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Teleconnections of soil moisture and rainfall during the 1993 midwest summer flood

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[1] Here, we investigate the role of spring soil moisture distribution during the 1993 summer flood in North America. A series of idealized numerical experiments are performed using a regional climate model with different soil moisture conditions. It is concluded that the abnormally dry conditions in the Southwest may be partially responsible for the meridional location of the intense flooding in the Upper Midwest. Furthermore, the abnormally wet soil moisture conditions in the Midwest are likely to be partially responsible for the flood's persistence and large magnitude, but not for its spatial location. These impacts are initiated via processes involving the local energy and water budgets and then propagated to the surrounding regions through the large scale dynamics. Depending on the location, soil moisture anomalies over relatively small regions can significantly alter rainfall both locally and in surrounding regions. *INDEX TERMS:* 1854 Hydrology: Precipitation (3354): 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 1833 Hydrology: Hydroclimatology. **Citation:** Pal, J. S., and E. A. B. Eltahir, Teleconnections of soil moisture and rainfall during the 1993 midwest summer flood, *Geophys. Res. Lett.*, *29*(18), 1865, doi:10.1029/2002GL014815, 2002.

1. Introduction

[2] To date, the 1993 summer flood over the Midwestern United States was one of the most devastating floods in modern history [*Kunkel et al.*, 1994]. Record high rainfall and flooding occurred throughout much of the Upper Mississippi River basin and persisted for long periods. *Bell and Janowiak* [1995] and *Trenberth and Guillemot* [1996] find that the spring and summer of 1993 storm track over North America is shifted considerably south of normal. They suggest that this shift acted as a duct for the moist low level from the Gulf of Mexico and favored the development of cyclonic storms and mesoscale convective complexes. *Namias* [1991] speculate 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 anti-cyclonic flow. He argues that the increase in sensible heating encourages the growth of a high via an increase in pressure. However, it is not widely investigated whether the soil moisture conditions during summer floods play a role in the strengthening and anchoring the associated cyclonic flow.

[3] *Higgins and Shi* [2000] show that summer precipitation in the Midwest is characterized by an out-of-phase relationship with summer precipitation in the Southwest. That is, when dry conditions exist in the Southwest wet conditions tend to exist in the Great Plains and Midwest. During the Midwest summer flooding of 1993, [*Higgins and Shi*, 2000] found that the North American monsoon system (NAMS) experienced its latest onset date on their data record (1948–1996).

[4] To date, many numerical studies have investigated the 1993 Midwest flooding with particular emphasis on the soil moisture - rainfall processes in the flood region [e.g. *Beljaars et al.*, 1996; *Seth and Giorgi*, 1998; *Bosilovich and Sun*, 1999; *Pal and Eltahir*, 2001]. There is general agreement that soil moisture played a significant role in enhancing the flood conditions.

[5] In this study, we investigate the teleconnections between soil moisture in the Southwest and precipitation in the Midwest using a regional climate model. More specifically, we explore how local and remote surface soil moisture conditions can potentially impact summer rainfall over the Midwest.

2. Description of Numerical Experiments

[6] In this study, we use a modified version of the National Center for Atmospheric Research's (NCAR) REGional Climate Model (RegCM) described by *Giorgi et al.* [1993a, 1993b] and by *Pal et al.* [2000]. The initial conditions (except for soil moisture and sea surface temperature) and lateral boundary conditions for each simulation are taken from the NCEP Reanalysis data [*Kalnay et al.*, 1996]. The SST is prescribed using data provided by the United Kingdom Meteorological Office [*Rayner et al.*, 1996]. The vegetation is specified using the Global Land Cover Characterization data [*Loveland et al*, 1999].

[7] The model domain is shown in Figure 1. A horizontal grid point spacing of 55.6 km is used with 14 vertical sigma levels and 50 hPa model top. To investigate potential impacts of soil moisture on U.S. summer rainfall, we perform a series of idealized numerical experiments with three soil moisture configurations. Each simulation is initialized on the 25th of June of 1993 and run for 37 days. The first six days of each simulation are ignored for spin-up considerations.

[8] Our control simulation (CTL) is initialized using the derived soil moisture dataset presented in *Pal and Eltahir* [2001] (see Figure 1). The data are derived from the Illinois

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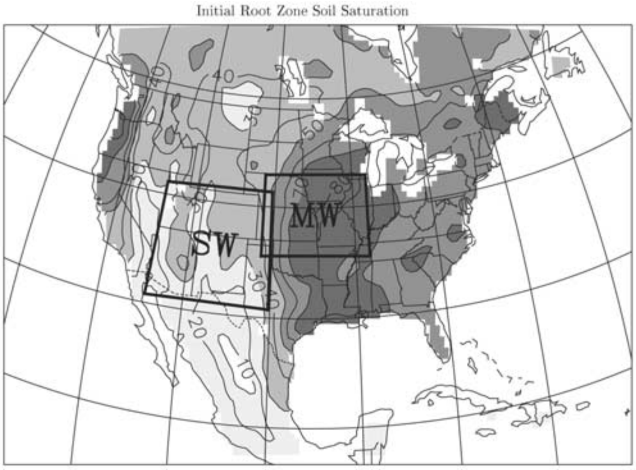


Figure 1. 25 June 1993 of the root zone soil saturation (%) used to initialize the model for the CTL simulations. The boxes indicate the regions over which the fixed patch anomalies are applied: MW denotes Midwest; and SW denotes Southwest. The contour interval is 10% and shading occurs at values above 10% and at intervals of 20%.

State Water Survey observations [*Hollinger and Isard*, 1994], the inferred 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 can contain significant errors especially in regions that significantly differ from the Midwest (such as the Southwest).

[9] In the second and third experiments, the soil moisture is initialized as in to the CTL simulation except over a specified region where it is perturbed and held fixed (i.e., the soil moisture does not respond to the atmosphere). Soil moisture over the unperturbed region is fully interactive. In the second experiment (25MW), we investigate the impacts of dry soil moisture conditions over the same region by holding the soil saturation over the upper Midwest at 25% (see Figure 1 box MW). In the third set (50SW), we investigate how a wet anomaly in the Southwest impacts the distribution of rainfall over the Midwest by holding the soil saturation over the Southwest at 50% (see Figure 1 box SW). We fix the soil moisture over the perturbed regions so that the response of the atmosphere to these anomalies can be emphasized. Experiments where the soil moisture in the region of the anomaly is allowed to interact result in similar conclusions (not shown). However, the impacts are not as strong as they are when soil moisture is fixed.

3. Results

[10] Since this is a mechanistic study, we do not present a rigorous comparison of the model simulations to observations which can be found in *Pal et al.* [2000]. Briefly, however, we compare the USHCN precipitation observations [*Karl et al.*, 1990] to the those of the CTL simulation (Figures 2a and 2b). Although some deficiencies exist, it

(a) USHCN (observed)   (b) CTL Simulation

(c) 25MW Simulation   (d) 50SW Simulation

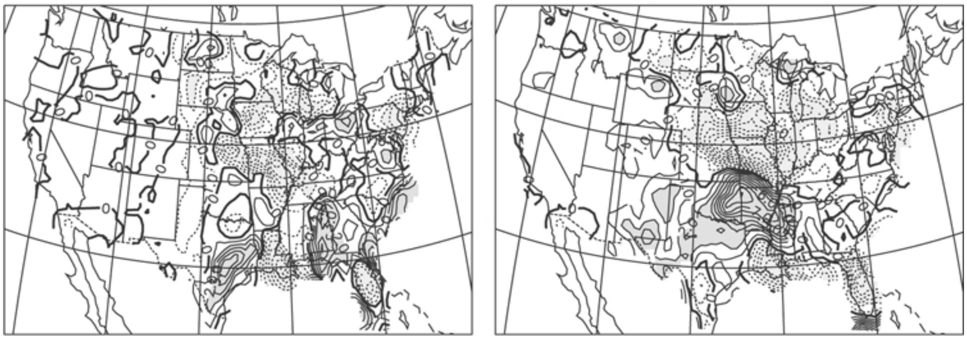


Figure 2. July 1993 Precipitation (mm/day): (a) USHCN observations; (b) CTL simulation; (c) 25MW-CTL; and (d) 50SW-CTL. The contour interval is 1 mm/day. In panels (a) and (b) shading occurs at values above 1 mm/day and at intervals of 2 mm/day while in (c) and (d) dark shading occurs at values above 2 mm/day and light shading below −2 mm/day. Note that only values for the United States are displayed.

can be seen that the model performs well in capturing the flood peak over the Upper Midwest as well as the dry conditions in the surrounding regions.

[11] Here we compare the differences in simulated precipitation between the CTL and 25MW experiments (Figure 2c). Dry conditions over the Upper Midwest result in an overall reduction magnitude of the flood peak. The greatest reduction in the flood peak occurs over the southern portion of the anomaly region. The anomaly also results in significant changes to the distribution of rainfall along the Atlantic Coast and Gulf Coast states. However, there is little impact on rainfall in the Southwest.

[12] The changes in precipitation resulting from the soil moisture anomaly are due to the impact of soil moisture on the the local climate. The dry anomaly over the Upper Midwest tends to result in a decrease in energy per unit depth of planetary boundary layer over the perturbed region which tends to decrease the likelihood and amount of convective precipitation (not shown). These local mechanisms were discussed at length in *Pal and Eltahir* [2001] and are thus not elaborated upon here.

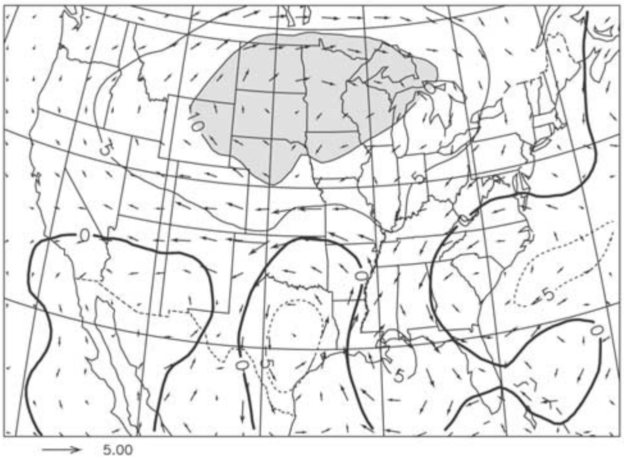
[13] The changes to the local convective environment tend to induce changes in the large-scale circulation which in general favor a positive soil moisture - rainfall feedback. In Figure 3a, it is clear that the dry soil moisture anomaly over the Upper Midwest results in a high pressure anomaly and hence, a slight northward shift in the storm track location. This is reflected in the larger decrease in precipitation over the southern portion of the anomaly region.

[14] The mechanisms responsible for the high pressure anomaly are initiated by the decrease in convection over the perturbed region resulting from the local processes. This results in a decrease in diabatic heating and thus an anomalous high pressure. The increase in pressure tends to increase the descending motion (or weaken the ascending motion) and thus results in anomalous anti-cyclonic flow and less rainfall. Since this anomaly occurs in the region of the storm track during 1993, a slight northward shift in the storm track occurs. This inturn tends to further reduce the likelihood of development of storms over the anomaly region. All of these factors act to enhance the soil moisture - rainfall feedback. Because the local soil moisture anomaly impacts the storm track strength and location, significant changes to the distribution of precipitation also occur over regions outside of the anomaly. It should also be noted that this dry anomaly over the Upper Midwest has only minor impact on the strength of the Great Plains low-level jet (LLJ; not shown).

[15] Figure 2d displays the precipitation distribution of the 50SW experiments. As expected, an increase in soil moisture over the Four Corners States results in a significant increase in precipitation over the same region (about double). However, strikingly, the soil moisture anomaly results in a more dramatic reduction rainfall over the flood region. The majority of the flood peak shifts south to the Great Plains where the increase in rainfall is as dramatic. In addition, there tends to be a general decrease in rainfall over the remaining regions.

[16] Similar to the 25MW experiments, the wet soil moisture anomaly over the Four Corners States results in an increase in convective rainfall via the impact of soil moisture on the energy and water budgets of the region. However, we see clearly from Figure 2d that these local mechanisms must have pronounced impacts at the synoptic scale. Indeed a widespread low pressure anomaly extends across the southern and eastern two thirds of the United States (Figure 3b). The anomalous low pressure results in anomalous cyclonic flow and causes the storm track to shift to the south. Again similar to the 25MW experiments, the increase in convection over the anomaly region generates a low pressure with increased heating and ascent. At lower levels, the westerly air flowing over the Mexican Plateau becomes anomalously moist and cool due to the wet soil moisture anomaly (not shown). This tends to result in a significant weakening of the capping inversion over the LLJ and thus favors the development of convective rainfall further upstream of the LLJ over the Great Plains and Gulf Coast.

(a) 500 hPa Winds and Geopotential Heights (25MW-CTL)



(b) 500 hPa Winds and Geopotential Heights (50SW-CTL)

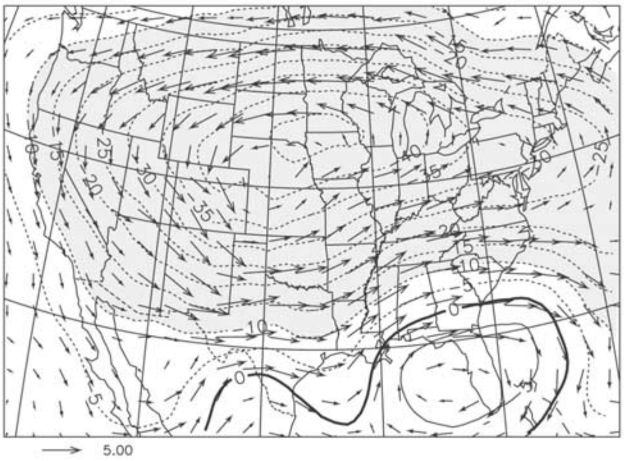


Figure 3. July 1993 500 hPa simulated between geopotential heights (m; contours and shading) and winds (m/s; vectors): (a) 25MW-CTL; and (b) 50SW-CTL. The contour interval is 5 m. Dark shading occurs at values above +10 m and light shading occurs below -10 m. Every fourth wind vector is plotted.

[17] The resulting anomalous convection (increased ascent and heating) extends the low pressure anomaly from the Southwest to the east. Thus, contrary to the 25MW experiment, soil moisture causes a decrease in the strength

of the LLJ (not shown). The increased convective activity further upstream along the LLJ tends to degrade its intensity. This tends to reduce the amount of moisture transported into the Upper Midwest and hence results in non-flood-like conditions. In addition, the enhanced lifting over the Great Plains tends to cause low-level divergence in the Midwest and thus a further reduction in rainfall.

4. Discussion of Results and Conclusions

[18] Our experiment show that soil moisture in both local and remote regions is to play a significant role in the distribution of United States precipitation. More specifically, the abnormally wet soil moisture conditions in the Midwest are likely to be in part responsible for the flood's persistence and large magnitude (primarily via local mechanisms), but not for its spatial location. However, the abnormally weak NAMS observed in 1993 may be partially responsible for the meridional location of the intense flooding in the Upper Midwest (primarily via remote mechanisms).

[19] The mechanisms through which soil moisture impacts summer rainfall over the Midwest initiate at the local scale. That is, soil moisture impacts convective precipitation via processes involving the energy and water budgets [*Pal and Eltahir*, 2001]. Through the changes in local convective environment, an additional mechanism is introduced to the large-scale dynamics which tends to enhance the soil moisture - rainfall feedback. In short, an increase in soil moisture acts to increase the convective activity via the local mechanisms. The increase in convection tends to result in anomalous ascending motion due to an increase in diabatic convective heating. 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.

[20] These findings are consistent with what *Namias* [1991] proposes for droughts in that dry soil moisture conditions may act to anchor the associated anti-cyclonic flow. However, the mechanisms presented in this study are different than those speculated by Namias. *Xue* [1996] finds that desertification, which is similar to a dry soil moisture anomaly, over Mongolia tends to result in anomalous descending motion and hence impacts the large-scale dynamics. Here we suggest that contrapositive to be true as well. That is, wet soil moisture conditions appear to play an important role strengthening and anchoring the associated cyclonic flow.

[21] Since the impacts of soil moisture anomalies are transmitted to the large-scale, changes in the distribution of rainfall over nearby regions can result. For example, a wet anomaly in the Southwest tends to remove the capping inversion over the Great Plains and thus favors the development of rainfall further to south (upstream along the LLJ). Thus, there is a significant southward shift in the flood peak location. Similarly, *Lanicci et al.* [1987] suggest that dry soil moisture conditions over northern Mexico are critical for the formation of capping inversion over the Great Plains.

[22] In conclusion, 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 perturbations over relatively small regions induce significant changes to the distribution of rainfall not only over the perturbed region, but also over remote regions. The mechanisms presented here appear to play an important role in both the persistence and intensity of extreme precipitation events.

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