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Soil moisture–precipitation feedback on the North American monsoon system in the MM5-OSU model

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SUMMARY

In this study, the Pennsylvania State University/National Center for Atmospheric Research fifth generation Mesoscale Model (MM5) linked to the Oregon State University (OSU) land-surface scheme, is used to assess the strength of soil moisture–precipitation feedback in the region of influence of the North American monsoon (NAM). Two control simulations are made with external forcing taken from the National Centers for Environmental Prediction re-analysis, and with a nested horizontal resolution of 30 km, for the period 1 June to 30 September in wetter than average (1999) and drier than average (2000) monsoon seasons. These two model runs are then repeated with a prescribed precipitation rate anomaly in July over the entire NAM region, and comparisons made between atmospheric and land-surface states in the two control runs and the two runs with anomalous precipitation. The results show that size and importance of soil moisture–precipitation feedbacks in the NAM region have substantial interannual variability, and that the resulting behaviour has a strong dependency on the intensity of the prescribed precipitation anomaly. It is also shown that a marked precipitation anomaly in the NAM region results in modified soil moisture, rainfall, and surface temperature, which persist for about one month, and that a precipitation anomaly within the NAM region not only has an impact on soil moisture locally, but also causes a remote, downwind soil moisture anomaly one month later. Analysis of the modelled response to the soil moisture anomaly indicates that not only land–atmosphere interactions, but also the large-scale atmospheric circulation act together to determine the modified precipitation and soil moisture fields in the NAM system.

KEYWORDS: Land surface processes Rainfall

1. INTRODUCTION

The North American monsoon (NAM) system occurs from July through September (Douglas *et al.* 1993) in the south-western USA and north-west Mexico. Its interannual variability is believed to be related to conditions in the eastern tropical Pacific Ocean (Higgins *et al.* 1999) and also to more local land-surface processes (Oglesby and Erickson 1989; Beljaars *et al.* 1996; Giorgi *et al.* 1996; Gutzler and Preston 1997). This study puts emphasis on investigating the role of land-surface processes in the variability of the NAM system.

Variability of the soil moisture field strongly influences land-surface processes in general, and the magnitude of water and energy fluxes to the atmosphere in particular (Yeh *et al.* 1984). Soil moisture can provide long-term memory, or persistence, in land-surface boundary conditions and may influence large-scale atmospheric circulation over a sustained period (Schär *et al.* 1999). Observations and modelling studies suggest that a positive soil moisture–precipitation feedback may magnify and/or prolong hydroclimatic anomalies in several different climate regions (Barnett *et al.* 1989; Eltahir 1998; Pal and Eltahir 2001), and in the NAM region antecedent precipitation which is above or below normal could therefore influence subsequent monsoon rainfall by creating soil moisture anomalies (Small 2001). One hypothesis for positive soil

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moisture–precipitation feedback is via the role of radiation (Eltahir 1998; Zheng and Eltahir 1998), but in the case of the NAM system the response of rainfall to soil moisture is likely to be a more complicated process for several reasons. First, the topography of the south-western USA and central Mexico where the NAM occurs is complicated and is known to influence precipitation, so the location of anomalous surface conditions could be critical (Small 2001). There is also substantial interannual variability in the NAM, and the influence of soil moisture could be nonlinear and depend on whether the monsoon is wetter or drier than average. In addition, NAM precipitation is strongly influenced by the atmospheric water content and instability in the atmosphere, so the effect of atmosphere circulation could be significant in determining the soil moisture–precipitation feedback.

In this study, we used the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) fifth generation mesoscale model (MM5; Grell *et al.* 1994) linked to the Oregon State University land-surface scheme (OSU; Chen and Dudia 2001), hereafter referred to as the MM5-OSU model. We used the MM5-OSU model to investigate soil moisture–precipitation feedback in the NAM by studying how prescribed precipitation anomalies impact subsequent soil moisture and surface fluxes, and by tracking the coupled surface water and atmospheric circulation in the NAM region and surrounding areas. The model and simulation design are presented in section 2 and the validation of the control experiments is described in section 3. The results of the sensitivity experiments and the soil moisture–precipitation feedback over the NAM region are given in section 4 and discussed in section 5; conclusions are given in section 6.

2. MODEL AND SIMULATION DESIGN

(*a*) *Numerical model description*

Based on our previous study with the MM5-OSU model (Xu and Small 2001), we chose to use the Grell cumulus convective parametrization and the RRTM* radiation scheme for convection simulation in this study. The planetary boundary layer (PBL) was modelled by the high-resolution Blackadar scheme. The OSU Land-Surface Model (LSM) is capable of predicting soil moisture and temperature in four layers (10, 30, 60, and 100 cm thickness) as well as canopy moisture and water-equivalent snow depth. It also provides surface and underground runoff accumulations as outputs. The OSU LSM makes use of vegetation and soil type when calculating evapotranspiration, and includes the effect of variables such as soil conductivity and the gravitational flux of moisture. The OSU LSM can be used in MM5 to provide surface fluxes to the PBL scheme using surface-layer exchange coefficients along with radiative forcing and precipitation rate as input parameters (Chen *et al.* 1997; Chen and Dudhia 2001). Using the OSU LSM modelling system (which explicitly accounts for land–atmosphere interactions) rather than the alternative **slab** model enables us to study soil moisture–precipitation feedback in the monsoon region.

(*b*) *Control simulations*

A year with less than average NAM precipitation (1999) and one with more than average NAM precipitation (2000) were chosen, and control simulations (CTL) made from June 1 through September 30 in each case. For this purpose a 90 km coarse grid was selected, so as to permit realistic representation of low-level flow from both the Gulf of California and the Gulf of the Mexico (Fig. 1). A 30 km two-way nested grid centred over the NAM region was then used to allow for improved representation of the

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* Rapid Radiative Transfer Model.

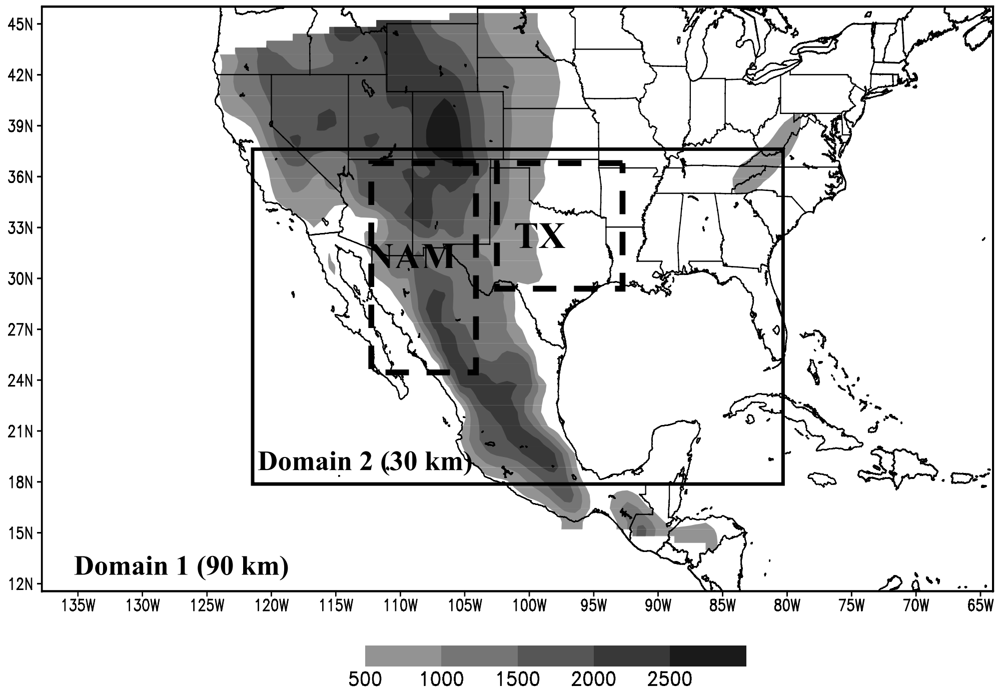


Figure 1. Domains used in the MM5 (see text) simulation runs. The outer box (Domain 1) is the area covered by the coarse 90 km grid with 40 × 684 grid squares; the inner box (Domain 2) is the area covered by the nested 30 km grid with 100 × 70 grid squares; and the two boxes with dashed outlines designate specific areas used in the analysis, namely the area most influenced by the North American monsoon (NAM; 112–105°W, 24–36°N) and Texas (TX; 102–93°W, 30–36°N). The shading indicates topography in intervals of 500 m.

complex topography and associated spatial variability in surface characteristics in the NAM region (Fig. 1).

The initial conditions were specific for June 1 in each year. These initial conditions and the time-varying boundary conditions were taken from the National Centers for Environmental Prediction (NCEP)/NCAR re-analysis dataset (Kalnay *et al.* 1996). The initial conditions included atmospheric and surface fields, the latter including soil moisture and temperature. The time-varying boundary conditions include both the atmospheric fields at the lateral boundaries of the coarse domain and sea surface temperatures (SSTs) throughout the coarse and fine domains. In practice, the relatively high-resolution (30 km) MM5 land–ocean mask is inconsistent with the coarse-resolution (2.5°) time-varying SST boundary conditions provided by NCEP. There are extensive coastal areas represented as ‘ocean’ in the MM5 model that were considered ‘land’ in the coarser resolution NCEP data from which SSTs are extracted. This results in the NCEP SSTs apparently being greater than 40 °C during the middle of the day in some coastal areas, and this in turn produces very high latent heating of the atmosphere and precipitation over nearby elevated topography. This problem is most severe along the Gulf of California, which is a critical area when simulating the NAM system. Consequently, we used Reynold’s SST data (Reynolds and Smith 1994) over the Gulf of California and in parts of the Gulf of Mexico at locations where the NCEP data actually represents land-surface temperatures. Replacing the high NCEP surface temperatures with more realistic SSTs greatly improves the simulated precipitation in coastal areas (not shown).

(*c*) *Sensitivity experiments*

The model experiments use the same forcing as CTL; but, in order to generate a soil moisture anomaly, prescribed precipitation anomalies were introduced for the entire month of July in the NAM region, which is defined as the area 24–36°N, 105–112°W (Fig. 1). The prescribed precipitation anomalies are calculated based on the climatology of precipitation from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) dataset (Xie and Arkin 1996) from:

$$P^{\mathrm{E}}(t, x, y) = F.P^{\mathrm{C}}(t, x, y) \tag{1}$$

where $P^{\mathrm{C}}(t, x, y)$ represents the field of mean precipitation in July calculated from the control run (as a function of time, t, and space, x and y, coordinates); $P^{\mathrm{E}}(t, x, y)$ is the field used to prescribe the precipitation anomaly in the NAM region for the sensitivity experiments; and F is a factor, defined as:

$$F = (\textit{climatological mean precipitation})/(\textit{precipitation in the simulated year}). \tag{2}$$

In other words, within the NAM region, F is the ratio of the precipitation climatology (this being the mean CMAP precipitation for July from 1979 to 2002) to the mean precipitation for July in the study year. In the 1999 experiment, F was set equal to 0.7, i.e. $P^{\mathrm{E}}(t, x, y)$ is slightly smaller than the $P^{\mathrm{C}}(t, x, y)$. In contrast, in the 2000 experiment F was set equal to 4.0, i.e. $P^{\mathrm{E}}(t, x, y)$ was much higher than $P^{\mathrm{C}}(t, x, y)$. In August and September the model was then integrated continuously, but the prescribed precipitation anomaly was not imposed.

3. VALIDATION OF CONTROL EXPERIMENTS

(*a*) *Precipitation*

Figure 2 shows the total precipitation for July, August, and September (JAS) 1999 and 2000 as given by observations and in the two control experiments. The observed precipitation in the USA is taken from the US CPC real-time analysis dataset (Higgins *et al.* 1996); CMAP data (Xie and Arkin 1996) are used in Mexico where gauge observations are less dense. In 1999 substantial precipitation was observed over the western portion of the NAM region, with high values extending from the Sierra Madre Occidental (SMO, the western mountains in Mexico) to Arizona and also significant precipitation in the south-eastern USA. However, precipitation was relatively light throughout most of Texas (TX). In 2000 (Fig. 2(b)), precipitation was again low in TX and New Mexico, but there were regions with significant precipitation in the south-eastern USA and over the SMO. The most noticeable differences between the two years 1999 and 2000 (Fig. 2(c)), is that there was less precipitation during 2000 over most of Mexico, Arizona, New Mexico and TX, but more over the south-eastern USA.

Comparison of Figs. 2(d)–(f) with Figs. 2(a)–(c) shows that the control simulations capture the precipitation patterns in the two simulated periods reasonably well. The two zones with high precipitation in the south-eastern USA and the SMO are reasonably well reproduced and, in particular, the reduction in precipitation between 1999 and 2000 over northern Mexico, eastern Arizona, all of New Mexico, and TX is well captured (Fig. 2(f)). However, compared to observations, both control simulations systematically overestimate precipitation in south-eastern TX near the Gulf of Mexico, and precipitation is underestimated over Arizona in 1999 and overestimated over northern New Mexico in 2000.

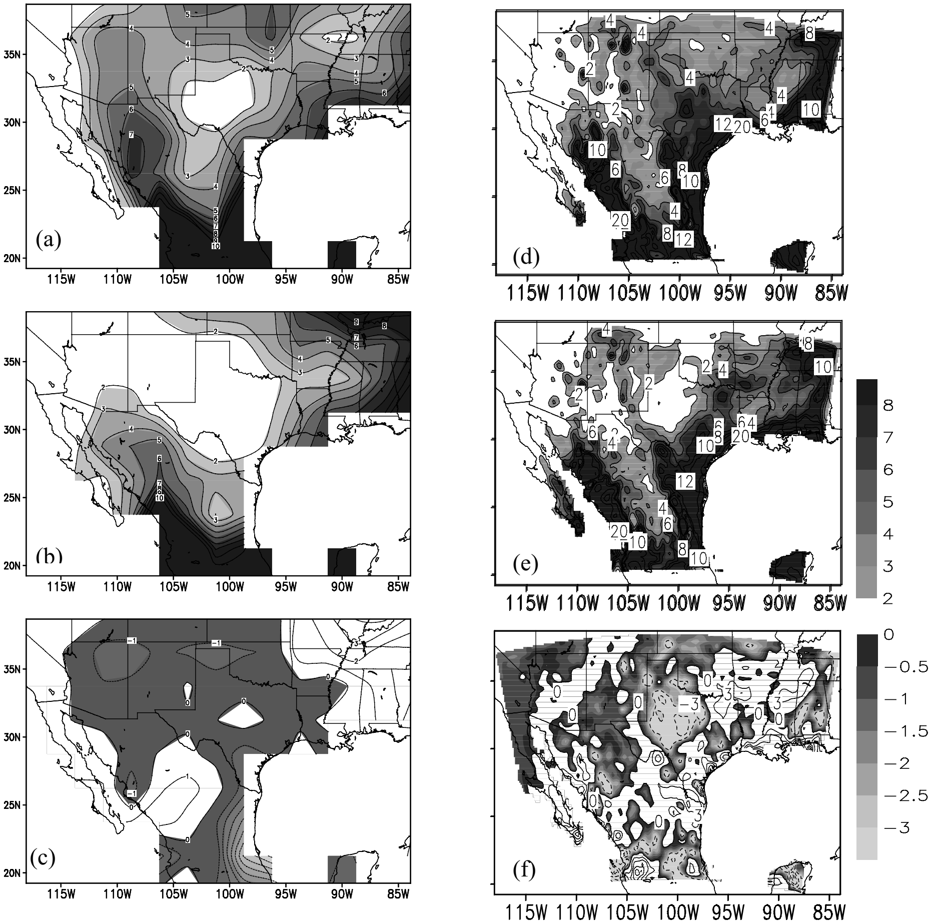


Figure 2. (a) Total precipitation (mm) for July, August and September (JAS) 1999; (b) as (a) but for JAS 2000; (c) the difference in total precipitation (JAS 2000 minus JAS 1999) for the CMAP (see text) observations; (d) total precipitation given by the control runs for JAS 1999; (e) as (d) but for JAS 2000; (f) as (c) but for the control experiments.

Table 1 gives the monthly total precipitation derived from observations and also values calculated in the control simulations averaged over the regions shown as NAM and TX in Fig. 1. In July and August 1999, the simulated precipitation is reasonably close to observations in the NAM region, the difference being less than 20% (Table 1a); while in September 1999, the modelled precipitation in the NAM region is about 34% and 19% less than the CPC and CMAP observations, respectively. The modelled precipitation over the three summer months is significantly overestimated in the NAM region in 2000 (Table 1b), typically by a factor of two or greater. As was the case for the NAM region, the simulated precipitation in the TX region is overestimated in July and August 1999 and underestimated in September 1999. However, the error in the model estimates in the TX region is much greater than that in the NAM region. In 2000, the simulated precipitation in the TX region in August (∼1.3 mm day^{-1}) is much greater than the observed precipitation (∼0.2 mm day^{-1}), while the precipitation in July and September 2000 is relatively close to observations.

TABLE 1. PRECIPITATION IN 1999 AND 2000

	NAM		TX	
	CPC/CMAP	MM5 (CTL)	CPC/CMAP	MM5 (CTL)
(a) 1999				
July	2.4/3.5	2.8	1.8/1.3	1.7
August	1.5/1.5	1.7	1.3/0.6	1.9
September	1.0/0.8	0.6	2.4/1.8	1.0
(b) 2000				
July	0.6/0.6	1.6	1.7/1.2	2.1
August	1.0/0.7	2.0	0.2/0.2	1.3
September	1.1/ –	2.5	1.2/ –	1.2

Monthly total precipitation (mm) averaged over the NAM (North American monsoon area, 112–105°W, 24–36°N) and TX (Texas, 102–93°W, 30–36°N) regions from US Climate Prediction Center real-time analysis datasets (CPC) and the CPC Merged Analysis of Precipitation data (CMAP), compared with that simulated in the control runs (CTL) of the Pennsylvania State University/National Center for Atmospheric Research fifth generation Mesoscale Model (MM5). No CMAP data were available for September 2000.

In summary, we find that in most areas (except south-eastern TX) the control simulations reproduce the precipitation pattern in JAS of 1999 and 2000 reasonably well, although precipitation is sometimes underestimated or overestimated. In particular, the precipitation simulated in the NAM region in the wet year (1999) is much better than that simulated in the dry year (2000), the magnitude of the simulated precipitation in 2000 being much greater than that observed. Given the focus of this study on the NAM system, it is fortunate that the simulated precipitation in the NAM region is closer to observations than in the TX region.

(*b*) *Soil moisture*

Figure 3 shows the average volumetric soil moisture content in the full modelled soil layer (0–2 m) in JAS in 1999 and 2000, as given by the NCEP/NCAR re-analysis fields and by the control experiments. In 1999, the NCEP/NCAR re-analysis field (Fig. 3(a)) shows a large area with low volumetric soil moisture content (less than 0.15 m^3m^{-3}) across the entire south-western USA. Volumetric soil moisture content is relatively high (greater than 0.20) throughout southern Mexico and the south-eastern USA. In 2000 (Fig. 3(b)) the distribution of volumetric soil moisture content is similar to the pattern in 1999. However, the difference between 2000 and 1999 (Fig. 3(c)) indicates that soil moisture was less in 2000 than in 1999 across the entire study area and was much less in the NAM region, a result consistent with the lower precipitation in that year (see Fig. 2(c)).

Comparisons between the NCEP/NCAR re-analysis field (Figs. 3(a)–(c)) and the model simulated results (Figs. 3(d)–(f)), suggest that the MM5 model captures the overall soil moisture patterns in 1999 and 2000 and the interannual difference between the two years fairly well, except for areas in eastern Mexico and the south-eastern USA. In the two model simulations, the NAM region is the driest area in the domain studied, with drier soils in western regions and wetter soils in eastern regions. Table 2 presents a comparison between the NCEP/NCAR re-analysis estimates and the simulated mean monthly volumetric soil moisture content in the full modelled layer (0–2 m) averaged over the NAM and the TX regions. The simulated volumetric soil moisture content over the NAM region is close to the NCEP/NCAR re-analysis values, with a difference of

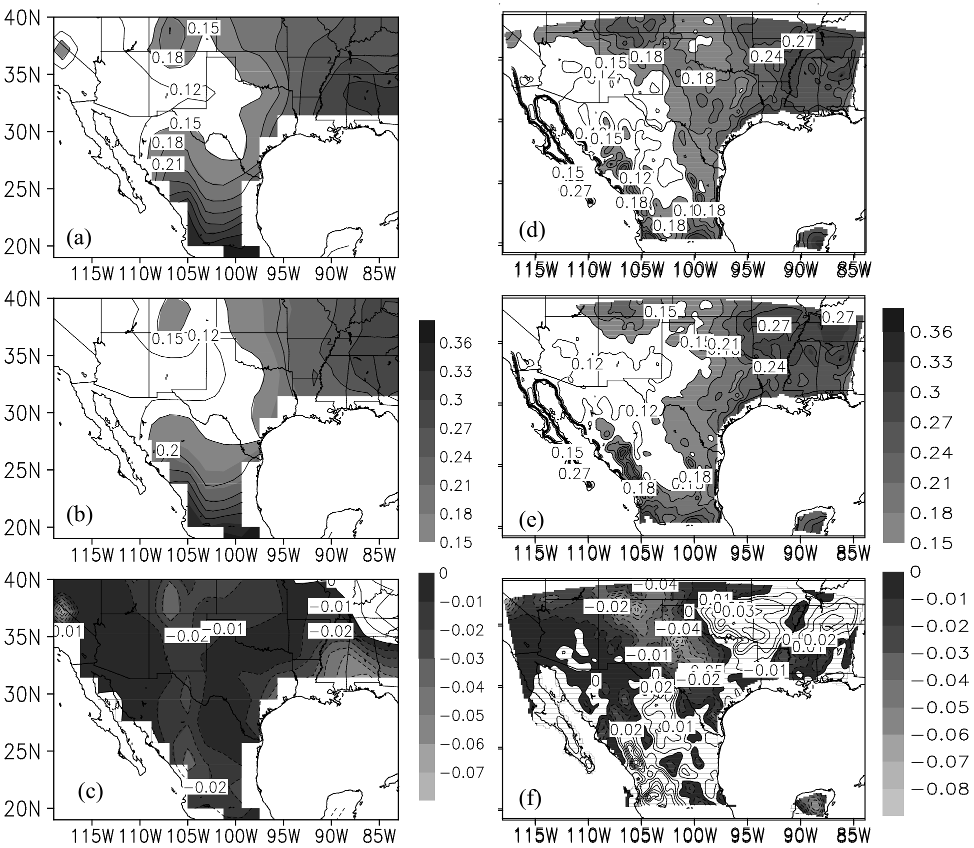


Figure 3. (a) The average volumetric soil moisture content (m^3m^{-3}) in the full modelled soil layer (0–2 m) for July, August, and September (JAS) from the NCEP/NCAR (see text) re-analysis field in 1999; (b) as (a) but for JAS 2000; (c) the difference in average volumetric soil moisture content (JAS 2000 minus JAS 1999); (d), (e) and (f) are as (a), (b) and (c), respectively, but for the control experiments.

TABLE 2. SOIL MOISTURE 0–200 cm IN 1999 AND 2000

	NAM		TX	
	NCEP/ NCAR	MM5 (CTL)	NCEP/ NCAR	MM5 (CNTL)
(a) 1999				
July	0.13	0.14	0.20	0.20
August	0.14	0.15	0.16	0.19
September	0.16	0.15	0.16	0.18
(b) 2000				
July	0.12	0.13	0.19	0.20
August	0.14	0.14	0.16	0.18
September	0.15	0.15	0.15	0.17

The volumetric soil moisture content in the full modelled soil layer (0–0.2 m) averaged over the NAM (North American monsoon area, 112–105°W, 24–36°N) and TX (Texas, 102–93°W, 30–36°N) regions as estimated by the NCEP/NCAR (see text) re-analysis and as simulated by the Pennsylvania State University/National Center for Atmospheric Research fifth generation Mesoscale Model (MM5) in the control runs (CTL).

less than 10%. In the TX region the error is a little higher, about 15–20%. The monthly average volumetric soil moisture content increases from July to September in the NAM region and its monthly average value is about 20–50% less than in the TX region, where the monthly average volumetric soil moisture content decreases with time.

In 1999, the NCEP/NCAR re-analysis estimates and simulated monthly average volumetric soil moisture content in both regions are somewhat higher than the corresponding values in 2000. In general, the control runs with the MM5 model seems to capture the volumetric soil moisture content estimated in the NCEP/NCAR re-analysis fairly well over the study region, but it should be remembered that the NCEP/NCAR re-analysis is known to significantly overestimate the yearly soil moisture cycle in certain regions, and to underestimate interannual variability because it tends to relax to climatology (e.g. Roads *et al.* 1999; Lenters *et al.* 2000; Heck *et al.* 2001; Kanamitsu *et al.* 2002). Therefore, it would clearly be preferable to verify the quality of MM5 simulation against actual soil moisture measurements, if this were feasible.

4. RESULTS

(*a*) *Soil moisture*

The differences between the two sensitivity experiments and the two control simulations in 1999 and 2000 are used to investigate the horizontal distribution and the duration of the soil moisture anomaly resulting from the imposed precipitation anomalies. In 2000, model results (Figs. 4(a)–(c)) show that the imposed increase in precipitation rate in July substantially increased the volumetric soil moisture content in the upper modelled layer (0–10 cm) in the NAM region and surrounding areas. The positive soil moisture anomaly in the NAM region is retained until the end of August, but is strongly reversed in September and there is then a significant positive anomaly in the south-eastern USA. This interesting result echoes the negative correlation between precipitation in the NAM region and the south-eastern USA reported by Higgins *et al.* (1997).

In August 2000 (Fig. 5(a)) the average volumetric soil moisture content in the upper layer (0–10 cm) over the NAM region in the experiment run is larger than in the control run, but then is less in September 2000. In contrast, the positive anomaly of soil moisture in the second modelled layer (10–40 cm), although small, is retained throughout August and September 2000. In fact, the positive anomaly in volumetric soil moisture content in the second modelled layer lasts on average about 10 days longer than that in the upper modelled layer (not shown) and, in this sense, the second layer therefore has a 10 day longer ‘memory’ than the upper layer. Although the increase in soil moisture generated by the higher precipitation is not large, it lasts about one month after the prescribed increase in precipitation and this memory effect facilitates a delayed soil moisture–precipitation feedback.

Modelled behaviour in the wetter than average year (1999) differs from that in the drier than average year (2000), see Figs. 4(d)–(f). Initially, the imposed (modest) reduction in precipitation over the NAM region in July results in some decrease in the volumetric soil moisture content in the upper modelled layer over the NAM region, and there is also a slight reduction in adjacent regions. However, the negative anomaly in volumetric soil moisture content in the upper modelled layer does not persist in the NAM region once the prescribed reduction in precipitation rate is removed. Nonetheless, it is interesting that a negative soil moisture anomaly is then generated over the south-eastern USA (east of 95°W) in August 1999 which persists until September. Thus, the negative soil moisture anomaly signal appears to move east in 1999, a result similar

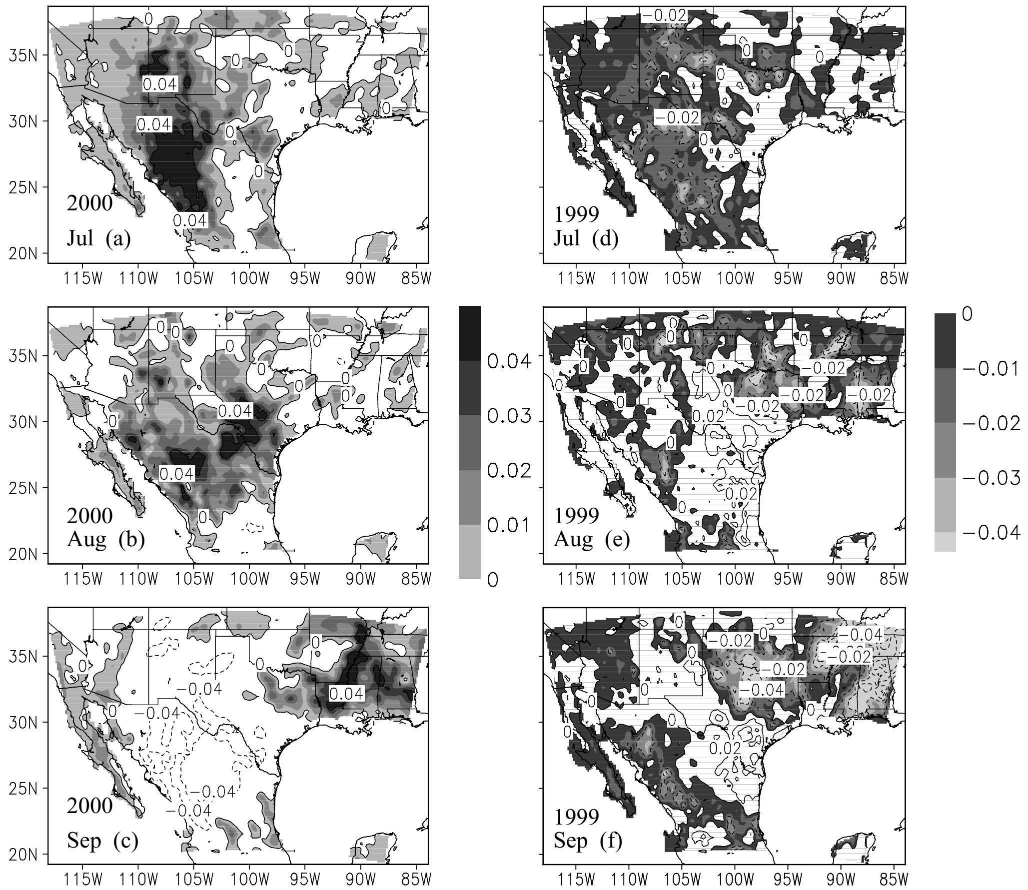


Figure 4. The difference in volumetric soil moisture content (m^3m^{-3}) in the upper modelled soil layer (0–10 cm) calculated in the two anomaly experiments relative to the two control runs: (a), (b), and (c) are for the individual months of July, August, and September, respectively, in 2000; (d), (e), and (f) are for July, August, and September, respectively, in 1999. The shaded contoured areas in (a), (b) and (c) indicate positive values, but those in (d), (e), and (f) indicate negative values, in each case in steps of 0.02 m^3m^{-3}.

to the behaviour in 2000 when the positive anomaly moved eastwards from the south-western to the south-eastern USA. This eastward movement implies that a precipitation anomaly in the NAM region not only has an immediate impact on soil moisture locally, but also causes a remote soil moisture anomaly downwind in the following month. Once the prescribed decrease in precipitation in July is removed, the (small) negative anomaly induced in volumetric soil moisture in 1999 (Fig. 5(b)) in the NAM region persists until September in both the upper modelled layer and the second modelled layer.

In summary, analysis of the differences in modelled soil moisture fields with and without imposed precipitation anomalies in July, suggests that the response of soil moisture strongly depends on the strength of the imposed precipitation anomaly, and that the anomalous soil moisture in the NAM region is predicted to move eastwards towards the south-eastern USA where it may persist for two months. This result suggests that soil moisture in the south-eastern USA may, in part, be predictable from knowledge of soil wetness in the south-western USA.

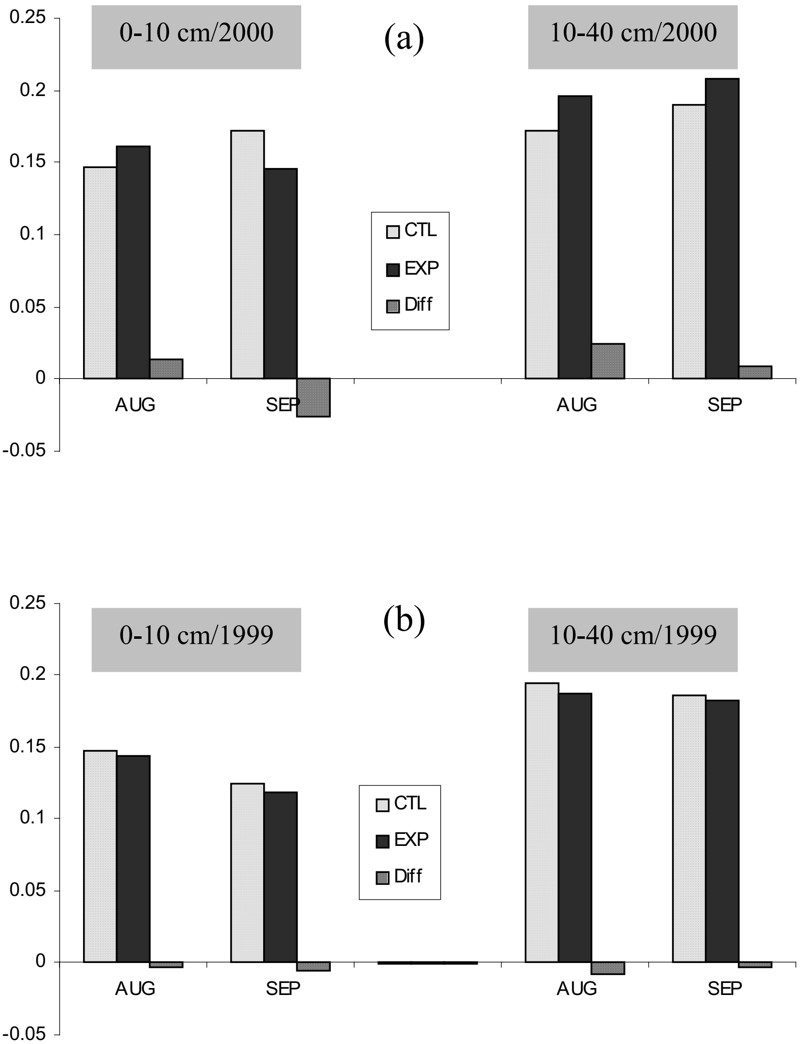


Figure 5. Volumetric soil moisture content (m^3m^{-3}) for August and September averaged over the North American monsoon region (24–36°N, 105–112°W) in the upper modelled soil layer (0–10 cm) and middle modelled soil layer (10–40 cm): (a) in 2000 and (b) in 1999. Values are given for the control runs, CTL, and model experiments, EXP, together with differences.

(*b*) *Precipitation*

In the year 2000, the difference in modelled precipitation in subsequent months following an imposed increase in precipitation in July (Figs. 6(a) and (b)) shows that precipitation is enhanced through most of the NAM region in August, but that the strongest anomaly is centred west of the NAM region (Fig. 6(a)), i.e. the soil moisture anomaly in the NAM region appears to produce a downwind precipitation anomaly. By September (Fig. 6(b)), the positive anomaly has shifted significantly eastwards to the south-eastern USA, and the NAM region then experiences a negative anomaly.

In contrast, the modelled difference in precipitation in August 1999 (Figs. 6(c) and (d)) shows that the largest decrease occurs in the south-eastern USA and that most of the NAM region (except for the western SMO) experiences a slight positive anomaly. By September, a small negative anomaly appears over the NAM region and the strongest

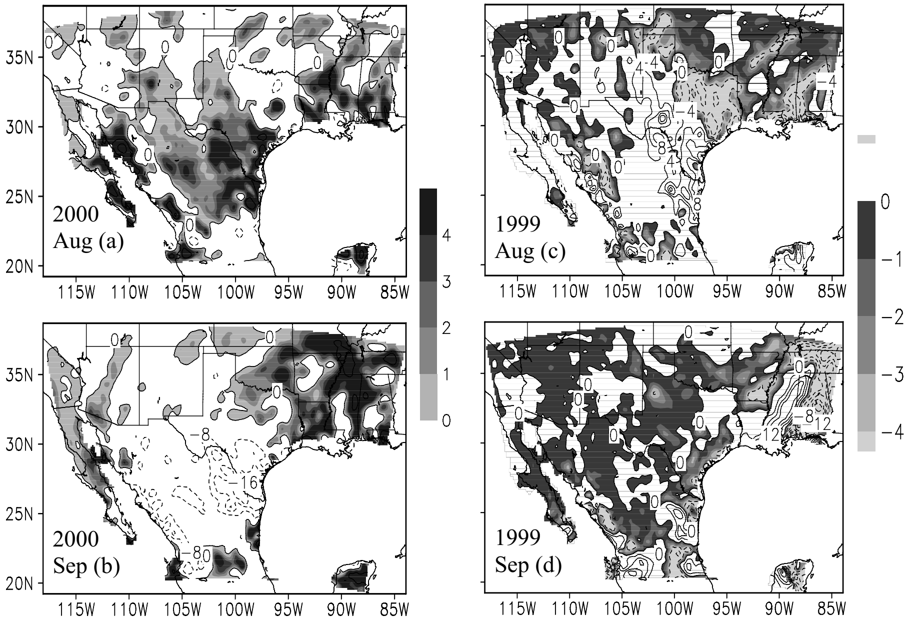


Figure 6. The difference in the monthly precipitation (mm) between the anomaly experiments and the control runs in: (a) August 2000, (b) September 2000, (c) August 1999, and (d) September 1999. Shaded areas in (a) and (b) indicate positive values, but in (c) and (d) indicate negative values.

negative anomaly remains in the south-eastern USA. Thus, imposing a weak negative precipitation anomaly in July 1999 had little effect on the subsequent precipitation within the NAM region itself.

In summary, we find that subsequent precipitation in the NAM region is in part determined by soil moisture status in July, but the impact varies with the strength of the anomaly. The model simulations in 2000 suggest there is a positive soil moisture–precipitation feedback in the NAM region which may be retained for one month, but the 1999 simulations do not exhibit such consistency. In fact, because the small negative soil moisture anomaly that occurs in July then disappears in August (see Fig. 4(b)), precipitation in the NAM region increases slightly in August.

(*c*) *Surface temperature*

In August 2000, there is a negative surface temperature anomaly of, on average, 0.48 degC between the model run with a prescribed increase in precipitation and the control run, across the entire NAM region and most of the TX region (Fig. 7(a)), corresponding to the positive anomaly of precipitation (Fig. 6(a)). The minimum value is in central Mexico and TX, consistent with the location of the maximum precipitation anomaly. By September, the negative anomaly shifts into the south-eastern USA and the NAM region has an average positive anomaly of 0.89 degC.

In August 1999, there is a negative surface temperature anomaly of, on average, 0.19 degC for the NAM region (except for a portion of Arizona), but there is a large positive anomaly in the entire south-eastern USA (Figs. 7(c) and (d)). By September 1999, the negative anomaly in the NAM region is small and a positive surface temperature anomaly spans much of the western coast of Mexico and Arizona. The NAM region has an average surface temperature anomaly of 0.08 degC and the south-eastern USA still has a positive surface temperature anomaly.

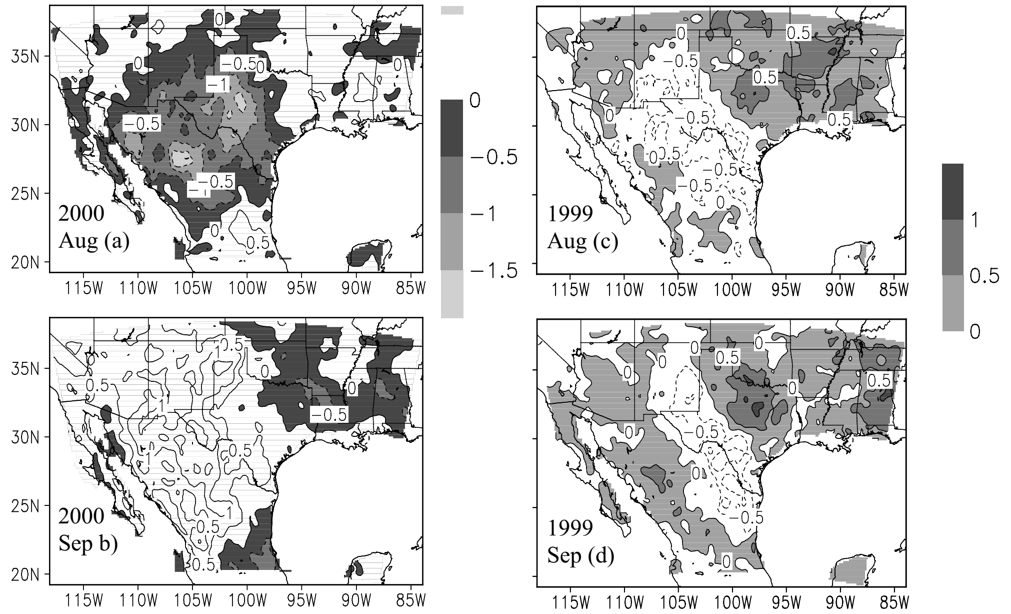


Figure 7. Differences in the mean monthly surface temperature (K) between the anomaly experiments and the control runs in: (a) August 2000, (b) September 2000, (c) August 1999, and (d) September 1999. Shaded areas in (a) and (b) indicate negative values, but in (c) and (d) indicate positive values.

5. DISCUSSION

The results given in the previous section indicate the presence of positive feedback in the soil–precipitation interaction in the MM5 model, both in and downwind of the NAM region. Because moisture remains stored in the soil, this feedback persists after the prescribed increase in precipitation has been removed at the end of July. It is of interest to explore what aspects of the MM5-OSU model are responsible for this positive feedback, and it is feasible to study the origins of this feedback by investigating the differences between modelled behaviour in the experimental runs and the control runs. The infiltration process is clearly the mechanism by which enhanced/reduced precipitation gives rise to enhanced/reduced soil moisture. However, the atmospheric processes which generate additional precipitation in response to greater soil moisture are less well defined and merit examination. At least two mechanisms appear to be acting in the model (and by inference in the real world) to give this response. These are described in the next two subsections.

(*a*) *Local land–atmosphere interactions*

When a strong precipitation anomaly was imposed in the NAM region during the 2000 simulation, the volumetric soil-moisture content in the full modelled soil layer (0–2 m) increased in July and again in August because the enhanced precipitation persisted (Figs. 4(a) and (b)). Table 3 shows that, in August, the average surface latent-heat flux in the NAM region increased by 8.0 W m^{-2} and the surface sensible-heat flux decreased by 8.1 W m^{-2}, in response to the 0.01 m^3m^{-3} increase in soil moisture, resulting in a lower Bowen ratio. With the increasing latent-heat flux, 0.27 mm more water vapour was released into the atmosphere. Moist static energy (MSE) increased at both

TABLE 3. AVERAGE SURFACE FLUXES, CLOUD COVER AND MOIST STATIC ENERGY

	P	SM	LH	SH	NR	BR	ET	*Cloud*	MSE_{850}	MSE_{500}
CTL	2.0	0.14	40.9	**100.2**	143.1	**2.5**	1.4	0.25	300415	288477
EXP	**2.2**	**0.15**	**48.9**	92.1	**143.5**	1.9	**1.7**	**0.26**	**300621**	**288566**
EXP – CTL	+0.2	+0.01	+8.0	−8.1	+0.4	−0.6	+0.3	+0.01	+206	+89
CTL	2.0	0.14	40.9	100.2	143.1	2.5	1.4	0.25	300415	288477
EXP	2.2	0.15	48.9	92.1	143.5	1.9	1.7	0.26	300621	288566
EXP – CTL	+0.2	+0.01	+8.0	−8.1	+0.4	−0.6	+0.3	+0.01	206	+89

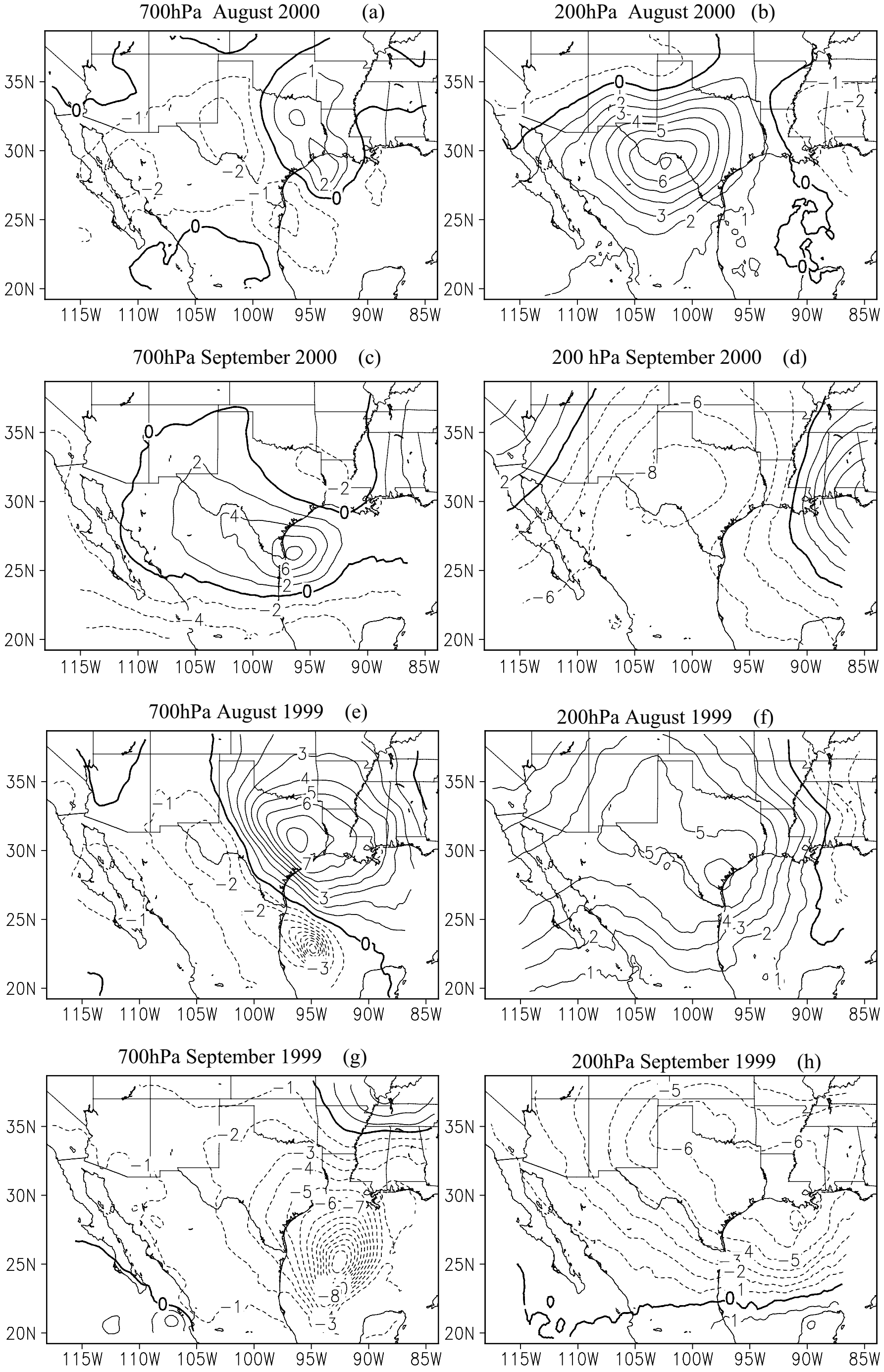
Average surface fluxes, cloud cover, and moist static energy for the North American monsoon region (112–105°W, 24–36°N) as simulated in August 2000 in the control run (CTL) and the experimental run (EXP), with largest values in bold, and the differences between them, using the Pennsylvania State University/National Center for Atmospheric Research fifth generation Mesoscale Model. Here P designates precipitation (mm); SM is soil moisture ($\mathrm{m^3 m^{-3}}$); ET is evapotranspiration (mm); LH is latent-heat flux ($\mathrm{W\ m^{-2}}$); SH is sensible-heat flux ($\mathrm{W\ m^{-2}}$); NR is net radiation ($\mathrm{W\ m^{-2}}$); BR is the Bowen Ratio (dimensionless); *Cloud* is the cloud fraction (%); and MSE_{850} and MSE_{500} are values of moist static energy ($\mathrm{J\ kg^{-1}}$) at 850 hPa and 500 hPa, respectively.

low- (850 hPa) and mid-levels (500 hPa) with increasing atmospheric water contents, and the height of the PBL decreased substantially from 1115.8 to 1068.5 m. Because the increase in MSE within the PBL (206 $\mathrm{J\ kg^{-1}}$) was greater than above the PBL (89 $\mathrm{J\ kg^{-1}}$), the convective system operating between 500 and 850 hPa became more unstable. In this way, the anomalous wet soil moisture conditions tended to increase the frequency (via an increase in instability) and magnitude (via an increase in MSE) of convective rainfall.

In fact, the MM5-OSU model may underestimate the increase in latent-heat flux by underestimating the increase in net radiation in this experiment. Water vapour is an important greenhouse gas, and the downward long-wave radiation increased when the vapour content of the lower atmosphere increased. The same process that moistens the lower atmosphere also cools the surface, and the outgoing surface long-wave radiation (given by the Stefan–Boltzmann Law) is reduced. Consequently, net surface long-wave radiation (NR) increased in the simulation. Similar responses have been found in previous studies (Betts and Ball 1995; Betts *et al.* 1996; Schar *et al.* 1999; Pal and Eltahir 2001). When the soil moisture increases, there is also an increase (+0.01) in fractional cloud cover (Table 3) and incoming surface solar radiation is therefore reduced. Because albedo is held constant (and independent of soil moisture) in the MM5-OSU model, anomalous soil moisture tends to decrease the modelled net surface solar radiation. In this way, the model calculates opposite responses in the short- and long-wave radiation components; but the August 2000 model simulation suggests that the change in NR dominates and there is a small positive anomaly (+0.4 $\mathrm{W\ m^{-2}}$) in net surface radiation (Table 3). However, wet soil tends to have a lower albedo than dry soil and there is much exposed bare soil in the NAM region, consequently the MM5-OSU model may be underestimating the positive anomaly in net radiation. Were the decrease in net solar radiation, in fact, less because of albedo change, and therefore the positive net radiation anomaly was larger, this would further increase the latent-heat flux and further moisten the atmosphere, presumably supplementing the increase in convective precipitation.

(*b*) *The influence of atmospheric processes*

The local land–atmosphere interaction phenomena just described operates in both experimental runs, but the modelled behaviour is different in these two runs, hence other mechanisms must be involved which complicate the response. Modification of


700hPa August 2000 (a)

200hPa August 2000 (b)

700hPa September 2000 (c)

200 hPa September 2000 (d)

700hPa August 1999 (e)

200hPa August 1999 (f)

700hPa September 1999 (g)

200hPa September 1999 (h)

Figure 8. Differences in monthly average geopotential height (m) between the anomaly experiments and control runs at: (a) 700 hPa in August 2000; (b) 200 hPa in August 2000; (c) 700 hPa in September 2000; (d) 200 hPa in September 2000; (e) 700 hPa in August 1999; (f) 200 hPa in August 1999; (g) at 700 hPa in September 1999; and (h) at 200 hPa in September 1999.

the atmospheric circulation in response to the modified surface fluxes is a possible mechanism.

In August 2000, the modelled geopotential-height difference field shows a negative anomaly over the NAM region and surrounding areas at lower levels (e.g. at 700 hPa, see Fig. 8(a)) and a positive anomaly at higher levels (e.g. at 200 hPa, see Fig. 8(b)) in response to the higher soil moisture. The local pressure over the NAM region will decrease (increase) with decreasing (increasing) geopotential height at lower (upper) levels. This situation is beneficial for convergence at lower levels and divergence at upper levels and, as a result, more moisture was transported into the NAM region at low levels, resulting in an increase of about 0.1 kg m^{-2} in the precipitable water in the troposphere and a positive precipitation anomaly (Fig. 6(a)). Presumably, the negative precipitation anomaly in September 2000 (Fig. 6(b)) is similarly related to the positive anomaly in geopotential-height difference field at lower levels (e.g. at 700 hPa, see Fig. 8(c)), the negative anomaly at higher levels (e.g. at 200 hPa, see Fig. 8(d)), and the resulting decrease of -0.2 kg m^{-2} in the precipitable water.

In August 1999, the geopotential height over the NAM region exhibits a negative anomaly at the lower levels (Fig. 8(e)) and a positive anomaly at the upper levels (Fig. 8(f)). Once the imposed reduction in precipitation in July was removed from this model run, the geopotential height at lower (upper) levels did not increase (decrease), and the precipitable water over the NAM region did not decrease, rather it increased slightly (0.01 kg m^{-2}). In other words, although the soil moisture decreased in August 1999 after the imposed decrease in precipitation in July, the water content in the atmosphere did not decrease. This behaviour is quite different to the positive correlation between the precipitation anomaly and the subsequent atmospheric water content in August 2000. In September, the negative anomaly in geopotential height at the lower levels remains, but the centre of the negative anomaly has shifted into the Gulf of Mexico. The upper level is also dominated by a negative anomaly which enhanced upper-level convergence and resulted in the precipitable water decreasing slightly, by about 0.01 kg m^{-2}. It should be noted that these results only apply in the year with a strong precipitation anomaly.

Based on the above results, the modelled soil moisture–precipitation feedback in the NAM region is very different in 1999 from that in 2000. Perhaps this is in part because of the strength of the prescribed precipitation anomaly in July 2000. Because the precipitation rate in the NAM region in July 2000 is significantly lower than the climatological average, we chose to impose four times the modelled precipitation rate in the control simulation in the equivalent experimental run. The resulting positive response in soil moisture in July is obvious (Fig. 4(a)) and this positive signal is retained in August in the NAM region (Fig. 4(b)). In contrast, the observed positive anomaly in precipitation in the NAM region is small in July 1999, so in our sensitivity experiment we imposed 0.7 times the precipitation rate given in the control simulation in the NAM region in July. The result shows that the resulting negative anomaly in soil moisture in August 1999 is not spatially coherent (Fig. 4(e)).

6. SUMMARY AND CONCLUSIONS

In this study, the Pennsylvania State University/National Center for Atmospheric Research fifth generation Mesoscale Model (MM5) linked to the Oregon State University (OSU) land-surface scheme, was used to assess the strength of soil moisture–precipitation feedback in the NAM region. Simulations were driven by the NCEP re-analysis. The horizontal resolution of the finest grid was 30 km and the model experiments began on June 1 and ended on September 30. We used the coupled MM5-OSU model to simulate the NAM climate and soil moisture in the monsoon seasons of the years 1999, which was wetter than average, and the drier than average 2000; these two model runs were then repeated with imposed precipitation rate anomalies in July over the entire NAM region. The primary results of this study are as follows:

- Increases or decreases in July precipitation influence the simulated hydrologic budget during July and throughout the remainder of the simulation. The soil moisture response to perturbed precipitation is not spatially uniform, even within the NAM region. Changes averaged over the entire NAM region are small, even though changes over portions of the area are rather large. In the two years for which experimental runs were made there is a modelled positive soil moisture–precipitation feedback in the NAM region, i.e. higher soil moisture enhances precipitation and lower soil moisture lowers precipitation. The strength of the response changes with the intensity of the imposed anomaly.
- Strong anomaly signals in soil moisture, rainfall, and surface temperature persist for roughly one month in the NAM region after the imposed precipitation anomaly has been removed and could yield a sustained positive soil moisture–precipitation feedback. Precipitation anomalies prescribed over the NAM region impact soil moisture and precipitation over the central and south-eastern USA. The precipitation anomaly in the NAM region not only impacts the soil moisture locally, but also causes a soil moisture anomaly downwind in the following month.
- With a strong increase in soil moisture, the PBL height decreases substantially. The amplitude of the MSE increases in the PBL much more than above the PBL. As a result of the increased difference in MSE between 500 and 850 hPa, the atmosphere becomes more unstable. Consequently, anomalously wet soil moisture conditions tend to increase the frequency (via an increase in instability) and magnitude (via an increase in MSE) of convective rainfall.
- The soil moisture–precipitation feedback over the NAM region shows a large difference between 1999 and 2000. This suggests that the soil moisture–precipitation feedback over the NAM region depends strongly on the intensity of the prescribed initial anomalies. Both land–atmosphere interactions and large-scale atmospheric circulations appear to be involved in the modelled soil moisture–precipitation feedback.

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