Land surface influence on summer climate predictability in the United States Midwest

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1. Abstract

Atmospheric prediction models include a surface module through which land surface boundary conditions (e.g., land cover, soil moisture and LAI) are introduced into the model simulations. Variables that depict these land surface conditions are increasingly being obtained from satellite sources and by integrating them into atmospheric modeling systems, significant advances are being made in delineating the role of land surface structure and heterogeneity on global and regional climate. In this study we explore local and regional scale impacts of changes in land surface conditions on climate processes and the associated feedbacks with particular emphasis on the central United States. Specifically, we employ the Colorado State University Regional Atmospheric Modeling System (RAMS Version 4.3) to investigate the roles of contrasting land covers and soil moisture variability in the initiation and subsequent organization of summertime convection in the U.S. Midwest for the August 2000 case study period. Results indicate that a more realistic representation of the surface boundary affects the amount and spatial distribution of precipitation and improves the model-generated precipitation as compared to NCEP observations.

2. Study Motivation

The influence of changes in land surface variables such as soil moisture on the development of convective systems can be an important forcing factor during weak synoptic flow regimes. Prior observational analyses based on NCEP/NCAR Global Reanalysis (GR) dataset suggest that August 2000 would be a candidate period to examine these impacts (Carleton et al., 2007). Diurnally averaged surface meteorological variables from the NCEP GR data revealed changes around August 5-6, 2000, which coincided with the aftermath of heavy convective precipitation events associated with a major change in the synoptic atmospheric circulation around that time. In the subsequent weeks a high pressure ridge developed over the Midwest and the synoptic-scale environment became unfavorable for convection, yet convective precipitation across the southern parts of Illinois and Indiana occurred prominently.

Did the soil moisture and vegetation provide a mechanism to force this convective precipitation and how it organized in the later part of the month?

3. Data and Methodology:

Simulation Domain & Model Set-Up

- Chen and Cotton (1983) radiation scheme
- Explicit microphysical representation of precipitation with no convective parameterization
- LEAF-2 Land Surface scheme
- Midwest domain with 5 km grid spacing
- Lateral boundary forcing by the North American Regional Reanalysis with weak internal nudging to maintain the large-scale variability in the simulation
- Simulation length: 1-31 August 2000

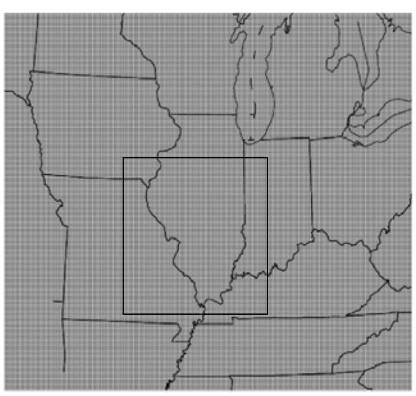

Figure 1. The domain of the model run. The inside box is the region of interest where the precipitation is averaged for time series analysis (92W & 86W and 37N & 41N)

Soil Moisture and Leaf Area Index Data Assimilated in to RAMS

<u>Soil Moisture:</u> Retrospective North American Land Data Assimilation (NLDAS) soil moisture from the MOSAIC model (Cosgove et al. 2003) at approximately 12 km resolution (0.125 degree). Used as initial condition only.

Replaces default homogeneous soil moisture specified by model-user.

<u>Vegetation:</u> NASA Global Inventory Modeling and Mapping Studies (GIMMS) satellite-derived normalized difference vegetation index (NDVI) at 8 km resolution. Converted to leaf area index (LAI) using the algorithm by Sellers et al. (1996). Updated throughout the simulation.

Replaces default climatological LAI evolution prescribed per vegetation type in LEAF-2.

4. Results

4.1 Soil mositure and Leaf Area Index after 15 days of simulation

Both the spatial details and horizontal gradients in soil moisture over the entire model domain were greater in the heterogeneous soil moisture run compared to the homogeneous soil moisture experiment. Soil moisture was notably higher across a swath of the central Midwest extending from southern Minnesota through Iowa, Illinois, Indiana and western Ohio (Figure 2b).

This soil moisture pattern was remarkably similar to the LAI distribution in the model run with satellite-derived LAI (Figure 3b). The RAMS default LAI values were much larger over most of the model domain compared to the satellite-derived LAI.

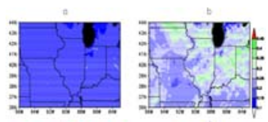

Figure 2. Volumetric soil moisture (m3 m-3) after 15 days of simulation from (a) default run (b)NLDAS run

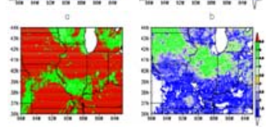

Figure 3 Leaf Area Index (m2 m-2) after 15 days of simulation from (a) default run (b) LAI run

4.2 Bias in precipitation of RAMS simulations from the NCEP observed precipitation (in mm)

The default run underestimated the rainfall band over the Kentucky, southern Indiana and Illinois, and central Missouri to a greater extent compared to the other model runs. Of the four experiments, the LAI run (Figure 4c) shows the least underestimation of the NCEP-CPC precipitation, indicating that the incorporation of satellite derived LAI does the most to improve the spatial correspondence between domain wide model and observed precipitation fields. Consequently, the runs that incorporate satellite-derived LAI and heterogeneous soil moisture (LAI and NLDAS+LAI) have lesser bias compared to the other two simulations.

In addition, the area averaged RMS error is smallest for the LAI run and also lower for the NLDAS+LAI run compared to the default run. While the domain-averaged RMS error for the NLDAS run (Figure 4b) is actually larger than that of the default run, a closer examination of the spatial structure of the difference matrix between the NLDAS and default runs shows a lower bias in the NLDAS run in the southern portion of the domain where all the model runs (except for the default) do relatively well compared to observations.

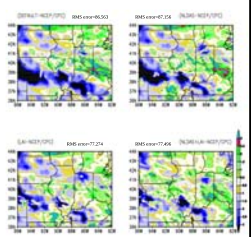

Figure 4: Averaged difference in precipitation of RAMS simulations from the NCEP observed precipitation (in mm) for August 2000.

4.3 Time series analysis of precipitation

The focal point of local convective activity was central and southern Midwest (91W-86W and 37N-41N). The time series of the area averaged rainfall for the month of August 2000 over this area is shown in Figure 5. There are obvious discrepancies between the model runs and observations over the 28-day period shown in the figure, especially on August 9-10 when the model failed to capture the August 9 rain event and towards the end of the month when the model overestimated rainfall. That said, the model runs that incorporated more realistic surface data performed better than the default run when compared to the observed data time series.
The rainfall from 16-17 August,2000 which is locally forced is better captured by the NLDAS run

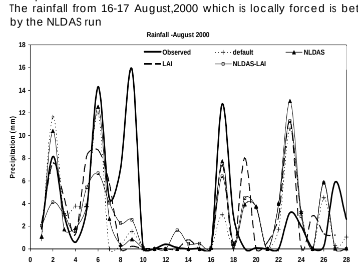

Figure 5: Area averaged time-series of rainfall for August 2000, for the region 92W & 86W and 37N & 41N.

4.3 Factor separation method-precipitation and heat fluxes

The factor separation technique described in Stein and Alpert (1993) was used to identify the relative contributions of soil moisture and vegetation to precipitation and surface heat fluxes based on the following formulation:

$$F_0 = f_0$$
$$F_1 = f_1 - f_0$$
$$F_2 = f_2 - f_0$$
$$F_{12} = f_{12} - (f_1 + f_2) + f_0$$

Where F0, F1, F2, F12 represent the RAMS default; contribution of variable soil moisture; contribution of satellite derived LAI and contribution due to the interaction of both soil-moisture; and LAI, respectively, to the precipitation and surface heat fluxes.

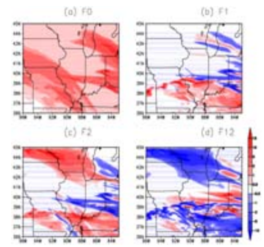

Figure 6 (a) Precipitation of default RAMS run; (b) Precipitation introduced by the heterogeneity of soil-moisture; (c) Precipitation by the introduction of satellite derived LAI and (d) Precipitation introduced by the interaction of heterogeneity in soil-moisture and satellite LAI for the days 16-20 August 2000

- The locally forced rainfall event (August 16-20, 2000) was better captured by the NLDAS run over the south central Midwest and the NLDAS factor analysis (F1) results (Figure 6 b) for that period shows positive values over the southern Illinois, Indiana and central Missouri compared to the default run. (Figure 6 a)
- Similarly, incorporating satellite derived LAI (F2) instead of the RAMS Leaf-2 climatological LAI clearly leads to enhanced precipitation in the southern portion of the domain. (Figure 6 c)
- However, the influence of the combination of these boundary conditions when the individual effects are not taken into consideration results in opposite precipitation fields (i.e., negative values for the southern region of the domain – Fig. 6d). This implies that the real improvement in precipitation in the model simulation comes from enhancing surface heterogeneity through the individual contributions of NLDAS soil moisture and satellite-derived LAI.

The analysis of surface heat fluxes for 11-15 August, 2000

- The effects of using heterogeneous soil moisture in RAMS leads to enhanced values in Sensible Heat (H) fluxes field and lower values in Latent Heat (L) fluxes field over Missouri (Figures 7(b) and 8(b)) compared to the RAMS default run with homogenous soil moisture (Figures 7(a) and 8(b)).
- The RAMS run with satellite LAI (Figures 7(c) and 8(c)) indicates much higher values of H field and much lower values of L field compared to the default run

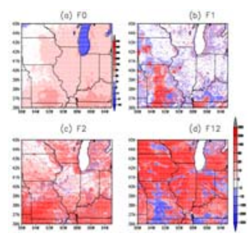

Figure 7. Same as Figure 5 but for Sensible heat flux for 11-15 August, 2000

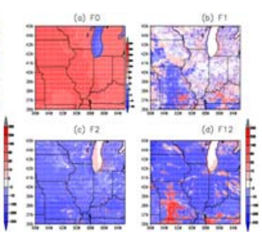

Figure 8. Same as Figure 5 but for Latent heat flux for 11-15 August, 2000

4.4 Spectral Analysis of Moisture Flux Convergence

Vertically integrated moisture flux convergence (MFC) is derived as a post-processing step using the following relation

$$MCF = -\frac{1}{g}\int_{P_{Top}}^{Ps} \nabla.(q\bar{v})dp$$

In order to gain further insights into the spatial scales of moisture organization, we conducted spectral analysis of moisture flux convergence. Factor separation method is applied to these spectral powers [S(k)] as follows:

$$F0 = S(k)_{default}$$
$$F1 = \frac{S(k)_{NLDAS} - S(k)_{default}}{S(k)_{default}}$$
$$F2 = \frac{S(k)_{LAI} - S(k)_{default}}{S(k)_{default}}$$
$$F12 = \frac{S(k)_{NLDAS+LAI} - [S(k)_{NLDAS} + S(k)_{LAI}] + S(k)_{default}}{S(k)_{default}}$$

The spectral powers of MFC field for default run (Figure 9(a)) and fractional spectrums for NLDAS (Figure 9(b)), LAI (Figure 19(c)) and NLDAS+LAI (Figure 9(d)) for the month of August, 2000 clearly shows that the incorporation of new boundary conditions very much influenced the scale and amplitude of the convective organization over the US Midwest.

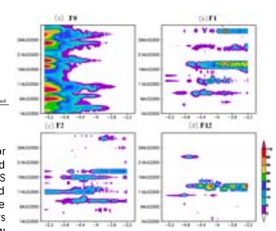

Figure 9: Spectral Power of MFC for (a) default; Fractional Spectral powers of MFC with respect to the default run for (b) NLDAS (c) LAI and (d) NLDAS+LAI for August 2000.

Heterogeneity in soil-moisture helped to enhance the MFC spectral power mainly for 16-20 August, 2000. This period included days of locally forced rainfall events over central and southern parts of US Midwest. This enhancement is evident for systems with length scales of 100 km (log k = -4.2) or less indicating that the main effect of heterogeneity in soil moisture was on local scale convection. The incorporation of satellite derived LAI values also enhances the spectral powers of the MFC field but the influence is less. However, its influence was also evident on larger scale convective systems which is absent in NLDAS run. Additionally, the enhancement in the MFC spectral power by the combined effect when excluding the individual effects (Figure 9(d)) was more obvious from 11-15 August, which is a period low convective activity.

5. Conclusion

This study shows that incorporating more realistic LAI factor improves RAMS rainfall simulation over the southern Illinois and Indiana of the mid-August 2000, rainfall spells. Even better simulation of precipitation is produced by using both the NLDAS soil moisture data and the satellite derived LAI data together. **Clearly, the higher H fields and lower L fields during 11-15 August, 2000 influenced the initiation and organization of convection in the days following (i.e., August 16-20) possibly by decreasing the time for reaching the convective temperature.**