Regional Response of the NCAR CCM1 to Anomalous Surface Properties

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ABSTRACT

Sensitivity tests of the National Center for Atmospheric Research (NCAR) Community Climate Model - 1 (CCM1) response to surface forcing from sea surface temperature (SST) and soil moisture on precipitation are presented. Four experiments were performed, including a control experiment using climatological SSTs, an experiment with 1988 SSTs, which are generally thought to have contributed significantly to the 1988 Drought in the United States, and experiments using an artificial soil moisture anomaly. For each experiment, three model simulations were performed, and were initialized from arbitrary conditions.

The results show that in CCM1, the 1988 SST experiment produced more precipitation in the United States compared to the control case. While precipitation increased in the U.S., the differences were found to be small compared to the variability. Control simulations with larger amounts of precipitation showed the strongest response to soil moisture anomalies; however, the seasonal reduction of soil moisture reduced the overall sensitivity to the imposed anomaly. Furthermore, soil moisture differences in regions other than the anomaly region developed with comparable magnitudes.

(Keywords: Drought, GCM, SST, Surface interaction)

1. INTRODUCTION

Surface properties have a great deal of influence over both the regional and global climate. The effects of soil moisture and vegetation on the weather or short term climate have been analyzed and discussed by Namias (1962), Charney *et al.* (1977), Shukla and Mintz (1982), Rind (1982), Dickinson (1984), Yeh *et al.* (1984), Wolfson *et al.* (1987), Meehl and Washington (1988), Xue *et al.* (1990), Henderson-Sellers (1993), Yang *et al.* (1994) and many others. Sea surface temperatures (SSTs) can also affect regional climates through teleconnections (Trenberth *et al.*, 1988; Palmer and Brankovic, 1989; Kalnay *et al.*, 1990; Mo *et al.*, 1991; and Atlas *et al.*, 1993, to name a few). Of particular interest is the response of the precipitation patterns over the United States to variations in soil moisture and SST.

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During the summer of 1988, the midwestern United States suffered through one of the most intense droughts in recorded history. This case has been the focal point for many recent surface/atmosphere interaction studies. Observational analyses of this case have been discussed quite completely by Janowiak (1988), Ropelewski (1988), Namias (1991) and Trenberth and Branstator (1992). The analyses indicate that April and May were somewhat warmer and drier than normal, and by late May a strong stationary anticyclone had positioned itself over the United States. The associated northward displacement of the jet stream had reduced the number of precipitating storms in the United States, and those that did occur were quite weak. By June 1988, some midwestern states had received record low precipitation amounts, as the anticyclonic weather patterns persisted. Mid-July brought normal precipitation to the Midwest, but this was insufficient to restore normal surface moisture conditions or temperatures.

Studies of this case have focused mainly on the anomalous SSTs and soil water content, which occurred during the spring and summer of 1988, as being the cause of the drought. Namias (1991) linked a warm-dry, extratropical climate variation during March and April to the ensuing hot - dry drought months of May and June, and noted that the 1988 La Niña had not attained full strength until mid-May.

Trenberth *et al.* (1988) suggested that the 1988 SST anomaly in the eastern tropical Pacific Ocean had forced the changes in northern hemisphere circulation, and was the primary cause of the 1988 drought in the United States.The SST anomaly induced a northward shift of the Inter-Tropical Convergence Zone (ITCZ) (and its atmospheric diabatic heating) due to the La Niña phase of the El Niño Southern Oscillation (ENSO). Trenberth *et al.* (1988) used a steady-state planetary wave model to simulate the influence of the tropical heating anomalies, which reasonably reproduced the phase and wavelength of the northern hemisphere circulation, but not the magnitude of the anomaly. Trenberth and Branstator (1992) continued this work, finding that the eastern tropical Pacific heating anomalies were the most influential, as compared with other heating anomalies, in affecting the general circulation during the spring and summer. This also indicated that heating anomalies over the central United States were insufficient to instigate the drought, but could have had a role in its persistence. Similarly, Lau and Peng (1992) used a barotropic model to simulate long wave response to atmospheric divergent anomalies. The model utilized R15 resolution, and the subsequent anomalies imposed on the model may have been of a larger scale than in 1988. An eastern Pacific dipole anomaly associated with the northward shift of the ITCZ produced results similar to Trenberth *et al.* (1988). In particular, a divergent anomaly in the Gulf of Alaska was found to be essential to the development of the strong ridge over the contiguous United States. It was determined that both tropical and extratropical anomalous forcing could amplify the normal mode structure resulting in a stationary ridge in the United States.

Mo *et al.* (1991) found improved skill in National Meteorological Center (NMC) Medium Range Forecast (MRF) 30 day forecasts of the drought, initialized in mid-May, when 1988 SSTs were used, as opposed to the climatological SSTs. In particular, their results indicated that the simulations depended on both the 1988 SST boundary conditions and the initial atmospheric conditions. Further tests showed that a long period normal mode, related to barotropic instability, had been excited and was present in their May 1988 initial conditions. This implies that the conditions prior to May were important in the development and duration of the drought.

Using general circulation models (GCMs), Wolfson *et al.* (1987) and Atlas *et al.* (1993) tested the impact of the SSTs and analyzed soil moisture values on numerical simulations. Wolfson *et al.*'s (1987) GCM simulations of the 1980 drought show that soil moisture anomalies contributed to the below-normal precipitation, as compared to a climatological simulation. It was also found that the 1980 SST anomalies were not able to produce the upper air wave pattern that was associated with the drought; however, it was noted that this could be due to the short period of the simulation (10 days). Atlas *et al.* (1993) used the Goddard Laboratory for Atmospheres (GLA) GCM and May 1988 initial conditions, and found that precipitation over the United States decreased in simulations using the 1988 SSTs (as compared to climatological SSTs). This result was most robust when only tropical SST anomalies were considered. It is important to note that, in these simulations, soil moisture was derived from monthly mean temperature and precipitation, and was not permitted to interact with the modeled precipitation. When estimations of the anomalous 1988 soil moisture were considered, the strongest response of precipitation reduction was obtained. An experiment including both anomalies showed only small differences from the soil moisture alone.

Oglesby and Erikson (1989) demonstrated the persistence of an imposed soil moisture anomaly in the United States using the National Center for Atmospheric Research (NCAR) Community Climate Model 1 (CCM1). Their results also showed the importance of atmospheric moisture transport from the Gulf of Mexico on the Midwestern regional climate and on the maintenance of the soil moisture anomaly. However, the model was run in perpetual season format, where insolation was set at midsummer levels for several hundred days. This work was extended by Oglesby (1991) to include seasonal cycle simulations with soil moisture anomalies imposed on March 1 and May 1. The March 1 anomaly was significantly reduced within thirty days, due in large part to snow melt, as well as the smaller insolation during this time of the season that limited the impact of the anomaly. On the other hand, the May 1 anomaly persisted for the entire summer, supporting the contention that dry soil moisture can perpetuate itself through a positive feedback with the atmospheric general circulation.

Walsh *et al.* (1985) compared anomalies in atmospheric temperature, precipitation and a soil moisture index computed from synoptic scale observations in the United States. While there appeared to be a correlation between summertime temperature and soil moisture, the correlation between the soil moisture index and precipitation was less evident. This was attributed to the convective nature and horizontal variability of precipitation during the summer. Furthermore, a recent study of the observed United States hydrologic budget (Roads *et al.*, 1994) shows that precipitation anomalies are highly correlated with moisture flux convergence anomalies, but there is less correlation between surface evaporation and precipitation anomalies. Roads *et al.* (1994) suggest the use of higher resolution atmospheric numerical models to study the hydrologic budget because of the high degree of variability in precipitation. Given the discrepancy between model and observed results, we continue to study the impact of surface anomalies on the regional weather in a GCM.

This paper discusses further studies of the impact of surface properties (sea surface temperature and soil water content) on short-term regional climate. The NCAR CCM1 is utilized to extend the numerical simulations of SST to run from January through the end of August. This is intended to show whether the 1988 SSTs have any influence on the warm, dry spring

conditions, mid-summer drought observed that year. Other simulations are performed to test the model sensitivity to an imposed May 1 (day of the year 121) soil moisture anomaly, and the combination of 1988 SSTs and the soil moisture anomaly (imposed on May 1). Section 2 provides a brief description of CCM1 and the experimental design of the numerical simulations. Section 3 discusses the results of the experiments, and Section 4 summarizes the results.

2. MODEL AND EXPERIMENTAL DESIGN

The GCM used in this study is the National Center for Atmospheric Research (NCAR) Community Climate Model version 1, CCM1. The model has been described in great detail by Williamson *et al.* (1987), and only the specifics are reviewed here. The model was run at R15 resolution (7.5° longitude and 4.5° latitude) in the horizontal and 12 levels in the vertical, for the global domain. Oglesby and Erikson (1989) summarize the improvements of CCM1 over earlier CCM versions, which pertain directly to numerical simulations used in this study. Boer *et al.* (1991) compare the CCM1 statistics to observations and other GCMs. Furthermore, Giorgi (1990) compared the CCM1 January climate of R15 and T42 resolutions to observational analyses and found that CCM1 (R15 and T42) produced reasonable simulations of the U.S. atmospheric circulation. The simulations presented here will be 230 days, initialized on January 15, and terminated on September 1 (day of year 15 - 245), so that this will test the sensitivity of CCM1 to anomalous forcing. Independent initial conditions were derived from the archived CCM1 interactive soil hydrology run. It may be important to note that these experiments were completed prior to the release of NCAR CCM2 (with more advanced physics and a standard higher resolution) to the general scientific community. In the future, this work will make use of CCM2, as well as a limited area atmospheric numerical model.

The response of CCM1 precipitation in the United States to local idealized soil moisture deficits and the 1988 SSTs will be tested in these experiments. The responses will be relative to a control run of CCM1. For each experiment, three model simulations were performed. The ensemble means of each experiment, as well as the individual simulations, will be discussed. Table 1 outlines the initial conditions, boundary conditions and durations for each numerical simulation. Six simulations with periods of 230 days and six simulations of 120 days have been run.

The control run (Experiment #1) was initialized on January 15 with data from the last three years of an archived 10 year run with surface hydrology and climatological SSTs. The second experiment uses the same initial conditions as the control, but the climatological SSTs are replaced by the analyzed monthly mean SSTs (from Climate Analysis Center) of 1988. The duration of both these simulations is from January 15 through September 1. Given that the initial conditions are essentially arbitrary, variations in the atmospheric circulations should be mostly due to the anomalous SSTs, as well as the physical processes included (or neglected) in CCM1.

Surface/atmosphere interactions have been studied in great detail, yet there remain some conflicting results of the extent to which soil moisture can affect precipitation. Using synoptic scale observational data, Walsh *et al.* (1985) found little correlation between soil moisture and precipitation, yet many GCM studies have shown some correlation (Atlas *et al.*, 1993; Oglesby,

Table 1. List of CCM1 numerical simulations. The first column is the Experiment number, the second is the origination of the initial condition for that case, and the third is the type of perturbation imposed at the surface boundary. 1988 SST' implies that the anomalous sea surface temperatures of 1988 are used after initialization, and 'SM' implies that the idealized soil moisture anomaly described in the text is used to perturb the initial soil moisture field in the United States. For the May 1 simulations, May 1 indicates that an anomaly has been imposed at that time and the case from which the May data was obtained is also identified. Note that each experiment was performed with 3 arbitrary initial conditions.

Exp. No.	Initial Conditions	Boundary Conditions	No. of Simulations
1	Jan 15, Archived data	Control SST	3
2	Jan 15 Archived data	1988 SST	3
3	May 1, from Exp.#1	SM	3
4	May 1, from Exp.#2	1988 SST & SM	3

1991). From the control experiment, the data from May 1 (day 121) will be used for initial conditions, with the exception that soil moisture over the United States will be reduced to 0.03 m for Experiment #3. The soil moisture in May averages about 0.12 m in Experiment #1, therefore the anomaly removes 75% of the averaged soil moisture, which is significant. The area of the perturbation is all land points in North America between 365 and 495 latitude, henceforth referred to as the United States Region (Figure 1a). This domain was chosen to compare results with Oglesby (1991). For completeness, a fourth simulation combines the anomalous SSTs and soil water content, where initial conditions were derived from the second experiment (with 1988 SSTs) on May 1, and have the same imposed soil moisture anomalies as the third experiment. This should identify whether the forcing of the perturbations has any combined influence on North American precipitation produced by CCM1.

3. RESULTS

Figure 1a shows the land / sea boundaries for the North American region. The shaded area indicates where the soil moisture anomaly is imposed for Experiments 3 and 4. Data in the shaded area will be horizontally averaged and presented in filtered time series to study the evolution of the model hydrology. The 1988 SST anomalies from the CCM1 climatological SSTs for the month of June are presented in Figure 1b, and will be used in Experiments 2 and 4. In addition to the time series, monthly mean data for the model simulations, both ensemble averaged and the individual simulations, as well as instantaneous horizontal projections, have been studied.
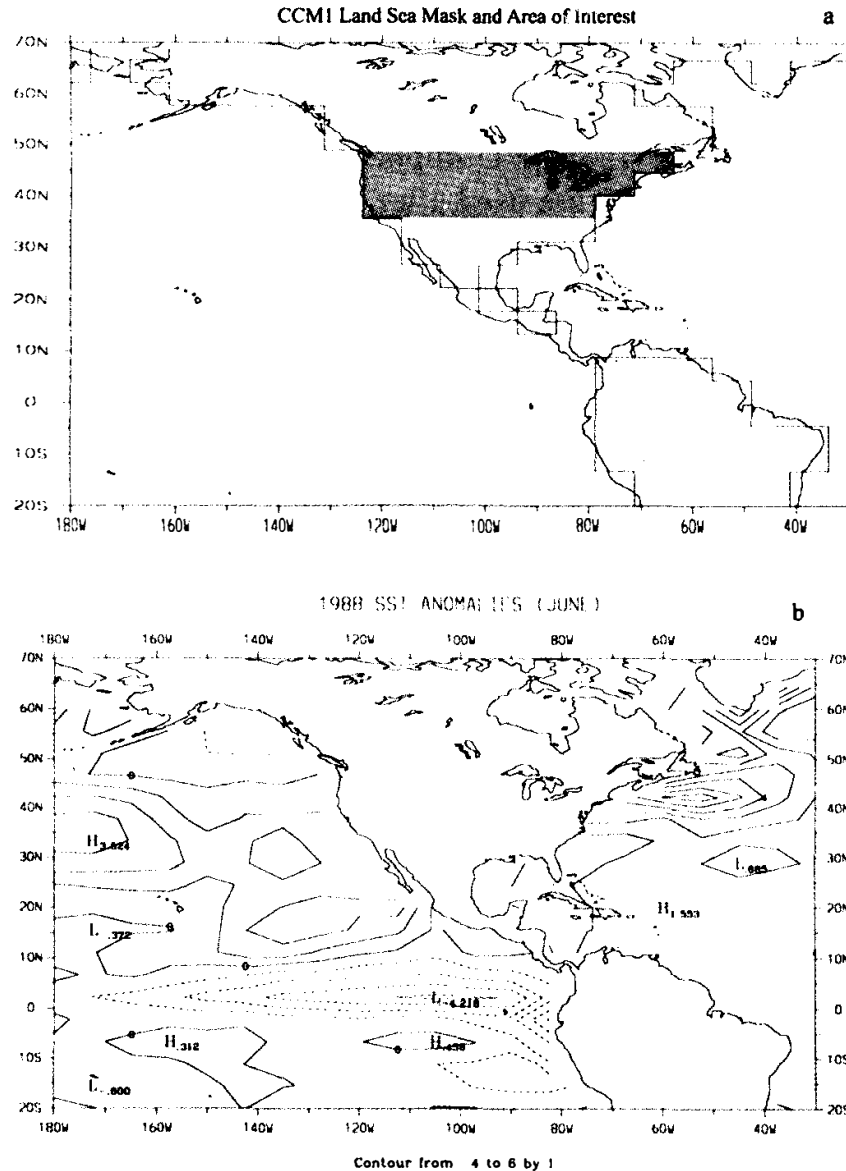
Fig. 1. (a) The straight lines show the land / sea mask used in CCM1 as compared to actual continental outlines. The shaded region highlights where the soil moisture anomaly is imposed in Experiments 3 and 4, this is also the region where the model data of CCM1 is area averaged for time series plotting.(b) SST Anomaly used in Experiments 2 and 4 (units in K).

To appropriately identify which results are the most significant, we will employ the t - test, computed by,

$$t = \left| \frac{x_1 - x_2}{\{(s_1 + s_2)/2\}^{1/2}} \right| \quad \text{where} \quad t = \begin{cases} 2.78 & \text{is } 95\% \\ 2.13 & \text{is } 90\% \end{cases} \qquad 1$$

where x is the ensemble mean of the experiment and s is its variance. Three model simulations of each experiment were performed because there is inherent model variability. The variability may influence results had only one simulation been investigated. We use the t-statistic as a simple method to weigh the magnitude of the ensemble mean difference between two ex-

periments, and the standard deviation of the means. This is an arbitrary way of determining the importance of the difference between two experiments and considers the variability in each experiment.

3.1. Experiment 1: Control

The results presented here will be relative to this control experiment. Three arbitrary initial conditions were derived from the NCAR CCM1 data archives. For the control experiment, the standard CCM1 climatological SST data set is used for boundary conditions, along with the hydrologic budget over the land surface. Figure 2a shows the area averaged (shaded area in Figure 1a) time series of accumulated precipitation for each control case and the ensemble mean. There is some natural variability in each of the control simulations, with a difference of 200 mm in accumulated precipitation between the wet year (#3) and the dry year (#1).

With regard to these simulations, it is also important to note the seasonal variation of several model variables. Figure 2b shows the ensemble mean time series of soil moisture for the control experiment. The modeled soil water seems to be quite comparable to the Roads *et al.* (1994) estimation of soil water based on the climatological observation of the U.S. hydrology budget (see their Figures 4 and 5). There may be a slight difference in the phase, but that should be expected from the bulk soil water model utilized by CCM1. Roads *et al.* (1996) compare CCM1 precipitation to observation. In this control run, CCM1 precipitation slightly overestimates the summertime precipitation rate reported by Roads *et al.* (1994) by ~0.5 mm/day. Evaporation is greater than precipitation for much of the spring and summer in the United States Region, and by late summer an equilibrium between evaporation and precipitation has been reached. This corresponds to the season variations in 500 mb heights and surface temperature (Figure 2c and Figure 2d). These seasonal variations become important when interpreting the sensitivity simulations. Figure 3 is the time and ensemble averaged deviation of the zonal mean 500 mb heights for Experiment 1. A strong "quasi-stationary" high is positioned over the United States. This ridge will need to be amplified in order to make the control simulation even drier.

3.2. Experiment 2: 1988 SSTs

The sea surface temperatures from 1988 are used in this experiment because of the substantial amount of research that has been performed for this case. The hypothesis of this experiment is based on some of the arguments presented in the introduction, in that, if the 1988 SST anomalies are the sole cause of the drought within the United States Region, then by replacing the climatological SSTs with the anomalous SSTs in CCM1, we expect that the ensemble mean climate in this region should be drier than the (presumably normal) control simulation.

For the ensemble average of simulations, CCM1 does not intensify the ridge over the U.S. Region compared to the control experiment. The quasi-stationary wave height differences in June (Figure 4a) show some height falls off the coasts, but little increased heights over the United States. In July of the 1988 SST Experiment, the ridge over the U.S. is weaker than the
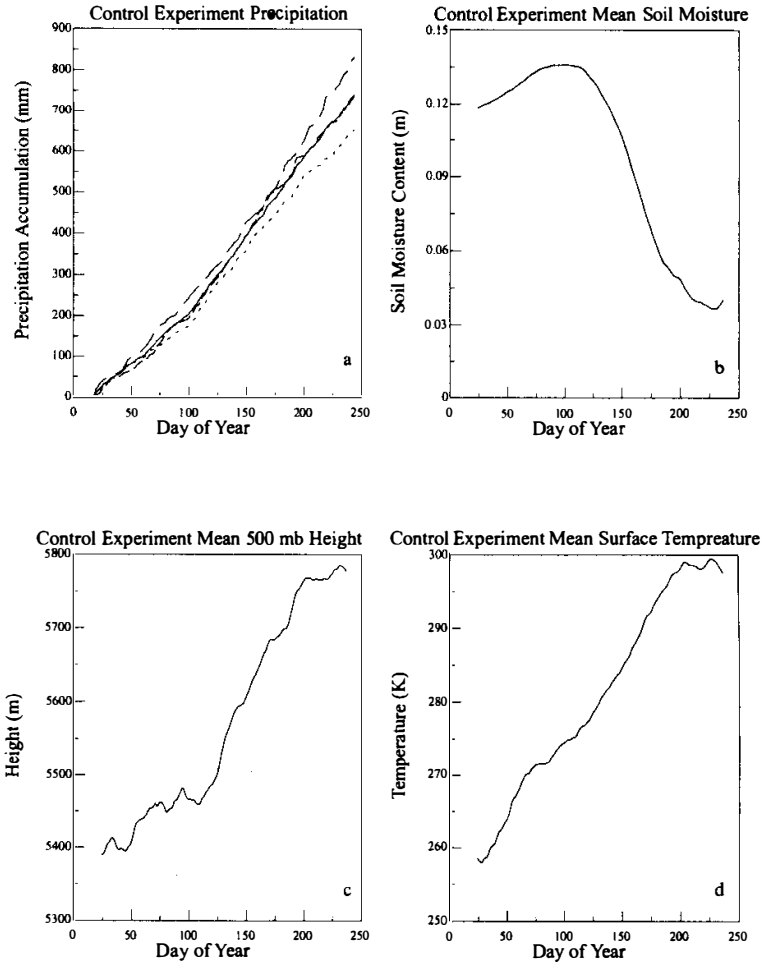
Fig. 2. (a) Accumulated precipitation of the control experiment for the ensemble mean (Solid), Year 1 (short dash), Year 2 (medium dash), Year 3 (long dash). Ensemble averages for the control experiment soil moisture (b), 500 mb height (c), and surface temperature (d), (May 1 is day 121, and September 1 is day 245).
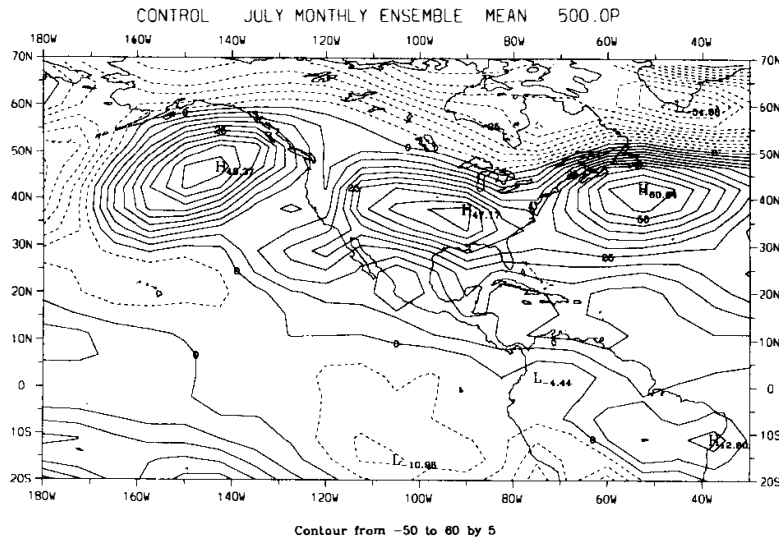

Fig. 3. Quasi-stationary 500 mb heights of the July monthly ensemble mean during July (units in meters). Defined as the time average height deviation from the zonal mean.

ridge in the control (Figure 4b). At the land surface in the U.S. Region, the soil moisture differences between the ensemble means of the two experiments is quite small for much of the period (Figure 5a), with generally larger values in the 1988 SST experiment, due mainly to increased precipitation. The differences in ensemble mean accumulated precipitation generally increase throughout the period (Figure 5b).

In general, this pattern exists in each of the member simulations that make up the en-
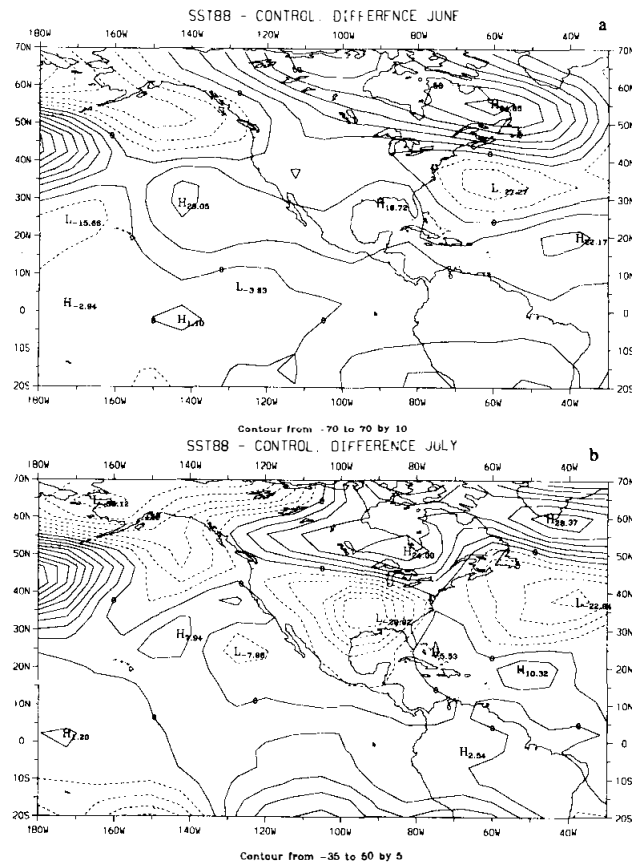

Fig. 4. Quasi-stationary 500 mb height difference between Experiment 2 and the control experiment (units in meters) for (a) June and (b) July.

semble. While the trends displayed by these simulations are quite interesting, significance tests of the differences in monthly mean 500 mb heights, as well as the precipitation and soil moisture in the United States Region, for these cases show small differences relative to the variability in the experiments. Figure 5c shows the individual accumulated precipitation differences for each simulation, and demonstrates the variability of this experiment. By the beginning of June in year #3, accumulated precipitation is much larger than its control counterpart, yet though June and July, these differences are remarkably reduced. On the other hand, years #1 and #2 show dramatic increases in accumulated precipitation throughout the summer months. Given the wide range of variability in these results, more simulations are certainly required to derive a reliable signal.

Mo *et al.* (1991) demonstrated that the atmospheric initial conditions, in addition to the 1988 SSTs, were crucial to the development of dry conditions in the U.S., and that sea surface temperature anomalies that occurred in 1988 alone may not be sufficient to cause the drought,.
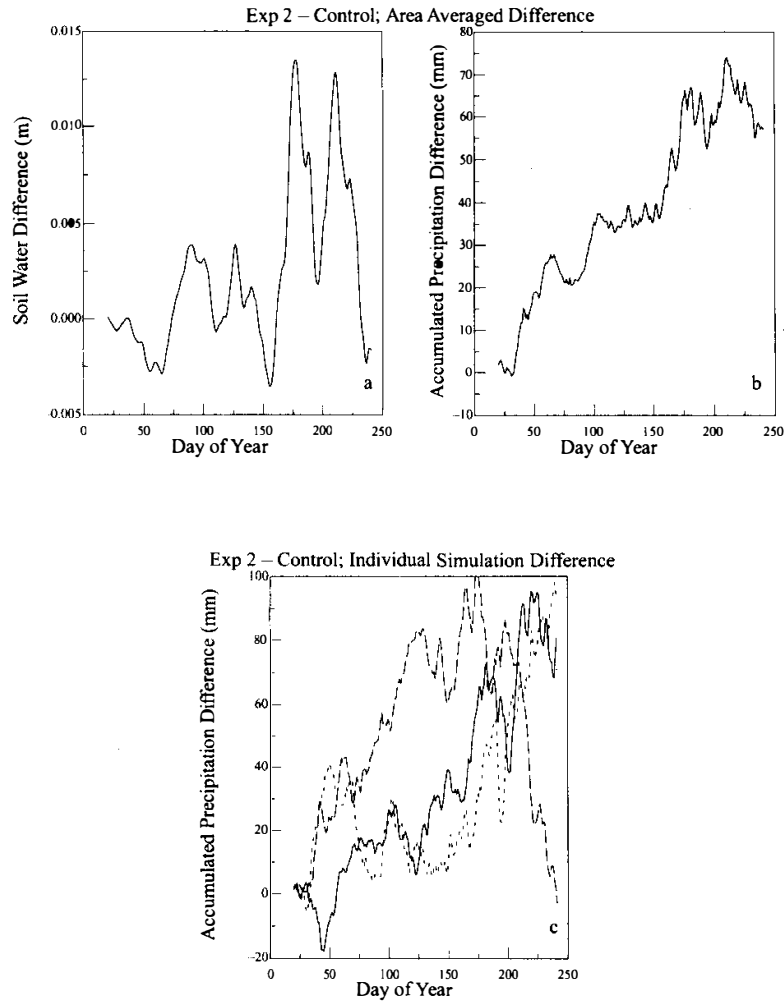
Exp 2 – Control; Area Averaged Difference

Exp 2 – Control; Individual Simulation Difference

Fig. 5. Area averaged time series difference between Experiment 2 and the control experiment for ensemble mean soil water (a) and accumulated precipitation (b). No statistically significant (at 90 %) differences were found in a and b. (c) Area averaged time series difference between Experiment 2 and the control experiment for each simulation, year #1 (solid), year #2 (short dash) and year #3 (long dash) (May 1 is day 121 and September 1 is day 245).

There is, of course, no information on the observed atmospheric wave pattern included in these simulations. Trenberth and Branstator (1992) note that the eastern tropical Pacific heating anomalies are important to the development of the intense ridge over the U.S. in 1988, but that inadequate heating in CCM may limit its ability to simulate the anomalous wave pattern.Trenberth and Branstator (1988) find 2 mm/day (~4 mm/day or less is found in Experiment 1) precipitation rates in the eastern tropical Pacific during May and June, while observations indicate precipitation rates closer to 6 - 10 mm/day. Ose *et al.* (1994) showed that uncertainties in the SST fields can be as important as the SST anomalies in simulating the general circulation. While the heights in the Gulf of Alaska were lowered slightly, an organized divergent anomaly, which could have helped the development and maintenance of the stationary ridge over the United States, never developed (Lau and Peng, 1992).

3.3. Experiment 3: Soil Moisture Anomaly

These experiments were performed in order to expand on the simulations of Oglesby and Erikson (1989) and Oglesby (1991). Initial conditions were derived from each of the control simulations on May 1 (day 121), and the climatological SSTs were used. An artificial perturbation in the initial soil moisture is imposed over the United States Region. The hypothesis of this experiment is that once in place, dry surface soil can perpetuate itself by influencing the atmospheric circulation and reducing precipitation. Oglesby and Erikson's perpetual season simulations showed quite a strong atmospheric response to the soil moisture anomaly. This experiment is designed to test the endurance of an imposed anomaly, and its impact on the precipitation, as well as investigate the feedback between soil moisture and precipitation with the seasonal cycle in place.

Horizontal projections of the monthly mean fields are qualitatively comparable to the results of Oglesby and Erikson (1989) and Oglesby (1991) for May and June, following the perturbation of the soil moisture. The soil moisture is less than the Control Experiment, and the land surface temperature becomes much warmer, about 7 K maximum (Figure 6), due to the reduction of latent heat flux in the surface heat budget. Note that the variability of thesensitivity experiment induced surface temperature differences away from the perturbation region (on the order of 2 K). Dramatic upper level ridging, demonstrated by Oglesby and Erikson (1989) in perpetual season simulations is never realized in the seasonal cycle simulations. Furthermore, as the simulations progress in time, the coherence and intensity of the soil moisture anomaly is not maintained in space and time for all cases.

The time series of ensemble mean soil moisture difference is presented in Figure 7a. The imposed anomaly is substantial (statistically significant points are marked in the diagram). The difference in soil moisture continues to decrease through May and June. To interpret the results, remember that, in this region, the control soil moisture is undergoing a seasonal reduction, due to increased insolation, surface temperature and evaporation. The time series of ensemble mean soil water in Experiment #3 shows little fluctuation. Therefore, the decreasing magnitude of the soil water deficit in Figure 7a is not related to increasing soil moisture in the anomalous simulations, but rather to the seasonal cycle of the control simulation. Note that after one month, the differences between the two cases is no longer very large, and by the end of July there is virtually no difference between the soil moisture of both experiments. This implies that dry soil can persist for the entire summer season, but its existence may not be due entirely to a feedback with precipitation. Figure 7b shows the ensemble mean accumulated precipitation difference between both cases. The trend indicates that the accumulated precipitation is less in the anomalous soil moisture experiment; however, the differences are small, especially during the first 150 days when the soil moisture anomaly is most significant. Examination of the day-to-day and monthly mean analyses generally show warmer and drier conditions in the U.S. Region for most of the simulation, but the perturbations are not significant when compared with the seasonal variations and natural variability.

A closer inspection of the individual simulations reveals that, in May and June, when the soil moisture anomaly was most significant, the differences in accumulated precipitation for each simulation was quite small (Figure 7c). Later in the period, the deviation of the accumu-
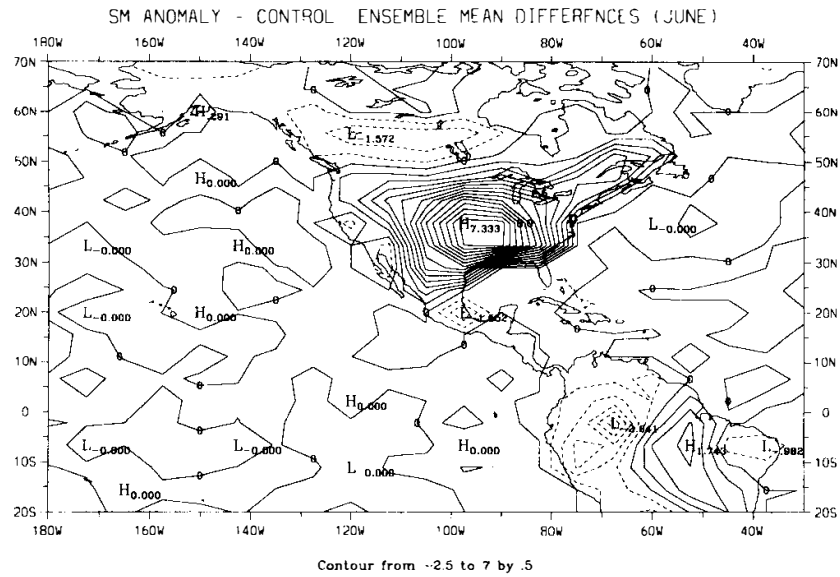
SM ANOMALY - CONTROL ENSEMBLE MEAN DIFFERENCES (JUNE)

Fig. 6. Ensemble mean difference field etween Experiment 3 and the control June monthly mean surface temperature (units in K).

Exp 3 – Con; Area Averaged Difference

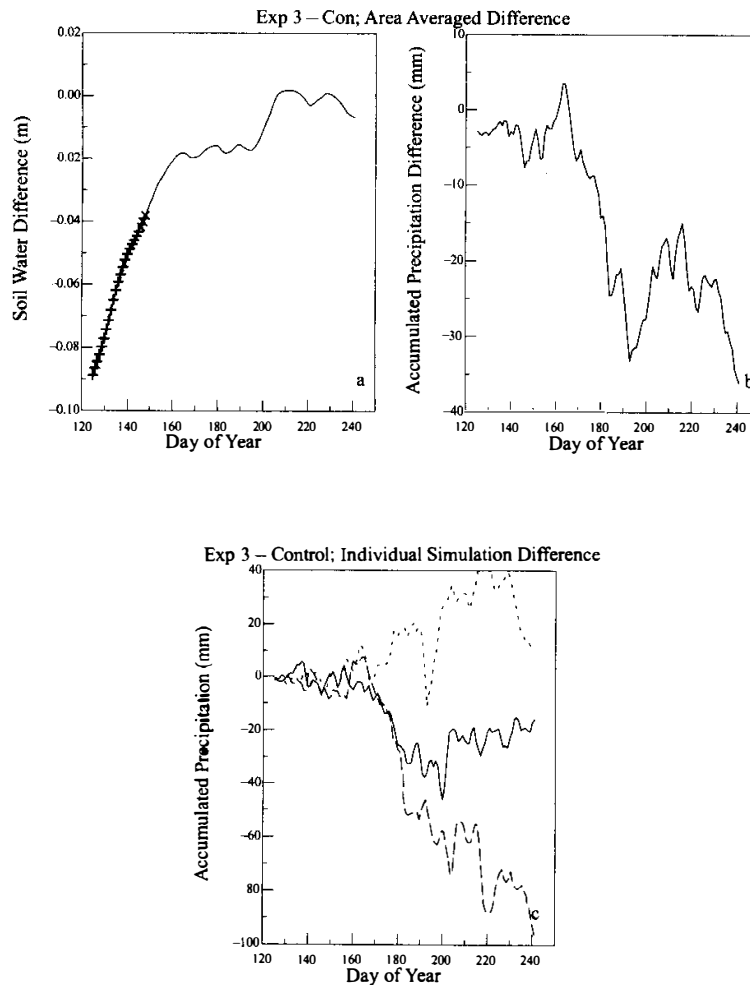Exp 3 – Control; Individual Simulation Difference

Fig. 7. As in Figure 5, except for the differences between Experiment 3 and the control. Statistically significant differences are marked with + (95%) and × (90%) in a and b. No statistically significant (at 90 %) differences were found in b (May 1 is day 121, and September 1 is day 245).

lated precipitation in each case becomes quite large. In fact, year #2 shows an increase in precipitation, as compared to its control counterpart. These features lead to uncertainty in this experiment. Oglesby (1991) used only one seasonal simulation, which may not be entirely representative of the processes involved. Note that year #3 exhibited the largest accumulation of precipitation in the control experiment, and when the soil moisture of this simulation is reduced, the largest reduction of precipitation occurs compared to the other simulations. Figure 8 shows the horizontal projection of the soil water difference between year #3 of the control and Experiment 3 for the month of July. A substantial anomaly still exists across the central United States, but the anomaly recovers in the Pacific Northwest. The horizontal variability of the precipitation is quite large. It is also worthwhile to note that soil water away from the initially perturbed region has been modified by amounts comparable to the remnant of the original anomaly.

In general, the ensemble monthly mean differences between this case and the control show results that are qualitatively similar to previous results (Wolfson *et al.*, 1987; Oglesby and Erikson, 1989 and Atlas *et al.* 1993). The soil moisture anomaly generally produces warmer surface temperature and lower surface pressure as compared to a control run. A correlation between the soil moisture anomaly and the resultant upper level atmospheric circulation is not clear. The day-to-day soil moisture horizontal projection shows relatively dry conditions for the entire period. If the seasonal reduction in soil water is accounted for, the net influence of the soil moisture anomaly on the control case is less than expected because dry conditions will occur seasonally in CCM1.

3.4. Experiment 4: Combination of 1988 SST and Soil Moisture Anomalies

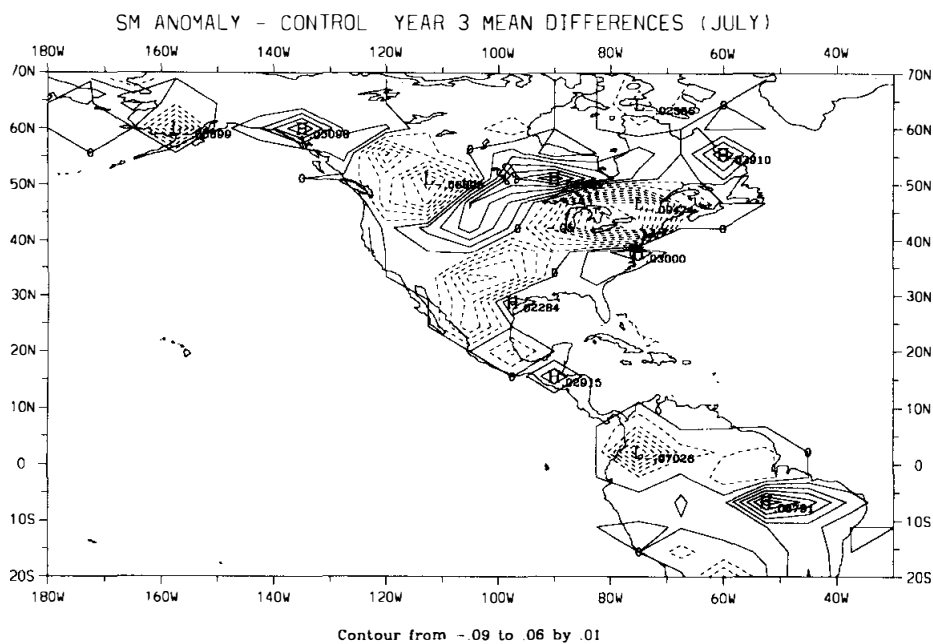Wolfson *et al.* (1987) and Atlas *et al.* (1993) have tested the combined effects of soil

Fig. 8. Difference between the third simulations of Experiment 3 and the control of soil water content (units in meters of liquid water).

moisture and sea surface temperature anomalies in a GCM. In both studies, the soil moisture was fixed at observed values for their respective anomalous cases, and both showed soil moisture to be very influential, but the combined cases did not amplify the precipitation anomaly more than soil moisture alone. For example, Atlas *et al.*'s (1993) 1988 combined simulations were only slightly enhanced, as compared to the soil moisture anomaly case, which was the most significant.

As in the previous experiment, the soil moisture is perturbed on May 1 (day 121) in the U.S. Region, and the atmospheric conditions are derived from Experiment 2 (1988 SST). The original intent of this experiment was to test the enhancement of dry conditions brought about by the 1988 SSTs. Because the 1988 SST experiment essentiality produced more precipitation than the control, this experiment has become an extension of the soil moisture sensitivity case.

Figure 9a shows the time series of ensemble mean soil moisture difference in the U.S. Region between this experiment and Experiment 2. The most noticeable feature is the increased number of significant points in the late summer, as compared to the previous experiment with climatological SST. Also note that the ensemble mean differences are always negative for the entire simulation period. This would indicate that the soil moisture anomaly more strongly influenced the hydrologic cycle with the 1988 SSTs present.

The differences also extend to accumulated precipitation in the U.S. Region (Figure 9b). In this case, the accumulated precipitation is significantly less than in the 1988 SST experiment. There is still substantial variability in each simulation, but through the summer, all simulations show a general reduction of precipitation (Figure 9c). As in the previous experiment, the comparison of the horizontal projections yields results that are qualitatively similar to previous work. In general, the surface temperature is warmer and surface pressure is lower in the perturbation region as compared with the unperturbed case. The interesting difference is that the influence on precipitation is somewhat more significant in this experiment, as opposed to the previous experiment with climatological SSTs.

Since Experiment #2 produced larger amounts of precipitation in the region of interest, as compared to the control experiment, the results tend to indicate that the artificial soil moisture anomaly has the most influence on simulations with the higher amounts of precipitation (see also Simulation #3 of Experiment #2). The soil moisture anomaly used in these simulations is very large, possibly beyond the range of natural variability. The correlation between soil moisture and precipitation in the model may be a result of the large scale coherence of the anomaly in the GCM and the absence of heterogeneous variability in soil moisture and precipitation (Walsh *et al.*, 1985). Atlas *et al.* (1993) used realistic surface anomalies, but the amount of surface water was independent of the modeled precipitation.

4. SUMMARY

Sensitivity tests of the NCAR CCM1 response to surface forcing from sea surface temperature and soil moisture have been presented. CCM1 has been used in a seasonal cycle mode with a hydrologic budget at the land points, and initial conditions were derived from an Irchived CCM1 simulation. For each sensitivity experiment, three independent simulations were utilized.

Exp 4 – Exp 2; Area Averaged Differences

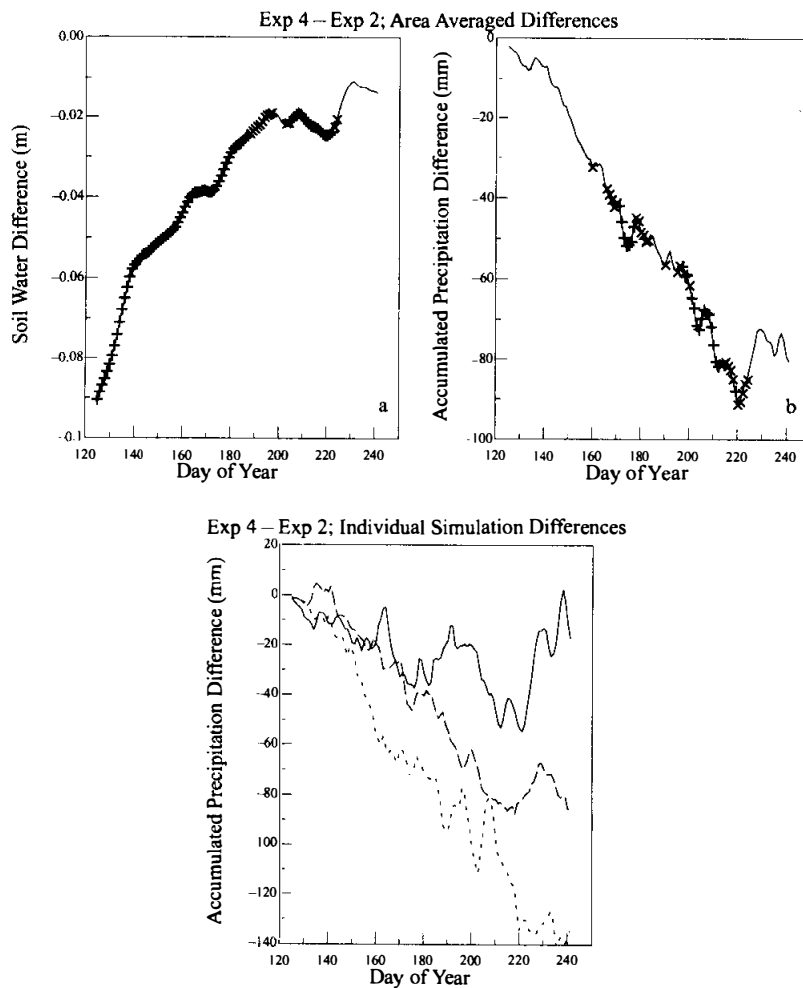Exp 4 – Exp 2; Individual Simulation Differences

Fig. 9. As in Figure 5, except for the differences between Experiment 4 and Experiment 2. Statistically significant differences are marked with + (95%) and × (90%) in a and b (May 1 is day 121, and September 1 is day 245).

Four experiments were performed, including a control experiment using climatological SSTs, an experiment with 1988 SSTs (which are generally thought to have contributed significantly to the 1988 drought in the United States), and experiments using an artificial soil moisture anomaly. For each experiment, three model simulations were performed, and were initialized from arbitrary conditions. The results show that in CCM1, the 1988 SST did not cause the simulated weather pattern over the U.S. to be drier than the control with climatological SST. In fact, each separate simulation, as well as the ensemble mean, produced more precipitation in the United States Region, in comparison with the control. This resulted from a reduction in the upper level ridge over the region. It should be stressed that, although each simulation produced consistent results, the differences were found to be small compared to the variability in the experiment.

The model response to artificially reduced soil moisture was also tested. The experiment was similar to that of Oglesby (1991), and was initialized on May 1 from the control simulation. While the model produced results similar to those of previous studies, the differences between the experiments were small after approximately 30 days. While the perturbed experiment stayed relatively dry for the simulation period, the control simulation produced a sea-

sonal reduction of soil water (comparable with observations), and eventually the anomalous soil moisture case was indistinguishable from the control case. The ensemble mean perturbed soil moisture experiment did show less precipitation than the control; however, due to the large variance in the data, the reduction in precipitation was not statistically significant. One of the soil moisture anomaly cases had produced more precipitation than its respective control case, leading to the large variance and uncertainty in the experiment. Also, the soil moisture of unperturbed regions showed differences of the same order of magnitude of those in the perturbed region.

One final experiment was performed, where the soil moisture anomaly of experiment 3 was imposed on the 1988 SST experiment. In this experiment, the most significant differences were obtained, specifically in the reduction of precipitation. Since the 1988 SST experiment was more moist than the control experiment, the soil moisture anomaly had the strongest impact on the more moist simulations. This marks a trend in all of the results, where the soil moisture reduction affected areas that received larger cumulative precipitation in the unperturbed (with respect to soil moisture) simulations.

Oglesby (1991) points out that natural variability exists in the CCM1 simulation of the general circulation. The uncertainty found in these sensitivity simulations indicates that the natural variability in the model has a strong influence on the simulation. A larger number of samples should help provide more significant statistics. Unfortunately, summertime precipitation is usually very difficult to simulate numerically, especially in coarse resolution GCMs. Furthermore, the large scale atmospheric wave anomaly, which could be very important in the 1988 drought, is not included in this GCM study. The present work represents the initial experimentation of an ongoing research project.Similar studies are currently underway utilizing more sophisticated tools, such as more physically complete GCM (CCM2, released to the scientific community after much of the present work was completed) and a high-resolution, limited-domain atmospheric numerical model.

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