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A feedback mechanism between soil-moisture distribution and storm tracks

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SUMMARY

How the distribution of soil moisture impacts the location and persistence of the storm track and the resulting distribution of precipitation is investigated. Particular attention is given to North America where an extensive series of numerical experiments using a regional climate model are performed to investigate these issues. The findings suggest that soil-moisture distribution has a pronounced impact on the large-scale dynamics via a meridional displacement of the storm track. The displacement tends to enhance the local soil moisture–rainfall feedback over the region of the anomaly. The initial feedback is induced by the local effects of soil moisture on the boundary-layer energy budget and then propagated to the large-scale through modifications to the geopotential heights. Because of soil moisture's impact on the large-scale dynamics, a local soil-moisture anomaly can induce both flood- and drought-like conditions in surrounding regions. Experiments with a dry anomaly applied either over the upper Midwest or Great Plains display a northward shift in the storm track. This shift tends to result in drought-like conditions in the region of the anomaly and both flood- and drought-like conditions in surrounding regions. Anomalous wetting in the Southwest impacts the distribution of precipitation not only locally, but also over most of the United States; drought-like conditions are simulated to the north and east of the anomaly region while flood-like conditions are simulated locally and eastward. Overall, the impacts of soil-moisture distribution on the large-scale dynamics and the location and intensity of the storm track play a significant role in determining summer rainfall distribution. Soil-moisture anomalies over relatively small regions can induce floods and droughts not only locally, but also over remote regions.

KEYWORDS: Hydro-climatology Precipitation Water resources

1. INTRODUCTION

Extreme persistent droughts and floods over midlatitudes are typically associated with meridional displacements from the normal position of the storm track (e.g. Namias 1955; Trenberth and Guillemot 1996; Hurrell and van Loon 1997; Mo *et al.* 1997; Bell *et al.* 1998). The causes of these displacements and their persistence, however, remain relatively unknown.

Many recent observational studies investigating summer drought and flood events over North America, for example, conclude to one degree or another that anomalous tropical Pacific sea surface temperatures (SSTs) are responsible (e.g. Palmer and Branković 1989; Namias 1991; Bell and Janowiak 1995; Trenberth and Guillemot 1996; Bell *et al.* 1998). These studies, however, differ on their assessment of the extent to which the anomalous tropical SSTs are responsible for extreme summer precipitation events and suggest other potential mechanisms are likely to exist.

Observational studies of Namias (1955, 1982, 1991) indicate that droughts over the United States are often associated with anomalous upper-level anticyclones, resulting in a northward shift in the storm-track location. Both the works of Bell and Janowiak (1995) and Trenberth and Guillemot (1996) find similar results for flood years in that the storm track is shifted south of normal.

Namias (1982, 1991) further speculates that the anomalously dry soil-moisture conditions associated with droughts are likely to play a role in the persistence of droughts by strengthening and anchoring the associated anticyclonic flow. He argues that the increase in sensible heating encourages the growth of a high via an increase in pressure. Trenberth and Guillemot (1996) also suggest that soil moisture may play a role in increasing the persistence of extreme summer precipitation events (both flood

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and drought). In this study, we investigate the pathways, if any, through which soil moisture impacts the location and intensity of the North American storm track during the summer.

Higgins and Shi (2000) show that summer precipitation in the Midwest is characterized by an out-of-phase relationship with precipitation associated with the North American Monsoon System (NAMS). Before the NAMS onset, there tends to be enhanced precipitation over the Great Plains and Midwest, while after the onset, rainfall significantly decreases in the Great Plains and Midwest. Lanicci *et al.* (1987) suggest that dry soil-moisture conditions over the Southwest and northern Mexico are critical for the formation of a rainfall suppressing capping inversion over the Great Plains.

Some recent observational studies have found significant links between soil moisture and summer climate on a local-scale (e.g. Betts and Ball 1994; Findell and Eltahir 1997; Eltahir 1998). Since observations of soil moisture are extremely limited at large spatial scales, these studies do not address soil moisture's impact on the large-scale climate. As a result, numerous numerical studies have been performed investigating the soil moisture–rainfall feedback using both general-circulation models (GCMs, e.g. Rind 1982; Oglesby and Erickson III 1989; Atlas *et al.* 1993; Beljaars *et al.* 1996) and regional climate models (RCMs, e.g. Seth and Giorgi 1998; Schär *et al.* 1999; Bosilovich and Sun 1999; Pal and Eltahir 2001). With a few exceptions, these studies indicate that there is a significant positive feedback between soil moisture and rainfall during months with pronounced convective activity, such as summers in midlatitudes.

Castelli and Rodriguez-Iturbe (1996) conclude, using an idealized framework, that soil moisture plays an important role in baroclinic dynamics. They suggest that dry soil-moisture conditions under the downdraught of a baroclinic wave and wet under the updraught accelerate the large-scale dynamics, resulting in positive, spatially structured, soil moisture–rainfall feedback. However, their model does not account for the meridional displacements in the storm track that may occur from changes in soil moisture as suggested by Namias (1982, 1991).

Oglesby and Erickson III (1989) confirmed the works of Namias (1982, 1991) in an investigation of the 1988 North American spring/summer drought using a GCM. They find that dry soil-moisture conditions lead to a northward displacement in the jet stream and hence conclude that soil moisture plays an important role in prolonging and/or amplifying North American summertime drought. They suggest that this modification to the jet stream position results from the changes in surface temperature due to the lower soil-moisture conditions. In a study of the Midwest flood of 1993, Pal and Eltahir (2002) suggest that the abnormally wet soil-moisture conditions in the flood region likely played a role in enhancing the persistence and intensity of the flood. At the same time, the abnormally dry conditions in the Southwest may have been partially responsible for the meridional location of the flooding region. They suggest that changes in convective heating resulting from the soil-moisture anomalies are responsible for the changes in storm-track location.

Over southern midlatitude oceans, model studies generally agree that SST anomalies modify the geopotential height in the same direction as the anomaly (e.g. Palmer and Zhaobo 1985; Ferranti *et al.* 1994) although some discrepancies exist (Peng and Whitaker 1999). More specifically, they suggest that SST anomalies act to alter the surface baroclinicity and displace the storm track meridionally. SST and soil moisture are not completely analogous; SST is positively correlated with temperature and humidity while soil moisture is positively correlated to humidity and negatively correlated to temperature. Thus, it is not obvious how anomalous soil-moisture conditions act to modify the large-scale dynamical patterns.

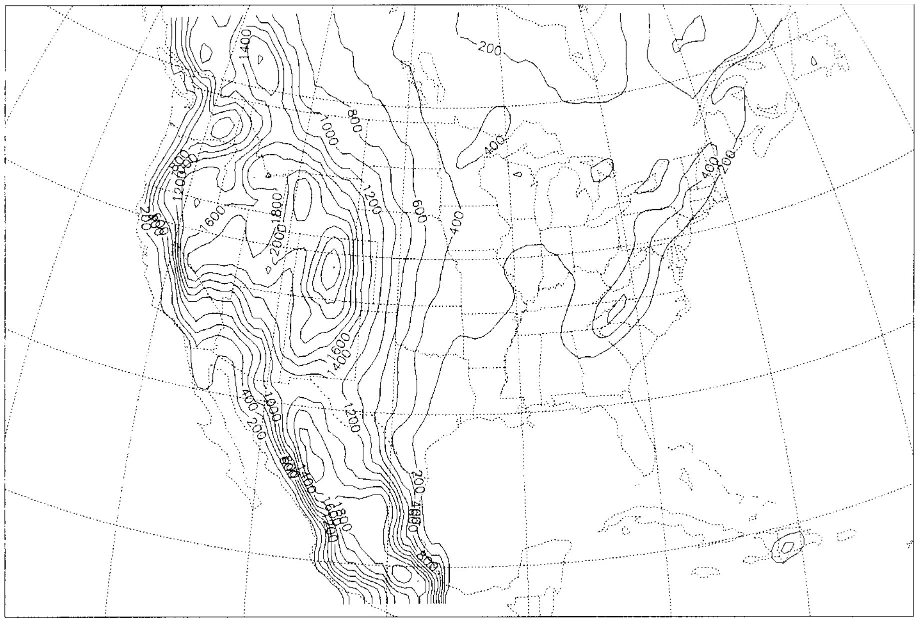

Figure 1. Domain and terrain height (m) used for the numerical simulations.

In this paper, we investigate the role that soil moisture plays in the climate system on both the local- and large-scale. Generally speaking, in numerical modelling studies of the soil moisture–rainfall feedback, soil-moisture anomalies are applied at continental-scales. Here, we investigate how anomalies applied over small regions of North America impact summer climate. Following the above works, we hypothesize that the distribution of soil moisture, both local and remote, plays an important role not only in determining the location and persistence of the storm track, but also in determining the size and location of precipitation peaks. Particular emphasis is placed on the mechanisms responsible for the feedbacks.

An extensive series of numerical experiments using an RCM are performed to investigate these issues. A relatively large domain is selected so that the large-scale dynamics are less constrained in position and strength (see Fig. 1). Section 2 gives a description of the numerical model and the experiments performed. The results and conclusions are described in sections 3 and 4, respectively.

2. DESCRIPTION OF NUMERICAL EXPERIMENTS

In this study, we use a modified version of the National Center for Atmospheric Research's (NCAR) Regional Climate Model (RegCM) to investigate the key questions brought forth in the introduction. The original model was developed by Giorgi *et al.* (1993a,b) and Giorgi and Shields (1999). Significant additional model modifications have been introduced by Pal *et al.* (2000).

The dynamical core of RegCM is based on the hydrostatic version of the Penn State/NCAR Mesoscale Model version 5 (Grell *et al.* 1994). The atmospheric radiative-transfer computations are performed using the Community Climate Model CCM3-based package (Kiehl *et al.* 1996) and the planetary boundary-layer (PBL) computations are performed using the non-local formulation of Holtslag *et al.* (1990). The resolvable (large-scale) cloud and precipitation processes are computed using a subgrid explicit moisture scheme (Pal *et al.* 2000). The unresolvable precipitation processes (cumulus convection) are represented by the Grell (1993) scheme implementing the Fritsch and Chappell (1980) closure assumption. Lastly, the surface physics calculations are performed using a soil–vegetation hydrological process model (Biosphere–Atmosphere Transfer Scheme (BATS); Dickinson *et al.* 1993).

RegCM requires initial conditions and time-dependent lateral boundary conditions for the wind components, temperature, surface pressure, and water vapour. For each simulation, these are taken from the National Centers for Environmental Prediction (NCEP) reanalysis data (Kalnay *et al.* 1996). The SSTs are prescribed using data provided by the Met Office (Rayner *et al.* 1996). The soil moisture for the control simulations is initialized using the derived dataset presented by Pal and Eltahir (2001). The vegetation is specified using the Global Land Cover Characterization data provided by the United States Geological Survey's Earth Resources Observation System Data Center (Loveland *et al.* 2000). Lastly, the soil texture class is prescribed according to the vegetation characterization.

Pal and Eltahir (2001) investigated the soil moisture–rainfall feedback using a small domain which was selected so that the effects of changes in soil moisture on the large-scale dynamics would be constrained. In this study, a relatively large model domain is used to develop an understanding of the soil moisture–rainfall feedback at large-scales (in addition to local-scales). By using the large domain, the remote dynamical impacts resulting from local changes in soil moisture can be studied.

Figure 1 depicts the domain and associated topography for the simulations presented in this study. The domain exists on a rotated Mercator projection centred at 38°N and 95°W with the origin rotated to 40°N and 95°W. In the horizontal, there are 129 points in the east–west direction and 80 in the north–south with a resolution of 55.6 km (approximately half a degree). There are 14 vertical sigma levels with highest concentration of levels near the surface. The model top is at 50 hPa.

Each simulation set comprises six 37-day runs initialized on 25 June on each of the following years: 1986, 1987, 1988 (drought), 1989, 1990 and 1993 (flood). 1988 and 1993 are selected to represent extreme years in precipitation and hence soil moisture. Although the 1988 drought during July was in its final stages, the soil-moisture anomaly remained dry (Findell and Eltahir 1997). The other years are considered more 'average'. The first six days of each simulation are ignored for spin-up considerations. The average of the six years is considered the climatology. The experiments are performed under several soil-moisture configurations which are described below.

Table 1 provides a description of the numerical experiments performed. The control simulations (CTL) are initialized using the 'observed' soil-moisture dataset described by Pal and Eltahir (2001). More specifically, they are derived from the Illinois State Water Survey observations (Hollinger and Isard 1994), the simulated dataset of Huang *et al.* (1996), and a climatology based on vegetation type. The final product provides a reasonable representation of the temporal (seasonal and interannual) and spatial (vertical and horizontal) variability of soil moisture for the United States. We realize that these are not the actual observations and may contain significant errors especially in regions that significantly differ from the Midwest (such as the Southwest). Figure 2 displays the average of the root zone soil moisture 25 June initial conditions for the six simulated years.

Three additional sets of experiments are performed where the soil moisture is initialized similar to the CTL experiments except over a specific region where it is modified and held fixed (one-way interaction). In this region, the surface impacts the

TABLE 1. DESCRIPTION OF EACH SIMULATION PERFORMED IN THIS STUDY

Simulation start dates:	
	25 June, 1986, 1987, 1988, 1989, 1990 and 1993
Simulation duration:	
	37 days (6-day spin-up)
Soil saturation:	
	CTL: observed Huang *et al.* (1996)/Illinois State Water Survey (HDG/ISWS) for each year
	25MW: fixed at 25% over the Midwest, CTL elsewhere
	25GC: fixed at 25% over the Gulf Coast, CTL elsewhere
	50SW: fixed at 50% over the Southwest, CTL elsewhere

CTL is control simulation (see text).

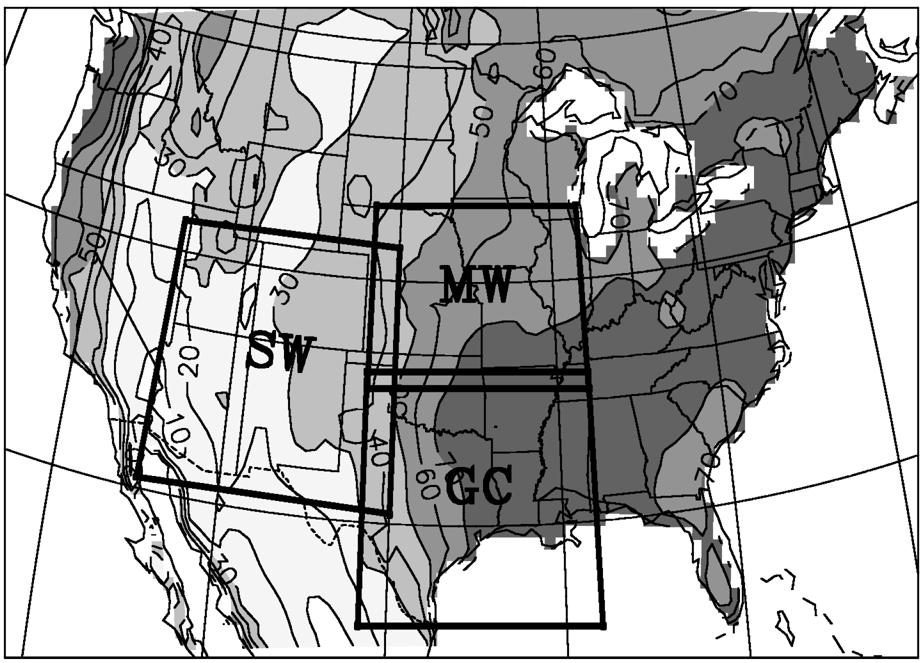

Figure 2. Plot of the 25 June climatology of the root zone soil saturation (%). The boxes indicate the regions over which the fixed patch anomalies are applied: MW denotes Midwest, GC denotes Gulf Coast; and SW denotes Southwest. The contour interval is 10% and shading occurs at values above 10% and at intervals of 20%.

atmosphere, but the soil moisture does not respond to the atmosphere. Soil moisture over the remainder of the domain is fully interactive. In the first set (25MW), the soil saturation is held fixed over the upper Midwest at 25% (see Fig. 2, box MW). The fixed patch spans from 88° W to 103° W in longitude and from 36° N to 44° N in latitude. In this scenario, we can investigate the impacts of soil moisture on both the local-scale and on the large-scale dynamics in the upper Midwest (and in remote nearby regions) under dry conditions. In the second set (25GC), the soil saturation over the western Gulf Coast and southern Great Plains (entry region to the Great Plains Low-Level Jet (LLJ)) is held fixed at 25% (see Fig. 2, box GC). The fixed patch spans from 88° W to 103° W in longitude and from 25° N to 37° N in latitude. The purpose of this set is to determine how a dry anomaly in the LLJ entry region impacts the local climate and large-scale circulation. In the third set (50SW), the soil saturation over New Mexico, Arizona, Colorado and Utah is held fixed at 50% (see Fig. 2, box SW). The fixed patch spans from 100° W to

115°W in longitude and from 31°N to 42°N in latitude. In this set, we investigate how anomalously wet soil-moisture conditions in the northern portions of the NAMS impacts the distribution of rainfall, particularly over the United States.

Note that we choose not to allow soil moisture over the anomalous regions to interact so that the response of the atmosphere to these anomalies can be emphasized. Additional fully interactive experiments result in similar conclusions (not shown). However, the impacts are not as strong as they are when soil moisture is fixed. Furthermore, the use of the large computational domain suggests that the model is potentially susceptible to chaotic effects (Giorgi and Bi 2000; Fukutome *et al.* 2001). Additional simulations performed with slightly perturbed initial conditions (both to the atmospheric variables and soil moisture) suggest that model internal variability is minor when compared with its response to changes in soil moisture applied in this study (not shown).

3. Results

(*a*) *Model comparison with precipitation observations*

Here we briefly compare the CTL simulations with the United States Historical Climatology Network (USHCN) observations of precipitation (Karl *et al.* 1990). A more rigorous model comparison with observations using the same model and domain configuration can be found by Pal *et al.* (2000). The USHCN data consist of 1221 high-quality stations from the United States Cooperative Observing Network within the 48 contiguous United States. The data are interpolated onto the RegCM grid defined in section 2 by exponentially weighting the station data according to the distance of the station from the centre of the RegCM grid cell, with a length-scale of 50 km.

Figure 3(a) displays the observed July USHCN precipitation climatology for the six simulated years (1986, 1987, 1988, 1989, 1990 and 1993). Because of the 1993 summer flooding in the Midwest, there is a pronounced peak over that region. Not including 1993 in the climatology tends to make the distribution more meridionally symmetric (not shown). Figure 3(b) displays the simulated precipitation climatology for the CTL simulations. Overall, the model tends to underpredict precipitation over most of the domain except the Gulf Coast region where there is an overprediction. Over the Midwest, the model performs well in capturing the region of precipitation above 3 mm day^{-1}. However, it is unable to reproduce observations in the region where precipitation exceeds 4 mm day^{-1} (Iowa, Missouri and Kansas). A considerable portion of the high bias over the Gulf Coast region can be explained by the July 1988 simulation where the predicted convective activity is far too pronounced (not shown). In addition, some of the underprediction of rainfall in the Midwest can be attributed to the excessive rainfall forming in the Gulf Coast region (upstream along the LLJ). Also of particular importance to this study, the precipitation over Colorado, Arizona, and New Mexico is underpredicted. The impacts of this will be discussed in further detail in subsection 3(d).

The precipitation underprediction over most of the domain tends to result in an underprediction of soil moisture. On top of this, there is also a tendency for soil moisture within BATS to dry more than is observed, particularly in regions with relatively high soil moistures (primarily due to the lower soil boundary (Yeh 2002)). For example, even though the model overpredicts precipitation in the Gulf Coast region, soil moisture over that region is underpredicted. Thus, in regions with a pronounced soil moisture–rainfall feedback, this underprediction is self-sustaining and tends to result in a further decrease in rainfall and soil moisture. This is likely to have played a role in the underprediction of precipitation across most of the domain. In spite of this underprediction, overall the model captures the general observed patterns of precipitation; however, significant

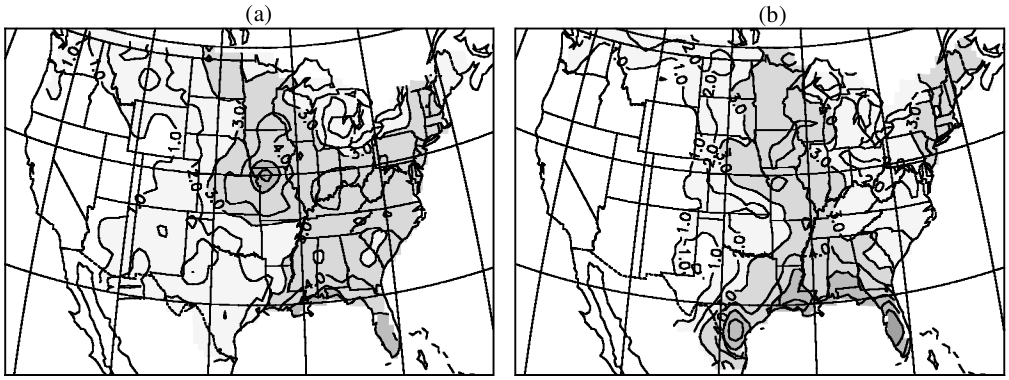

Figure 3. July precipitation climatology (mm day^{-1}): (a) gridded USHCN observations (see text) and (b) CTL simulations for the six years listed in Table 1. Contour interval is specified at 1 mm day^{-1}. Shading occurs at values above 1 mm day^{-1} and at intervals of 2 mm day^{-1}. Note that only values over the United States are plotted since the USHCN data only exist over the United States.

differences exist. It should also be noted that the model performs well in capturing the extremes in precipitation observed during the summers of 1988 and 1993 (not shown). These comparisons have been performed by Pal *et al.* (2000) and Pal and Eltahir (2002) using the same model domain.

(*b*) *Effects of a dry soil-moisture anomaly in the upper Midwest*

Pal and Eltahir (2001) showed that a significant positive feedback between soil moisture and precipitation exists over the mid-western United States. In this subsection we investigate the local impacts of soil moisture on the Midwest in a similar manner to Pal and Eltahir (2001) except using a large domain. To do so, we perform a set of experiments (25MW) using the observed distribution of soil moisture over the entire domain except for an isolated region in the Midwest where the soil moisture is held fixed at 25% of saturation (see section 2).

Although the dry soil-moisture anomaly is limited to the upper Midwest, Fig. 4 indicates that the dry anomaly not only results in drought-like conditions over the anomalous region, but also it tends to result in both drought- and flood-like conditions in surrounding regions. In particular, a significant reduction (light shading) in rainfall between 105°W and 87°W and a general increase occurs in the eastern Seaboard states (east of 87°W). This out-of-phase relationship is somewhat consistent with the observational study of Higgins *et al.* (1997). To investigate this response in further detail we look first to the impacts of soil moisture on the local climate and then to the large-scale climate.

(i) *Feedback on the local climate.* In early studies, researchers focused on the soil moisture–rainfall feedback as a water recycling process, neglecting the radiative processes. However, Betts and Ball (1994), Entekhabi *et al.* (1996), Eltahir (1998), and Schär *et al.* (1999) suggested that soil moisture not only impacts the water budget of the surface and the PBL, but also the energy budget. In this section, using the perspective of the above studies, we investigate how a dry soil-moisture anomaly over the Midwest impacts the local climate. But first, we provide a brief description of the mechanisms and pathways through which soil moisture impacts the near-surface variables that affect boundary-layer processes and rainfall according to that of Pal

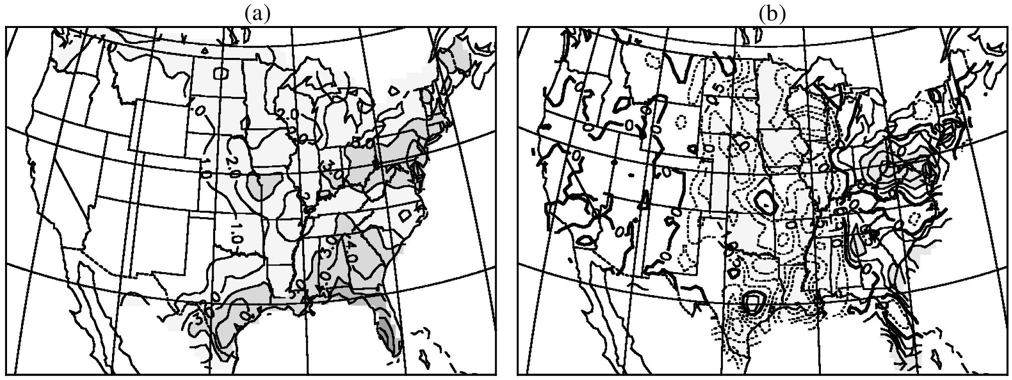

Figure 4. July simulated precipitation climatology (mm day^{-1}) for the (a) 25MW simulations and (b) difference between the 25MW and the CTL simulations for the six years listed in Table 1. The soil moisture in each is initialized according to the merged HDG/ISWS dataset (see Table 1) and is fully interactive except in the 25MW simulations over the Midwest region where the soil saturation is held constant at 25%. Note that only values for the United States are displayed. In (a) the contour interval is 1 mm day^{-1} and shading occurs at values greater than 1 and at intervals of 2. In (b) the contour interval is 0.5 mm day^{-1} with dashed contours denoting negative values. Values greater than the absolute value of 1 mm day^{-1} are shaded.

and Eltahir (2001). Since Pal and Eltahir (2001) provide a more detailed description of the local soil moisture–rainfall feedback mechanism, only a brief summary of the dominant feedbacks is provided here. Note that each of these studies differs on the exact mechanisms and pathways; those presented here (which are also similar to those of Eltahir (1998) and Schär *et al.* (1999)) are what we believe to be responsible for the changes in local rainfall.

It is well documented that anomalously dry soil-moisture conditions are typically associated with anomalously warm temperature and low humidity at or near the surface via an increase in sensible-heat flux and decrease in latent-heat flux. With this in mind, anomalously dry soil-moisture conditions also suggest a decrease in net surface long-wave radiation via an increase in outgoing long-wave radiation (Stefan–Boltzmann Law) and a decrease in the long-wave radiation emitted towards the land surface (greenhouse effect for water vapour). Both of these factors tend to decrease the net surface all-wave radiation. However, anomalously dry surface conditions are also associated with less clouds and, hence, more net surface solar radiation which acts to negate the decrease in all-wave radiation. It was shown by both Schär *et al.* (1999) and Pal and Eltahir (2001) that the long-wave radiation feedback outweighs the short-wave (cloud) feedback and thus anomalously dry soil-moisture conditions result in an overall decrease in net surface all-wave radiation.

Net surface radiation nearly balances the sum of the latent- and sensible-heat fluxes at long time-scales. The total energy of the PBL can be described by the moist static energy (MSE) which is proportional to the total heat flux. Thus, anomalously dry soils tend to decrease the flux (or supply) of energy into the PBL from below. Dry soils also tend to increase the PBL height (via an increase in sensible-heat flux) which tends to decrease the MSE per unit mass of air and increase the amount of entrained air of low MSE from above the PBL (Betts and Ball 1994). Each of these effects are additive and contribute to a decrease of MSE per unit mass of PBL air when soil moisture decreases. A decrease in the MSE of the PBL tends to decrease the magnitude and likelihood of occurrence of convective rainfall and, hence, result in a positive feedback between soil moisture and rainfall on the local-scale.

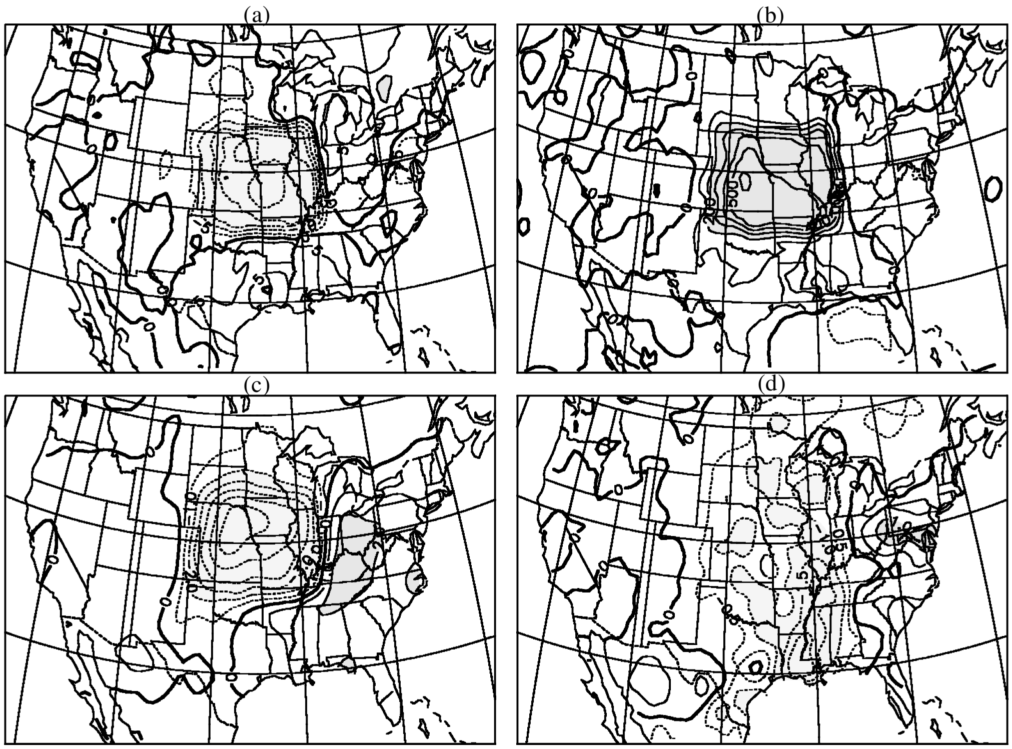

Figure 5. July simulated surface climatology difference between the 25MW and CTL simulations for the six years listed in Table 1: (a) net surface all-wave radiation (W m^{-2}), (b) planetary boundary-layer depth (m), (c) sigma 0.995 moist static energy (kJ kg^{-1}), and (d) convective precipitation (mm day^{-1}). The soil moisture in each is initialized according to the merged HDG/ISWS dataset (see Table 1) and is fully interactive except in the 25MW simulations over the Midwest region where the soil saturation is held constant at 25%. Note that only values over land are displayed. The contour intervals are: (a) 5 W m^{-2}, (b) 100 m, (c) 1 kJ kg^{-1}, and (d) 0.5 mm day^{-1}. Dashed contours denote negative values and shading denotes values greater than the absolute value of: (a) 10 W m^{-2}, (b) 200 m, (c) 20 kJ kg^{-1}, and (d) 1 mm day^{-1}.

Figure 5 compares the 25MW simulations with the CTL simulations and attempts to breakdown each of the major links of the soil moisture–rainfall feedback. Strikingly the anomalous upper Midwest region is evident in each field displayed. Figure 5(a) shows that the long-wave feedback dominates the short-wave feedback and results in an overall decrease in net surface all-wave radiation of approximately 20 W m^{-2} by decreasing soil moisture over the upper Midwest. This decrease is translated to the sum of the latent- and sensible-heat fluxes where a decrease of approximately 25 W m^{-2} is observed (not shown) and, hence, a decrease in the energy supplied from below the PBL. This decrease and along with the deeper more turbulent PBL (Fig. 5(b)) results in a decrease in the low-level MSE (Fig. 5(c)). These effects combine to result in an increase in atmospheric stability and hence a decrease in convective rainfall (Fig. 5(d)). Note that the decrease in convective rainfall is reflected by both a decrease in the number of rainfall events and the size of each event.

Furthermore, this decrease in convective rainfall, however, is not limited to the region of the anomaly as is the case with the net radiation, PBL depth, and MSE. Thus, the soil-moisture conditions also influence precipitation beyond the local-scale. To investigate the reasons why the changes in precipitation are not isolated to the anomalous region, we look to the large-scale dynamics.

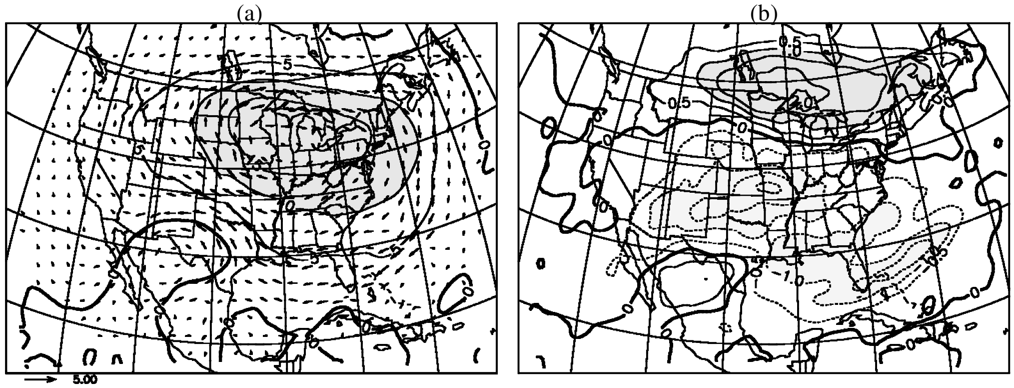

Figure 6. July differences between CTL and 25MW simulated 500 hPa for the six years listed in Table 1: (a) geopotential heights (m) and winds (m s^{-1}) and (b) zonal winds (m s^{-1}). The soil moisture in each is initialized according to the merged HDG/ISWS dataset (see Table 1) and is fully interactive except in the 25MW simulations over the Midwest region where the soil saturation is held constant at 25%. In (a) the contour interval is 5 m and shading occurs at values greater than 10 and at intervals of 20. In (b) the contour interval is 0.5 m s^{-1} with dashed contours denoting negative values. Values greater than the absolute value of 1 mm day^{-1} are shaded.

(ii) *Feedback on the large-scale dynamics.* Figure 6(a) shows the difference in 500 hPa geopotential heights (contours) and winds (vectors) between the CTL and 25MW simulations. The dry soil-moisture conditions induce an anomalous high pressure via a reduction in latent cooling (an increase in sensible heating) at the surface. The higher pressure suggests an increase in descending (weakened rising) motion and tends to suppress the formation of rainfall in both the convective and non-convective forms (Figs. 4(b) and 5(d)). In addition, the dry conditions tend to decrease the relative humidity (higher temperature and less moisture; not shown). Both of these effects tend to reduce the overall number of rainfall events and the magnitude of rainfall in each event (not shown).

The northward shift in the mean position in the storm track is simulated consistently in all of the years over the entire course of each month (not shown). The overall effects on rainfall, however, are greatest in the July 1993 simulations due to the larger rainfall magnitudes and greater number of rainfall events. In addition, the response is further enhanced in the July 1993 simulations due to the greater difference in soil moisture between the CTL and 25MW simulations. Similarly, the overall effects to rainfall are weakest in the July 1988 simulations since it is the driest of the years.

The higher pressure also suggests anomalous cyclonic flow and thus causes a northward shift in the storm track (Fig. 6(b)). Shifting the storm track north tends to alter the rainfall distribution over the region of the anomaly, but also in surrounding regions. This mechanism is responsible for the widespread simulated changes in rainfall (both positive and negative) particularly to the north, south, and east of the anomaly.

The dry soil-moisture anomaly over the upper Midwest has only a minor impact on the strength of the LLJ in that there is a small increase in its strength (less than 1 m s^{-1}, see Fig. 7). The slight increase in the LLJ strength does not transport enough new moisture to counteract the decrease in moisture resulting from the dry soil-moisture anomaly (see Fig. 7(a)). This is partly due to the fact that the response of the LLJ is primarily seen only over the land. Thus, little new moisture originated from the Gulf of Mexico as a result of the LLJ is advected into the Great Plains and Midwest. Competing factors control the response of the LLJ intensity to the dry soil-moisture anomaly.

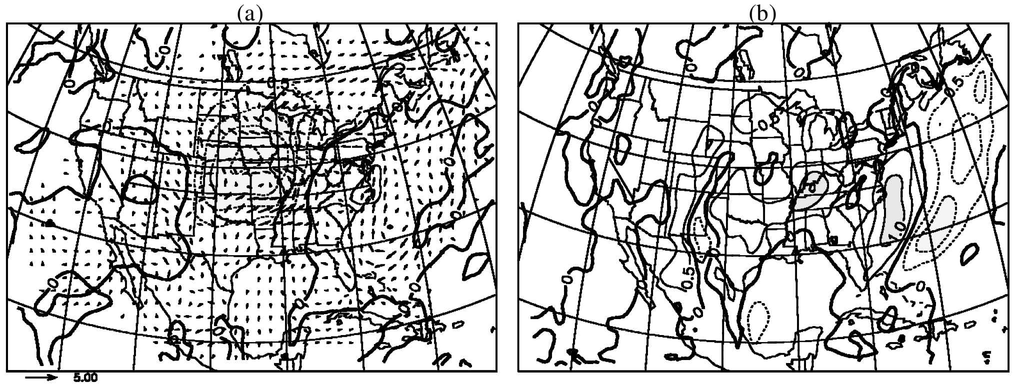

Figure 7. July differences between CTL and 25MW simulated sigma 0.895 for the six years listed in Table 1 (a) mixing ratio (g kg^{-1}) and winds (m s^{-1}) and (b) sigma 0.895 meridional winds (m s^{-1}). The soil moisture in each is initialized according to the merged HDG/ISWS dataset (see Table 1) and is fully interactive except in the 25MW simulations over the Midwest region where the soil saturation is held constant at 25%. The contour intervals are: (a) 0.5 g kg^{-1} and (b) 0.5 m s^{-1}. Dashed contours denote negative values and shading denotes values greater than the absolute value of: (a) 1 g kg^{-1} and (b) 1 m s^{-1}.

The increase in subsidence (weakened ascent) tends to result in a blocking (increase in low-level divergence) and reduction of the LLJ. In addition, the northward shift in the storm track acts to weaken (increase the distance of) the LLJ teleconnection between the Gulf of Mexico and the Midwest. However, the weakened ascent also tends to result in a lid over the LLJ. This lid acts to reduce the likelihood of the vertical motions that disturb the LLJ flow and hence increases the LLJ strength. These factors tend to negate each other and hence result in only a small increase in the LLJ intensity.

In summary, the mechanisms through which soil moisture impacts precipitation over the Midwest are consistent with, but not limited to, the local soil-moisture feedback theory presented above. Additional mechanisms are introduced to the large-scale environment in that the soil modifies the mean storm-track position and the pressure patterns. These mechanisms tend to enhance the soil moisture–rainfall feedback over the region of the anomaly and are roughly summarized in Fig. 8. The modifications to the storm track result in significant changes to the distributions of rainfall in surrounding regions.

(*c*) *Effects of a dry soil-moisture anomaly in the western Gulf Coast*

Here we investigate how anomalous soil-moisture conditions in the western Gulf Coast region impact precipitation. To do so, much like the 25MW experiments, we perform experiments using the observed soil-moisture distribution as initial conditions over the entire domain except for an isolated region in the western Gulf Coast region where the soil moisture is held fixed at 25% of saturation (25GC). By performing this set of experiments, we can determine the impact that drying upstream along the LLJ of the Midwest has on the rainfall in the Midwest and surrounding regions.

Similar to the 25MW experiments, a dry anomaly in the western Gulf Coast region results in a decrease in precipitation not only over the anomalous region, but also over the surrounding regions, particularly to the north and east (Fig. 9). Also, similar to the 25MW simulations, there is an increase in precipitation along the Atlantic Seaboard states.

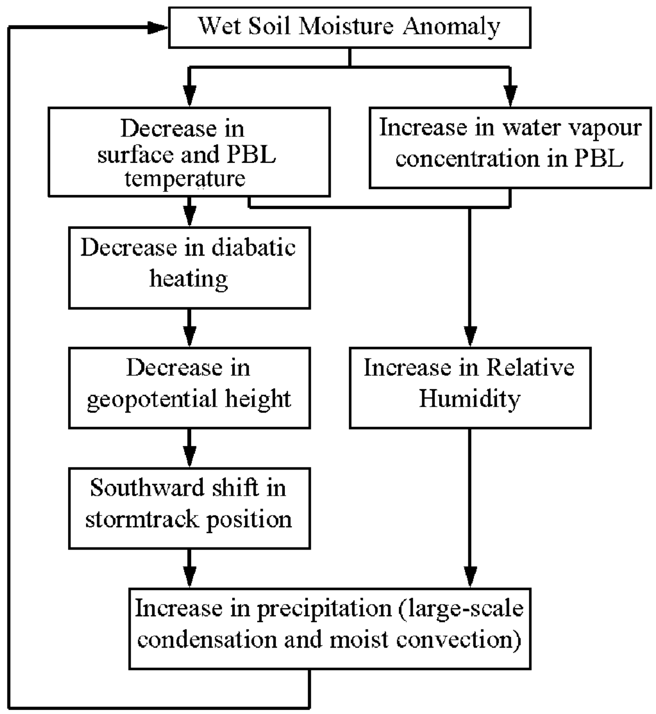

Figure 8. Diagram relating the major pathways through which anomalously wet soil-moisture conditions impact the large-scale climate. (PBL denotes planetary boundary layer.)

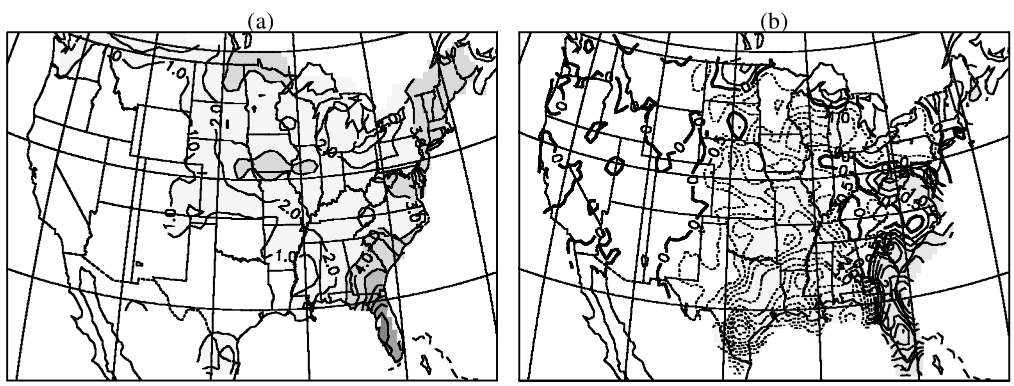

Figure 9. July simulated precipitation climatology (mm day^{-1}) for the (a) 25GC simulations and (b) difference between the 25GC and the CTL simulations for the six years listed in Table 1. The soil moisture in each is initialized according to the merged HDG/ISWS dataset (see Table 1) and is fully interactive except in the 25GC simulations over the western Gulf Coast region where the soil saturation is held constant at 25%. Note that only values for the United States are displayed. Contour intervals and shading are the same as those specified in Fig. 4.

In the region of the anomaly, there is an overall decrease in the energy per unit depth of the PBL (not shown) and hence a decrease in convective rainfall. The physical mechanisms responsible for the decrease are the same as those presented in subsection 3(b)(i) for the 25MW experiments. The increase in subsidence associated with the decrease in convection results in anomalous anticyclonic flow (Fig. 10(a)). Surprisingly,

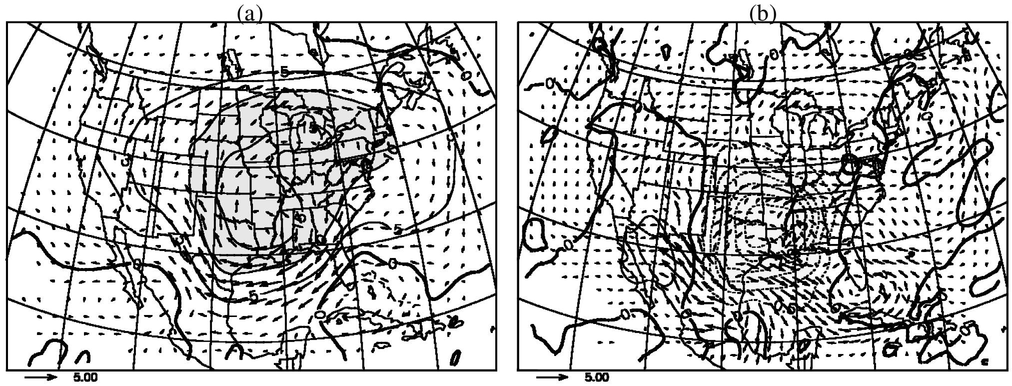

Figure 10. July differences between CTL and 25GC simulated (a) 500 hPa geopotential heights (m) and winds (m s^{-1}) and (b) sigma 0.895 mixing ratio (g kg^{-1}) and winds for the six years listed in Table 1. The soil moisture in each is initialized according to the merged HDG/ISWS dataset (see Table 1) and is fully interactive except in the 25GC simulations over the western Gulf Coast region where the soil saturation is held constant at 25%. The contour intervals are: (a) 5 m and (b) 0.5 g kg^{-1}. Dashed contours denote negative values and shading denotes values greater than the absolute value of: (a) 10 m and (b) 1 g kg^{-1}.

this widespread anomaly extends northward into Canada where there is an intensification of the storm track. Over the Midwest, the changes in the storm-track strength are relatively minor.

Overall, there is little change to the strength of the LLJ (Fig. 10(b)). However, upon closer inspection, it is seen that less warm moist air from the Gulf of Mexico enters the Great Plains region. Thus, the drier soil-moisture conditions also tend to reduce the moisture advected into the Great Plains. This tends to reduce further the formation of rainfall. Furthermore, the LLJ tends to advect the anomalous dry conditions into the Midwest. This tends to reduce the likelihood and magnitude of rainfall events in the Midwest and thus extends the anomalous subsidence region north of the soil-moisture anomaly (Fig. 10(a)).

(*d*) *Effects of a wet soil-moisture anomaly in the Southwest*

This subsection investigates how anomalously wet conditions in the Four Corners States impact precipitation over the Midwest. To do so, a series of simulations are performed where the soil saturation in Colorado, Utah, New Mexico, and Arizona is held fixed at 50% (50SW).

Figure 11 displays the rainfall distribution climatology of the 50SW experiments and its difference with the CTL simulations. As expected, an increase in soil moisture over the Southwest results in a significant increase in rainfall over the same region. However, strikingly, the soil-moisture anomaly results in a significant increase in rainfall in the Gulf Coast states (except southern Texas) and a significant decrease in rainfall in the upper Midwest states. From these results, it appears that soil moisture in the Southwest also has a pronounced impact on the distribution of rainfall east of the 100°W meridian.

Once again, the response of the distribution of rainfall initiates at the local-scale. The wet anomaly over the Southwest results in an increase in energy per unit depth of boundary by the same pathways described in subsection 3(b)(i). At the same time, the increased diabatic cooling results in an anomalous low pressure. This decrease in pressure extends over most of the United States and thus has a significant impact on

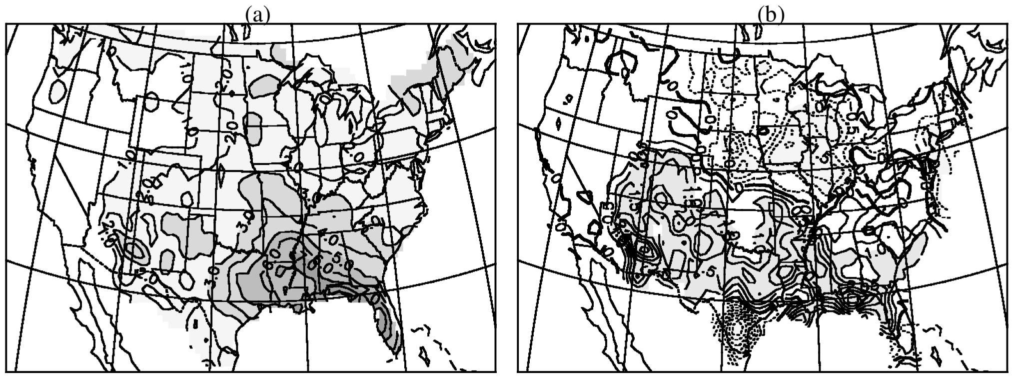

Figure 11. July simulated precipitation climatology (mm day^{-1}) for the (a) 50SW simulations and (b) difference between the 50SW and the CTL simulations for the six years listed in Table 1. The soil moisture in each is initialized according to the merged HDG/ISWS dataset (see Table 1) and is fully interactive except in the 50SW simulations over the Southwest region where the soil saturation is held constant at 50%. Note that only values for the United States are displayed. Contour intervals and shading are the same as those specified in Fig. 4.

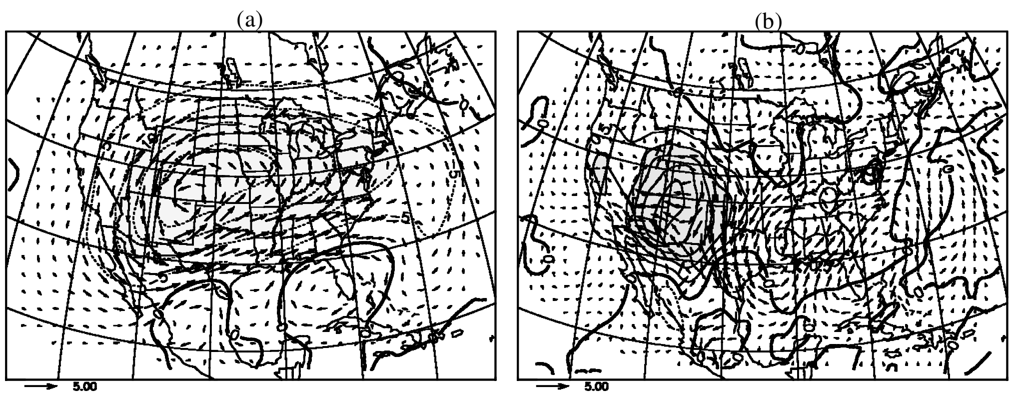

Figure 12. July differences between CTL and 50SW simulated (a) 500 hPa geopotential heights (m) and winds (m s^{-1}) and (b) sigma 0.895 mixing ratio (g kg^{-1}) and winds for the six years listed in Table 1. The soil moisture in each is initialized according to the merged HDG/ISWS dataset (see Table 1) and is fully interactive except in the 50SW simulations over the Southwest region where the soil saturation is held constant at 50%. Contour intervals and shading are the same as those specified in Fig. 10.

the rainfall distribution. The overall response of the large-scale patterns to the wet soil-moisture anomaly is consistent in each of the simulations (not shown). However, the response tends to be weaker in the July 1987 and 1988 simulations and stronger in the July 1993 simulations.

The spatial extent of the pressure anomaly is considerably larger than those of the 25MW and 25GC experiments. At lower levels, the westerly air flowing over the Mexican Plateau becomes anomalously moist and cool due to the wet soil-moisture anomaly (Fig. 12(b)). This tends to result in a significant weakening of the capping inversion over the LLJ. Thus, moist convection is more apt to occur over the Great Plains and Gulf Coast. The resulting anomalous convection (increased ascending motion) extends the low-pressure anomaly further to the east across the Gulf Coast.

Contrary to the 25MW and 25GC experiments, soil moisture has a pronounced impact on the strength of the LLJ in that the anomalous lifting has a tendency to degrade the strength of the LLJ (Fig. 12(b)). That is, the enhanced formation of rainfall tends to disturb/degrade the LLJ flow and thus reduces the formation of rainfall downstream in the Midwest.

In summary, the soil moisture in the Southwest exerts a significant control in determining the location of precipitation in the Great Plains and Midwest. Anomalously wet conditions in the Southwest tend to shift the precipitation from the upper Midwest into the Gulf Coast region. This shift results in drought-like conditions in the upper Midwest and flood-like conditions in the Gulf Coast, in addition to the anomalous Southwest region.

4. Discussion of results and conclusions

In this study, we investigate the local and remote physical pathways and mechanisms responsible for the soil moisture–rainfall feedback in North America during the summer. A series of numerical experiments are performed using a modified version of the NCAR RegCM to investigate these issues.

Overall, the results of the experiments suggest that the impacts of soil moisture on both the local- and large-scale summer climate prove to be an important factor in determining rainfall in the region of the anomaly and in surrounding regions. Soil-moisture anomalies over relatively small regions can induce and maintain flood and drought not only over the region of the anomaly, but also over remote regions. This mechanism appears to play an important role in both the persistence and intensity of extreme precipitation events.

The mechanisms through which soil moisture impacts precipitation are consistent with, but not limited to, the local theory of the soil moisture–rainfall feedback. Soil moisture, locally, impacts convective precipitation via processes involving the energy and water budgets. Through the changes in local convective environment, an additional mechanism occurs to the large-scale dynamics in that there is a meridional shift in the mean storm-track location. A dry anomaly tends to result in a northward shift in the storm track while a wet anomaly tends to result in a southward shift.

More specifically, it is shown that dry soil-moisture anomalies applied either over the upper Midwest or the Great Plains tend to result in drought-like conditions not only over the anomalous region, but also over nearby surrounding regions particularly to the north and south of the anomalies. These same anomalies tend to result in wetter than normal conditions over the Atlantic Seaboard states. This out-of-phase relationship is consistent with the observational findings of Higgins *et al.* (1997).

The most sensitive climatic response to soil moisture is seen when a wet anomaly is applied to the Southwest. As expected, this yields flood-like conditions over the anomalous region. However, strikingly, flood-like conditions occur directly to the east of the anomaly across the entire United States while drought-like conditions occur over the upper Midwest and eastward.

An increase in soil moisture acts to increase the convective activity in the region of the anomaly via the local mechanisms. The increase in convection tends to result in anomalous ascending motion due to a decrease in diabatic convective heating initiating from the cooler surface. Thus, an anomalous low pressure results and hence anomalous cyclonic flow. All of these factors tend to increase rainfall over the region of the anomaly thus resulting in a positive feedback. The response of rainfall to a dry anomaly is analogous (opposite in sign). These mechanisms are consistent with those of Pal and Eltahir (2002) where similar behaviours are displayed for the 1993 Midwest flood. Furthermore, Xue (1996) observed anomalous descending motion in numerical experiments investigating the response of climate to Mongolian desertification (which is similar to a dry soil-moisture anomaly).

Due to the impacts of soil moisture on the large-scale dynamics, the response is seen considerably beyond the region of the anomaly. The result of this significantly impacts rainfall in other regions. This suggests that soil-moisture conditions in one region can potentially induce flood and drought conditions in other regions.

United States rainfall is shown to be more responsive to soil moisture over the Southwest than in the Midwest and Gulf Coast. The main reason for the enhanced response is due to the impact of soil moisture on the LLJ. That is, a wet anomaly in the Southwest tends to reduce the strength of the capping inversion over the Great Plains and thus favours the development of rainfall over the Great Plains. This tends to disturb/degrade the LLJ flow upstream of the Midwest. Thus, there is a tendency for drier conditions in the Upper Midwest and wetter conditions in the Gulf Coast. This is consistent with the findings of Lanicci *et al.* (1987) where it is suggested that dry soil-moisture conditions over northern Mexico are critical for the formation of a capping inversion over the Great Plains.

Additional experiments were performed, but not presented, where a wet soil-moisture anomaly of 75% was applied to the Upper Midwest. The climatic response in these experiments is similar (opposite in direction), but weaker. Typically, values of soil moisture in the Midwest during the summer are around $50 \pm 20\%$ (Pal and Eltahir 2002). In the BATS scheme, the soils (root resistance) alone can only modify the maximum transpiration rate (2×10^{-4} mm s^{-1} or $\sim$500 W m^{-2}). However, peak day values of evapotranspiration over the FIFE* site in Kansas rarely exceed 450 W m^{-2} during July (Betts and Ball 1998). For soils representative of the Midwest (and most other portions of the domain), little control on transpiration is exhibited above values of 40% of saturation due to the nature of the BATS root-resistance function. In addition, the free drainage lower soil boundary tends to result in an overall underestimation of soil moisture, particularly in wet regimes. Thus, a positive soil-moisture anomaly in the Midwest has a considerably smaller effect on the climate than a negative anomaly. Note also that because of the representation of the root resistance within BATS, it is likely that the importance of controls of soil moisture on transpiration is underestimated in these experiments.

In the Southwest, the soil saturation is typically near the wilting point of the soils for BATS (25%). Therefore, in this region, a dry anomaly is likely to have a considerably weaker impact than a wet anomaly. From this, it can be concluded that the climate in arid regions is likely to be more responsive to a wet anomaly, while in humid regions the climate is likely to be more responsive to a dry anomaly.

We recall the findings of Seth and Giorgi (1998) in that, for sensitivity studies to internal forcings, domains much larger than the area of interest should be utilized. In this study, a large domain is selected to include the large-scale responses to soil moisture. However, since, these responses extend to near the boundaries (e.g. Fig. 12(a)), it is still conceivable that some of them are constrained or neglected due to their presence. With this in mind, it is unlikely that the qualitative results and mechanisms presented in this study change. If anything, the boundaries dampen the response of the large-scale to changes in soil moisture.

Recall that a wet soil-moisture anomaly tends to decease surface temperature and thus acts to decrease geopotential height in the region and slightly downwind of the anomaly. The decrease in height provides favourable conditions for both convective and

* First ISLSCP (International Satellite Land-Surface Climatology Programme) Field Experiment.

large-scale rainfall to form and thus is a positive feedback. In the case of SSTs over southern midlatitudes, a cold anomaly tends to decrease the geopotential height in the region and slightly downwind of the anomaly (e.g. Palmer and Zhaobo 1985; Ferranti *et al.* 1994). This suggests conditions conducive to the formation of rainfall. However, anomalously cold SSTs are typically associated with a decrease in rainfall due to the decrease in the flux of energy (latent and sensible) from the surface. Thus, the decrease in height tends to dampen the decrease in rainfall resulting from the cooler SSTs.

Lastly, these results suggest the importance of accurately initializing soil moisture in climate models according to the observations. Failure to do so can result in an inaccurate representation of the large-scale dynamics and hence severe errors in many hydrological fields.

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