly underestimates warm season precipitation in Arizona and New Mexico. This indicates that using climatologically average SSTs in the GCM may underestimate the strength of the influence of SSTs in the Pacific Ocean. In this paper, we first assess the performance of the CCM3 when forced with observed monthly SSTs relative to that when forced with climatological SSTs. In addition, to further explain the difference between these simulations, a series of sensitivity experiments are reported which investigate the importance of the magnitude and extent of the Pacific SST anomalies on the ability of CCM3 to simulate NAMS.

2. Models

[4] In this study, the NCAR CCM3 [*Kiehl et al.*, 1998] was used with resolution and physical parameterizations identical to those used in *Yang et al.* [2001]. Specifically, we used a 20-minute time step, T42 resolution (i.e., approximately $2.8^\circ \times 2.8^\circ$ transform grid) in the horizontal, and 18 atmospheric layers in the vertical, with the model top at 2.9 hPa. However, in the present study, we used two versions of the CCM3: CCM3.2 and CCM3.6, while *Yang et al.* [2001] used only CCM3.2. These two versions have identical physical parameterizations, but CCM3.6 differs in coding structure and includes bug fixes. This paper focuses on assessing their ability to model the circulation and rainfall pattern of the NAMS.

[5] The Land Surface Model (LSM) [*Bonan*, 1996] is the standard land-surface model used in the NCAR CCM3. In this study, the NCAR CCM3.2 was also coupled to an alternative land model, namely the Biosphere-Atmosphere Transfer Scheme (BATS) [*Dickinson et al.*, 1993].

3. Experiments

[6] Eight model experiments were made using two versions of CCM3, two different land-surface models, and different SST specifications (Table 1). In Experiments A, B, and G, the CCM3 was driven with identical annual cycles of climatological SSTs. Results from Experiments A and B were previously described in *Yang et al.* [2001]. In Experiment H, the CCM3 was forced with observed monthly SSTs as used in the Atmospheric Models Intercomparison Project (AMIP) [*Gates*, 1992] for the period 1979–1997.

[7] The remaining experiments (C, D, E, and F) examine the sensitivity of NAMS circulation and rainfall patterns as simulated in the CCM3 to the size and magnitude of the SST

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Table 1. Model and Sea Surface Temperature Specification and Integration Time Used in the CCM3 Experiments

Experiment	Version of CCM3	Land-surface model	SST specification	Integration (Years)
A	CCM3.2	LSM	Climatological	11
B	CCM3.2	BATS	Climatological	11
C	CCM3.2	BATS	1982 SST (small area)	6
D	CCM3.2	BATS	1982 SST (most of the Pacific)	6
E	CCM3.2	BATS	1983 SST (small area)	6
F	CCM3.2	BATS	1983 SST (most of the Pacific)	6
G	CCM3.6	LSM	Climatological	11
H	CCM3.6	LSM	AMIP SST	19 (1979–1997)

Note: In runs C and E, the SSTs observed in 1982 or 1983 are used in three small areas in the Pacific Ocean (Nino3:150°W–90°W, 5°S–5°N; Central North Pacific: 177°E–164°W, 26°N–36°N; Eastern North Pacific: 150°W–125°W, 35°N–50°N), while climatological SSTs are used elsewhere. In runs D and F, the SSTs observed in 1982 or 1983 are used in most of the Pacific (120°E–90°W, 20°S–50°N), while climatological SSTs are used elsewhere.

anomalies in the Pacific Ocean. The observed SSTs in the Nino-3 region show a strong positive anomaly (up to 3.6°C) during the period 1982–1983 (Figure 1). In the same period, the SST anomalies in the central north Pacific (CNP) and eastern north Pacific (ENP) are negative. The major differences between SSTs in 1982 and 1983 are that tropical SST anomalies increase approximately linearly from zero in January to about 3.6°C in December in 1982, while this is reversed in 1983 (Figure 1). It is of interest to see how the CCM3 responds to these differences.

[8] Experiments A, B, and G all have the same initial conditions. Only results from the last six years in these experiments were used for analysis (in fact, the results from the last six years are essentially identical to those from the last 10 years). Experiments C, D, E, and F were all initialized from the modeled status on December 31 of the 5th year in Experiment B and integrated for six years to allow the results to be readily compared with those from Experiment B (as well as the other experiments). Results from the run with AMIP SSTs were averaged for a period corresponding to the observed precipitation data.

[9] Time-average modeled precipitation data were evaluated relative to the data of *Legates and Willmott* [1990] (hereafter called LW) and *Xie and Arkin* [1996] (here after called XA), these being two data sets commonly used by the climate modeling community to assess modeled rainfall. The National Centers for Environmental Prediction (NCEP)-NCAR global reanalysis data [*Kalnay et al.*, 1996] were used to assess the atmospheric circulation and moisture fields.

4. Results

4.1. Precipitation

[10] Figure 2 shows that the CCM3 model run with the AMIP SSTs simulates the spatial distribution of precipitation more accurately than with the climatologically averaged SSTs, especially over Arizona, New Mexico, northwestern Mexico, and the tropical oceans. However, both experiments underpredict precipitation in the southwest United States and overpredict precipitation in Colorado, Kansas, the tropical eastern Pacific, the Caribbean, and the Gulf of Mexico.

[11] Figure 3 compares observed (LW and XA) monthly precipitation zonally averaged over land between 114°W and 104°W with that calculated by the CCM3 experiments using different specifications of SSTs. While both observations differ considerably in the tropics (0–30°N), and the LW data show a stronger monsoon rainfall, the observational data agree reasonably well elsewhere. *Yang et al.* [2001] reported that the CCM3 experiment with climatological SSTs underestimates the NAMS rainfall. This underestimation is reduced in the CCM3 when forced with the AMIP SSTs between 1979 and 1997. Arguably, the comparison between the run with AMIP SSTs and the XA climatology is better than with the LW climatology because, in the former case, both observations and data refer to the same averaging period (1979–1997). Relative to both observed data sets, the model with the AMIP SSTs tends to underestimate rainfall during the warm season in the southwest USA (30–35°N) and overestimates rainfalls south and north of this latitudinal band. In addition, the modeled monsoon peaks in June/July are one or two months earlier than the observed peaks.

[12] In the study of *Yang et al.* [2001], an old version of the model (version CCM3.2) was used, while the model data presented in Figure 2 and Figures 3c–3d were calculated with a more recent version (CCM3.6). It is of interest to document the differences between these two versions when depicting the NAMS. Figure 3e (calculated with CCM3.2) can be compared directly with Figure 3d (calculated with CCM3.6) because both use climatological SSTs

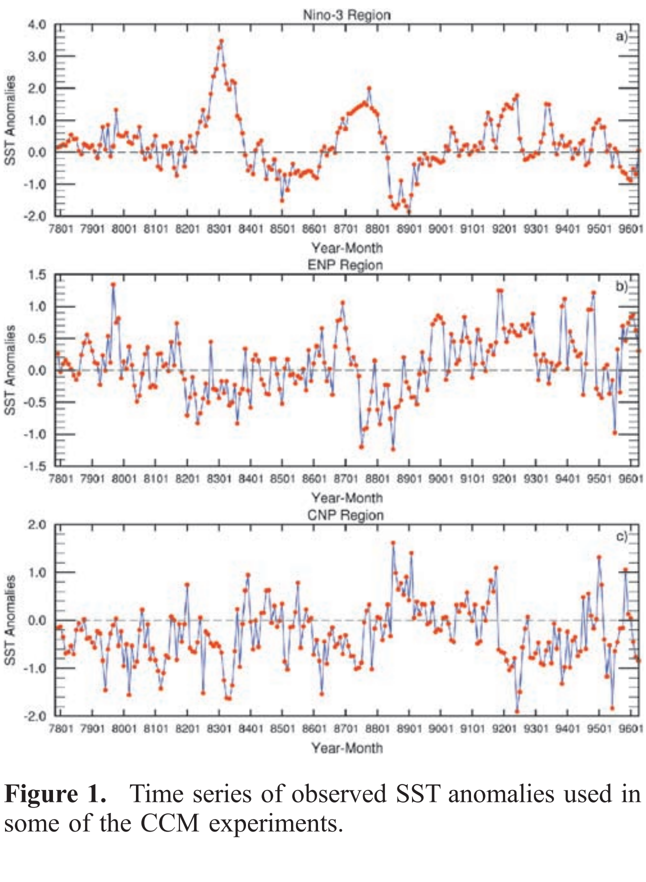

Figure 1. Time series of observed SST anomalies used in some of the CCM experiments.

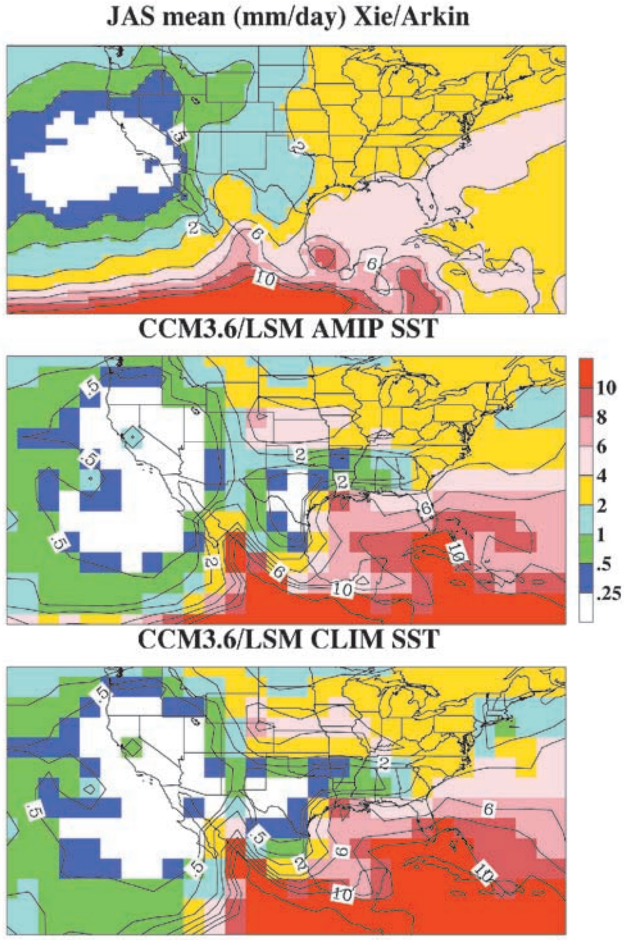

Figure 2. Comparison of mean precipitation in July–August–September (JAS) (mm/day) from (a) *Xie and Arkin* [1996], (b) Experiment H, and (c) Experiment G.

and the LSM model. The run with CCM3.6 yields a slightly more accurate simulation of the warm season rainfall in the southwest U.S. (30–35°N) than the CCM3.2, but other features are similar. Moreover, the simulation using CCM3.2 with BATS is similar to that with LSM. Therefore, sensitivity experiments to investigate the effect of SSTs were conducted using the CCM3.2 coupled with BATS.

[13] When the Pacific SSTs in the climatological run are replaced by the observed SSTs in 1982, the modeled results are essentially similar to those of the control run. However, significant differences occur when the 1983 SSTs are used repeatedly. Specifically, enhanced warm season rainfall is generated between 30°N and 35°N. These simulations together suggest that the magnitude of winter- and spring-time SST anomalies in the Pacific, especially in the eastern tropical Pacific, is important to the development and intensity of subsequent summertime rainfall in the southwest United States. A strong positive SST anomaly is associated with a modeled increase in rainfall over the southwest United States, a result consistent with that suggested by observations [*Higgins et al.*, 1999; *Castro et al*, 2001].

4.2. Circulation

[14] Consistent with the results given by *Yang et al.* [2001], the newer version of CCM3 forced with the AMIP SSTs simulates circulation patterns (Figure 4) that are broadly similar to the NCEP-NCAR reanalysis [*Kalnay et al.*, 1996]. However, the low-level (900 hPa) wind vectors in the model again show a stronger-than-observed convergence in the eastern tropical Pacific Ocean, the Caribbean Sea, and the Great Plains. These correspond with areas where the model overestimates precipitable water, precipitation, and rising motion. At the 200-hPa level, the reanalysis data indicate that the anticyclonic system is meridionally oriented with a center over western Mexico, but the model still shows an anticyclonic system that is displaced eastwards relative to reanalysis and has zonal orientation.

[15] In the experiments with the imposed anomalies in the Pacific SSTs, the size of the domain where these anomalies are imposed is important. If the size is as small

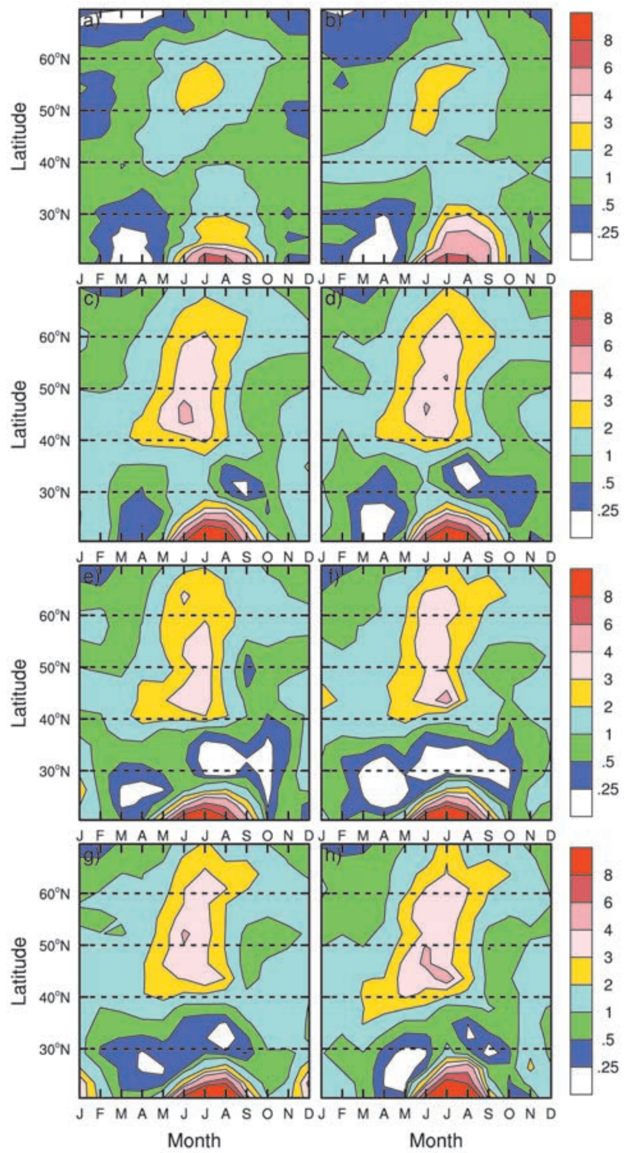

Figure 3. Latitude-month comparison of precipitation averaged over land between 114°W and 104°W from (a) *Xie and Arkin* [1996], (b) *Legates and Willmott* [1990], (c) Experiment H, (d) Experiment G, (e) Experiment A, (f) Experiment B, (g) Experiment D, and (h) Experiment F.

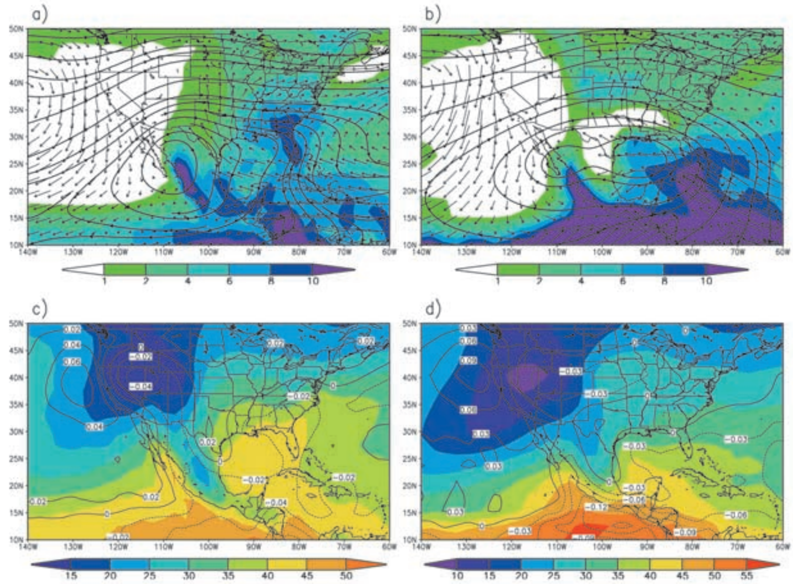

Figure 4. Mean JAS 925-hPa vector wind, 200-hPa streamlines, and precipitation (mm/day) (shaded) from (a) the NCEP-NCAR reanalysis [*Kalnay et al.*, 1996] and (b) Experiment H. Mean JAS 600-hPa vertical velocity (hPa/s) (contoured) and column-integrated precipitable water (mm) (shaded) from (c) the NCEP-NCAR reanalysis and (d) Experiment H.

as that used by *Castro et al.* [2001] to define their NAMS index, both the circulation and rainfall patterns show little difference with respect to each other and the control run. When the domain size over which the anomaly is imposed is increased to cover most of the Pacific Ocean, the most noticeable change is decreased rainfall in the Caribbean and the Gulf of Mexico. As a result, the precipitation pattern resembles better that obtained using the AMIP SSTs between 1979 and 1997. The run with the 1983 SSTs imposed across the Pacific produces rainfall enhancement in New Mexico. At the 200-hPa level, the anticyclonic system over the southern tier of the Gulf of California appears to be strengthened, while the other center over the Gulf of Mexico tends to be weakened. These changes compare favorably with observations.

5. Summary

[16] This study shows that simulations of the NAMS circulation and rainfall in the NCAR CCM3 are related to the way in which the Pacific SSTs are prescribed. Using identical annual cycles of the long-term mean climatological SSTs underestimates the mean NAMS rainfall, while using the SSTs that include interannual variations improves the model simulations. These results indicate that the influence of SSTs on the strength of the NAMS rainfall is a nonlinear process. Presumably, the long-term mean SSTs filter out the year-to-year transient features that may be important to the development of the NAMS while, on the other hand, these features in extreme years (e.g., ENSO) can lead to a nonlinearly strong response in the NAMS. This result is well illustrated by the sensitivity studies in which the observed 1983 SST is imposed in the Pacific Ocean while retaining climatological SSTs elsewhere. The resulting rainfall patterns in the southwest United States, the Caribbean Sea, and the Gulf of Mexico closely resemble those obtained using the AMIP SSTs. The improved simulation from the 1983 SSTs anomaly experiment implies that the magnitude and size of winter- and springtime SST anomalies are important factors influencing the summertime rainfall in the southwest United States. Further, this sensitivity study indicates that, in the extreme conditions, transient (as opposed to the long-term mean) SSTs influence monsoon precipitation climatology more than the mean SSTs.

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