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The influence of soil moisture anomalies on variability of the North American monsoon system

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Abstract. We examine the influence of land-atmosphere interactions, as moderated by soil moisture anomalies, on variability of the North American Monsoon System (NAMS). Sensitivity experiments, in which soil moisture was prescribed to field capacity, were completed with the MM5 mesoscale model linked to the OSU land surface scheme. Our results demonstrate that the NAMS precipitation response to soil moisture forcing depends critically on the location of anomalous surface conditions. Wet soil in the southern Rocky Mountains (SRM) during July, which could result from the melt of an above-normal snowpack, inhibits precipitation in the NAMS region. This is consistent with the observed negative correlation between SRM spring snowcover and NAMS summer precipitation [*Gutzler and Preston*, 1997]. In contrast, wet soil in the NAMS region enhances July precipitation within that area—a positive soil moisture-rainfall feedback exists. Our findings must be tested with experiments that incorporate anomalies constrained by regional-scale soil moisture observations.

Introduction

Much of the precipitation in the southwestern U.S. and northwestern Mexico occurs between July and September [*Douglas et al.*, 1993]. The North American Monsoon System (NAMS) is the source of much of this precipitation (Figure 1a). Year-to-year fluctuations in NAMS strength are substantial and influence various natural and human systems. *Higgins et al.* [1998] found that precipitation variability in the NAMS region is linked to conditions in the eastern tropical Pacific—positive (negative) SST anomalies favor wet (dry) winter/spring conditions and dry (wet) summer conditions. SST anomalies in other regions could also be important. Land surface processes may also affect NAMS variability. In this study, we test the hypothesis that land-atmosphere interactions, as moderated by soil moisture anomalies, influence variability of the NAMS.

Land-atmosphere interactions may influence NAMS variability because the land surface state affects the surface-atmosphere fluxes of water and energy. Soil moisture strongly controls the magnitude of these fluxes [e.g., *Yeh et al.*, 1984]. The soil moisture reservoir evolves on timescales as long as months or years, and therefore acts as a source of long-term "memory" [*Entekhabi et al.*, 1992] that may influence the atmosphere in two different ways. First, it is hypothesized that a positive soil moisture-rainfall feedback exists within some areas—wet (dry) soil enhances (inhibits) precipitation in that region [e.g., *Eltahir*, 1998]. Second, anomalous soil moisture conditions in one region may influence precipitation in adjacent areas, via effects on regional and global scale atmospheric circulation [*Barnett et al.*, 1989].

One possible source of soil moisture anomalies that could influence the NAMS is melt of an above or below-normal snowpack. *Gutzler and Preston* [1997] found a negative correlation between springtime snow cover in the Southern Rocky Mountains (SRM) (Figure 1b) and July/August precipitation in New Mexico, located at the northern edge of the NAMS region. They hypothesized that an above-normal SRM snowpack inhibits precipitation in the NAMS region, analogous to the relationship between Eurasian snow cover and the Southeast Asian monsoon [e.g., *Barnett et al.*, 1989].

The hypothesized model is that springtime melt of above-normal snow cover lowers land surface temperatures, weakening the ocean-to-land temperature gradient that drives the monsoon. An above-normal snowpack raises the surface albedo and acts as a "heat sink" during snowmelt, but this effect is limited to the snowmelt season (spring) [*Barnett et al.*, 1989]. The effects of above-normal snowfall may persist into the monsoon season via memory of the soil moisture reservoir, resulting from later snowmelt or wetter soil subsequent to snowmelt [*Gutzler and Preston*, 1997; *Vernaker and Zhou*, 1995; *Barnett et al.*, 1989]. Wet soil raises the evaporation rate and increases the thermal inertia of the soil, so the land surface stays cooler than normal during the summer months. Additional work is needed to gauge the duration and intensity of SRM soil moisture anomalies following the melt of anomalous snowpacks. However, we use this model as a guide to describe how snowcover could influence soil moisture.

Year-to-year fluctuations in monsoon rainfall are another possible source of soil moisture anomalies that could influence the NAMS. Above or below-normal rainfall yields anomalous soil moisture within the NAMS region that could influence rainfall later in the monsoon season, perhaps via a positive soil moisture-rainfall feedback [e.g., *Eltahir*, 1998].

Model and Simulations

We used the MM5 model coupled to the Oregon State University land surface model (OSU) to compare the effects of soil moisture anomalies in the SRM and NAMS regions on summertime precipitation. MM5 is a limited area, sigma-coordinate, non-hydrostatic, mesoscale atmospheric model [*Grell et al.*, 1994]. OSU calculates the water and energy balance for a single canopy and four soil layers [*Chen et al.*, 1996]. The MM5-OSU modeling system explicitly accounts for land-atmosphere interactions, enabling us to study the influence of soil moisture anomalies on monsoon precipitation. Earlier versions of the MM5 model have been used for NAMS simulations [*Stensrud et al.*, 1995], but the

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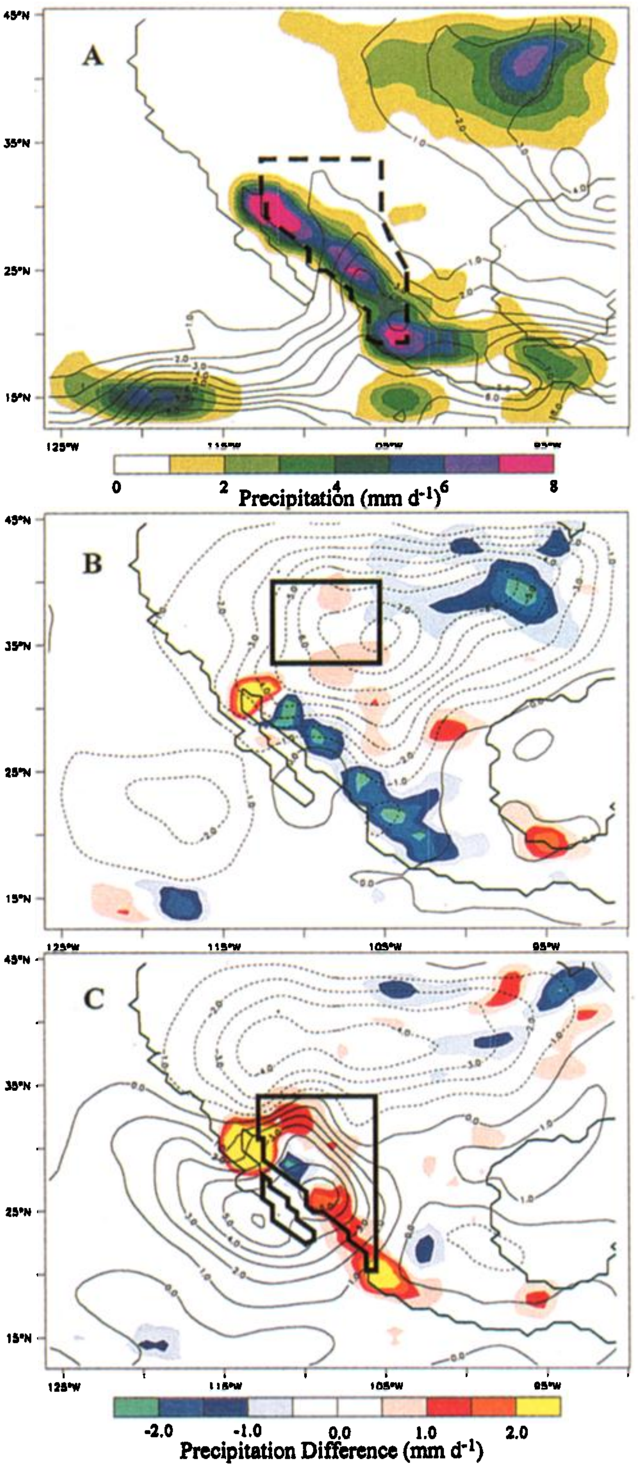

Figure 1. Model domain. (A) The region used to calculate NAMS average values is outlined with the dotted line. Colors denote simulated precipitation and contours represent observed precipitation (GPCP dataset) for July 1995 (B) Box shows SRM region where soil moisture was prescribed to field capacity in Mts-Wet case. Colors denote precipitation differences and contours denote 200 mb geopotential height differences (m) between the Mts-Wet and Control simulations during July. (C) Thick line shows location of prescribed soil moisture anomalies in the NAMS-Wet experiment. Colors and contours are the same as in B, but for differences between the NAMS-Wet and Control simulations.

influence of soil moisture state was not investigated.

We used a domain centered on the NAMS region (Figure 1) with a horizontal resolution of 60 km and 23 sigma layers in the vertical. National Center for Environmental Prediction (NCEP) Reanalysis data were used for initial and temporally-varying lateral boundary conditions, including initialization of soil moisture. Experiments were initialized on 1 June 1995 and ran continuously through 1 August 1995. Sea surface temperatures (SSTs) were fixed at June 1 1995 values, even though observed SSTs vary by several degrees during the simulated interval, as the model version used does not include temporal SST variations.

We compared results from a "Control" simulation to observations to assess the performance of the model in simulating the NAMS. Soil moisture evolved freely during this experiment. A "Mts-Wet" simulation was completed to explore the influence of above-normal soil moisture in the SRM on NAMS precipitation. Soil moisture was prescribed to field capacity across the SRM region (Figure 1b) throughout the experiment to represent the outcome of melt of an above-normal snowpack. This anomaly could also result from above-normal summertime precipitation in the SRM region. We also completed a "NAMS-Wet" simulation to examine the influence of above normal soil moisture content within the NAMS region. This simulation is identical to the control during June. Beginning on July 1, we fixed the soil moisture content at field capacity across the NAMS region (Figure 1c), to replicate the land surface forcing that could result from above-normal precipitation during the monsoon season.

Observations that constrain soil moisture fluctuations across the SRM and NAMS regions are limited. Therefore, it was necessary to choose the magnitude, duration, and spatial extent of the anomalies prescribed in our sensitivity experiments. We picked field capacity to represent wet soil. In the OSU model, evapotranspiration is not restricted by water availability when soil moisture is at or above field capacity, yielding the highest latent heat flux for a given set of atmospheric conditions. We held water content at field capacity across the SRM and NAMS regions, even though actual soil moisture anomalies are probably not as extensive or long-lived. Therefore, the anomalies prescribed here yield relatively intense forcing on NAMS precipitation. If the rainfall response to this forcing was not substantial, then there would be no reason to assess the influence of more realistic

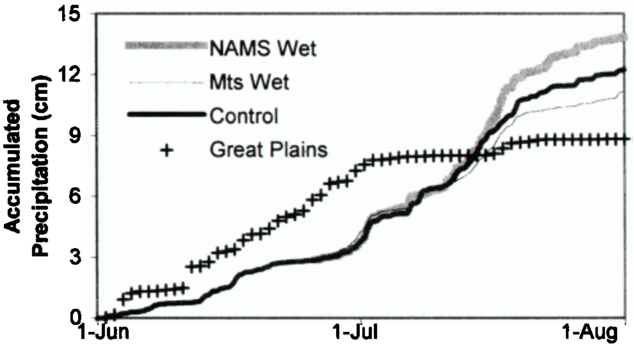

Figure 2. Accumulated precipitation in the various experiments averaged over the NAMS region. Accumulated precipitation over the Great Plains in Control is also shown.

soil moisture anomalies. However, the response to this forcing is dramatic, providing motivation for additional studies.

Results

The 1995 monsoon season was drier than normal (Table 1). The NCEP Reanalysis data shows that the 1995 June-to-July changes in atmospheric conditions associated with monsoon onset [*Higgins et al.*, 1998] were relatively weak. These are reproduced in the Control case, including (1) growth of a weaker than normal upper-troposphere ridge, (2) a shift from westerly to easterly mid-tropospheric winds, and (3) increased precipitable water.

The model also reproduces the onset of monsoon precipitation in July and the associated decrease in Great Plains precipitation [*Higgins et al.*, 1998] (Figure 2, Table 1). However, the magnitude of the June-to-July precipitation increase over the NAMS region is greater than that in the Global Precipitation Climatology Project (GPCP) dataset (Table 1). During July, the simulated pattern of precipitation is similar to the GPCP pattern over land (Figure 1a). The greatest precipitation occurs over the southern portion of the NAMS region, with high values extending along the Sierra Madre Occidental. The simulated precipitation is greater than observed over these mountains, perhaps reflecting the coarse resolution (2.5 degrees) of the GPCP data, resulting in an average bias throughout the NAMS region of ~50% (Table 1). The limited precipitation (< 1 mm d^{-1}) observed over the southern Great Plains and Western U.S. is also reproduced. The observed maximum over the tropical Pacific is misplaced south of the domain boundary in the driving NCEP fields, so the MM5 model does not reproduce this feature.

Southern Rocky Mountain soil moisture anomalies

During June, precipitation in the NAMS region increases slightly when soil is prescribed to field capacity in the SRM, as shown by the differences between the Mts-Wet and Control experiments (Figure 2, Table 1). During July, the NAMS response to wet soil in the SRM is more dramatic. Precipitation decreases throughout most of the monsoon region, by an average of ~0.5 mm d^{-1} or 20% (Figure 1b, Table 2). This result is consistent with *Gutzler and Preston's* [1997] hypothesis—anomalously wet conditions in the SRM inhibit monsoon precipitation. The NAMS response is the most spatially extensive change in the model domain, but other changes do exist. Precipitation decreases in the Midwest and increases locally in the area (New Mexico) from which *Gutzler and Preston's* [1997] precipitation data were taken.

The prescribed SRM soil moisture conditions modify the surface energy balance (SEB) in that region. This is the source of the precipitation changes throughout the domain. Wet soil raises the latent heat flux and reduces the sensible heat flux by nearly equal amounts, resulting in a decrease in surface temperature of 1.8 °C (Table 2). Net radiation and available energy are nearly unchanged (Table 2), so it is the change in partitioning of available energy between latent and sensible heat that drives the simulated changes in atmospheric circulation and precipitation.

Table 1. Precipitation (mm d^{-1}) in the NAMS region

	GPCP Climatology	GPCP 1995	Control	Mts-Wet	NAMS-Wet
June	0.94	0.78	1.17	1.30	1.17
July	2.73	1.74	2.80	2.35	3.34
July-June	1.79	0.96	1.63	1.05	2.17

GPCP Climatology calculated from data spanning 1987-1997.

Table 2. Ground Temperature (T_{grd} in K) and Surface Energy Balance (W m^{-2}) in SRM and NAMS Regions

	T_{grd}	LH	SH	NR	BR
Ctl (SRM)	291.1	69.7	83.5	193	1.2
MtsWet-Ctl (SRM)	-1.8	36.2	-32.2	1.4	-0.7
Ctl (NAMS)	302.6	24.1	146.7	211	6.1
NAMSWet-Ctl (NAMS)	-2.6	83.0	-78.0	8.5	-5.5

Values in control case (Ctl) and differences between experiments and control, averaged over SRM and NAMS regions. Latent Heat (LH); Sensible Heat (SH); Net Radiation (NR); Bowen Ratio (BR).

Reduced sensible heating of the atmosphere in the SRM produces circulation changes similar to the anomalies observed during dry years [*Higgins et al.*, 1998]. Reduced sensible heating leads to (1) a weakening of the upper-troposphere ridge centered over the northeastern corner of the NAMS region (Figure 1b) and (2) reduced mid-troposphere vertical velocity throughout the NAMS region. In addition, the water vapor flux from the Gulf of Mexico into the NAMS and Midwest regions is diminished.

The reduced water vapor flux into the Midwest is the source of decreased precipitation in that region. The Midwestern response is adjacent to an outflow boundary and the Control precipitation in this area differs from observed values (Figure 1a). Therefore, more work is required to test if the SRM land surface—Midwest rainfall link is reasonable. In contrast, the NAMS region is in the center of the domain, minimizing the possibility of inconsistencies between forcing within and outside of the domain.

North American monsoon system soil moisture anomalies

Wet soil in the NAMS region yields a different response—July precipitation increases over most of the monsoon region (Figure 1c). The magnitude of the change across the NAMS region (0.54 mm d^{-1} or ~20%) is similar to that resulting from wet soil in the SRM, but is opposite in sign (Figure 2, Table 1). As in the Mts-Wet case, the precipitation change in the NAMS region is the most spatially continuous throughout the domain. A small area of decreased precipitation exists within the NAMS region, linked to a substantial increase in latent heat flux and rainfall north of the Gulf of California. A similar effect exists in the Mts-Wet case (Figure 1b), and may be caused by the coarse resolution land-sea mask.

Prescribing soil moisture to field capacity yields larger SEB changes in the NAMS region than in the SRM (Table 2) because NAMS soil is dryer in the control. An increase in latent heat flux is balanced by a decrease in sensible heat flux, yielding a decrease in surface temperature of nearly 3 °C (Table 2). The changes in shortwave and longwave radiation yield a modest increase in net radiation (~9 W m^{-2}), so the simulated response to wet soil is consistent with *Eltahir's*

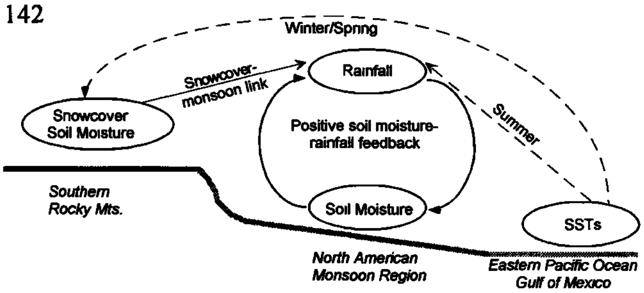

Figure 3: Schematic of atmosphere-land-ocean connections possibly influencing variability of NAMS.

[1998] soil moisture-net radiation feedback hypothesis. The boundary layer height decreases over the region with wet soil, from 1350 m to 980 m, due to the decrease in sensible heat flux. This concentrates slightly more energy in a shallower boundary layer, enhancing the vertical gradient in moist static energy. Therefore, the simulated pathway that links soil moisture and NAMS rainfall is analogous to that observed elsewhere [*Betts and Ball*, 1998; *Eltahir*, 1998].

The simulated changes in atmospheric state caused by wet soil in the NAMS region resemble the anomalies observed during strong monsoon seasons. There is an increase in upper-troposphere geopotential height centered on the climatological monsoon high (Figure 1c) and increased mid-troposphere vertical velocity and precipitable water throughout the NAMS region. Changes in the vertically-integrated water vapor flux are not spatially coherent.

An ensemble of simulations is needed to quantify the portion of changes in the sensitivity experiments resulting from internal model variability. However, several lines of evidence suggest that the changes largely reflect the response to surface forcing. First, the response in the NAMS region is the greatest in magnitude and extent throughout the domain, in both experiments (Figures 1b and 1c). Second, physically reasonable mechanisms link the imposed soil moisture changes to the precipitation response. Third, the atmospheric response resembles conditions observed in wet or dry years, for the NAMS-wet and Mts-Wet cases respectively.

Summary

The MM5-OSU model reproduces key features of the NAMS during 1995. The simulated responses to prescribed soil moisture anomalies are large, spatially consistent, and are the result of physically reasonable pathways linking SEB changes to modifications of the atmosphere. The influence of soil moisture forcing depends critically on the location of anomalous conditions. Wet soil in the SRM inhibits precipitation in the NAMS region during July, consistent with observations [*Gutzler and Preston*, 1997]. In contrast, wet soil in the NAMS region enhances precipitation within that region—a positive soil moisture-rainfall feedback exists.

Our findings are preliminary and need to be tested. First, we have only assessed the control climate and explored the sensitivity to wet soil during a single June-July interval. Second, optimization of the model configuration is possible, including improved soil moisture initialization and the representation of temporally varying SSTs. Third, an ensemble of simulations is needed to separate the response to surface forcing and internal model variability. Finally, we prescribed soil moisture to field capacity throughout the SRM and NAMS regions. Experiments that include more realistic forcing are needed. Anomalies should be set as initial conditions and then permitted to evolve freely. Surface and remotely sensed observations should be collected and used to constrain the extent and magnitude of initial anomalies.

NAMS precipitation is sensitive to the distribution of soil moisture and latent heating, so an accurate representation of the land surface state is a necessary element for a successful NAMS simulation. Limited data exist to assess if simulated land surface conditions are reasonable and to apply as temporally evolving boundary conditions. Therefore, additional surface and remotely sensed land surface data are needed to further our understanding of the NAMS.

We have treated the feedbacks in the SRM and NAMS regions independently, but linkages between these mechanisms may exist. First, the SRM influence on NAMS rainfall may trigger the positive feedback within the NAMS region. For example, below-normal soil moisture in the SRM enhances summertime NAMS precipitation, which could then be sustained or intensified by the soil moisture-rainfall feedback (Figure 3). Second, season-to-season memory of SST anomalies, via their influence on the atmospheric state over North America, could force both linkages to moderate monsoon precipitation in the same direction concurrently, particularly if SST anomalies yield opposing precipitation responses during winter/spring and summer [*Higgins et al.*, 1998]. For example, if negative SST anomalies limit snowcover but enhance monsoon precipitation, both land-atmosphere linkages could enhance summertime NAMS precipitation concurrently. Therefore, unraveling the sources of NAMS variability requires consideration of the interactions between the atmosphere, land, and ocean.

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