Progress Report for Year 1 of 3 Year Project
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# *Identifying Controls and Predictability of Extreme Drought Persistence from Remote Sensing Data*

PI: John D. Albertson
Department of Civil and Environmental Engineering
Duke University

## Summary of Highlights from Year 1.

In year 1 we have focused on three large activities:

1. Investigating potential for preferential states driven by feedback between soil moisture and both rainfall frequency and potential evapotranspiration,
2. Exploring climate impacts on precipitation in the Southern Great Plains, and
3. Studying the dynamics of PBL growth, including both models and radiosonde data

Here we review briefly the findings from each of the three activities.

*1. Feedbacks and Preferential States*:
Persistent states are often explained by local water recycling. Feedback between soil moisture and rainfall frequency may lead to bimodality in the frequency distribution of soil moisture (Entekhabi et al. 1992; D'Odorico and Porporato 2004). Additionally, soil moisture controls the partition of the sensible and latent heat fluxes and subsequently influences the atmosphere temperature and humidity and hence the PET. Figure 1 shows the feedback loops through soil moisture to precipitation and through soil moisture to evapotranspiration. As can be seen on the right soil moisture positively influences precipitation frequency (hereinafter, referred to as “Feedback I”). On the left, Figure 1 shows the soil moisture affects PET through surface atmosphere temperature, and PET determine the evaporation which then alter the water content in the soil. This feedback loops is referred to as “Feedback II” hereinafter.

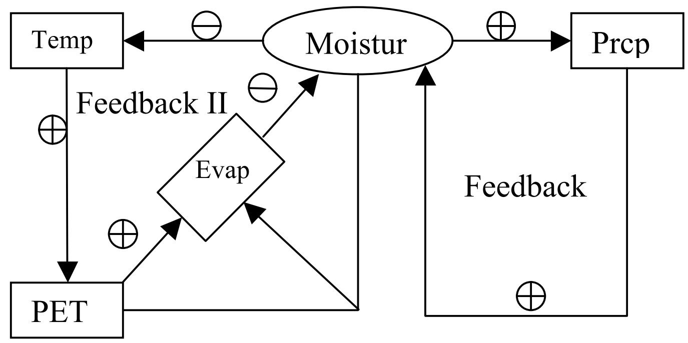


Figure 1 Feedbacks from soil moisture to rainfall and feedbacks from soil moisture to evapotranspiration

Figure 2 shows the comparison of soil moisture pdf with and without considering Feedback I. When the feedback was not considered, the pdf of soil moisture is unimodal, and soil trends to stay at one stable state. When the Feedback I was considered, bimodality in pdf of soil moisture appears. This means soil try to stay at either dry or wet state.

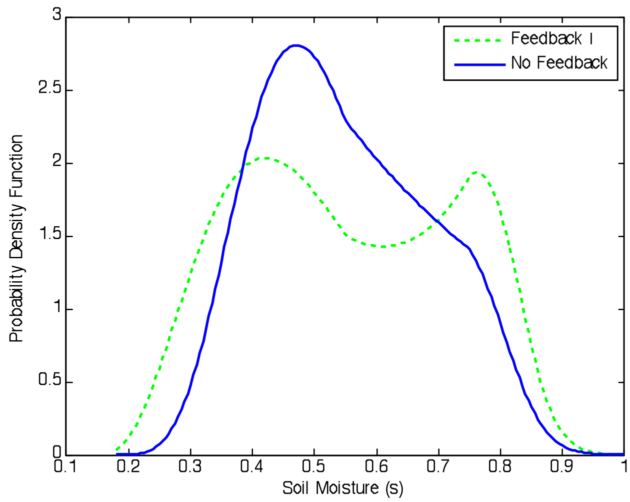


Figure 2 Probability density function of soil moisture with and without feedback I

Data from Peoria, Illinois (Hollinger and Isard 1994) were used to analyze the relation between soil moisture and PET (Figure 3). The correlation coefficients reach to -0.4316 for all data, and -0.1904 for soil moisture in summer. When soil is wetter, temperature is lower, and PET is also lower. There is a larger variation of PET for all seasons, and the corresponding coefficient is more negative. In summer, the PET does not change too much, and the corresponding coefficient is less negative. Although, correlation is weak in summer, the trend is still observable. For simplicity, the relation between soil moisture and PET in summer was assumed to be linear and applied to analyze its influence on soil system. It would be possible to give a more accurate result than that from a constant $E_{max}$.

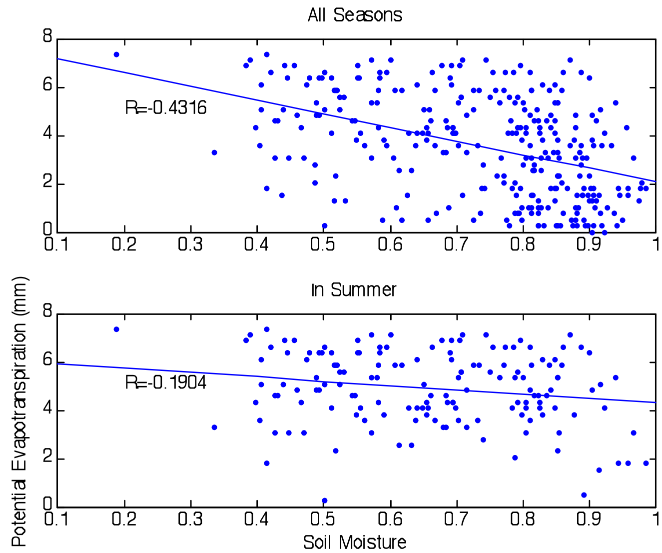


Figure 3 Correlation between Soil Moisture and Potential Evapotranspiration at Peoria, IL

Figure 4 compares the soil moisture probability density functions derived from constant PET and from PET as a function of soil moisture. Feedback II leads to a little higher dry (0.2<s<0.3) and wet (0.7<s<1.0) probability; Feedback II also makes the soil more unstable at wet-dry transition period (around valley of pdf). This feature seems to make soil system stay longer at either wet or dry states.

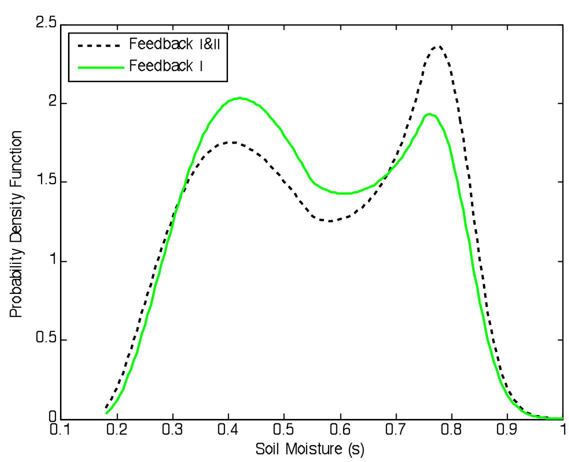


Figure 4 Probability Density Functions of Soil Moisture with and without Feedback II based on the Model Considering Feedback I

It is also interesting to compare impacts of Feedback II on pdf of soil moisture based on the model without considering Feedback I (Figure 5). It shows that the Feedback II itself tends to generate bimodality of the moisture pdf accentuating a possible wet state with soil moisture around 0.75.

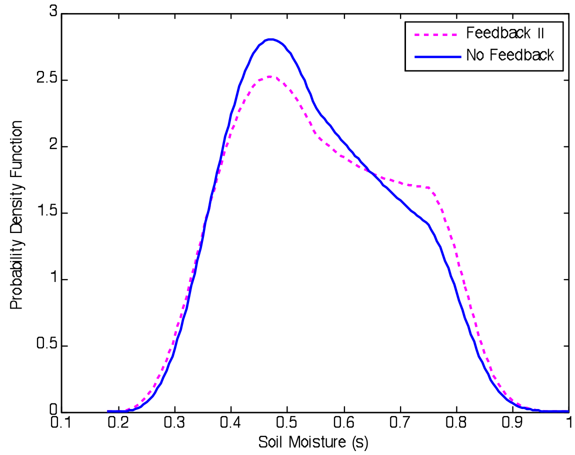


Figure 5 Similar to Figure 4 except Feedback I was not considered

Using the soil moisture data from Peoria, soil moisture distribution frequency is calculated and plotted in as histograms in Figure 6. Generally this histograms show a clear bimodality in soil moisture distribution, while the analytical solution for Feedback I and Feedback I&II also present corresponding bimodality. Comparing with the simple water balance model without any feedbacks (Figure 2), models including feedback I or I&II seem more reasonable. It may leads to the conclusion that soil moisture feedbacks cause two soil preferential states. Both the analytical solutions depict the outlines of preferential states, and the goodness of fit also partially determined by model's parameterization.

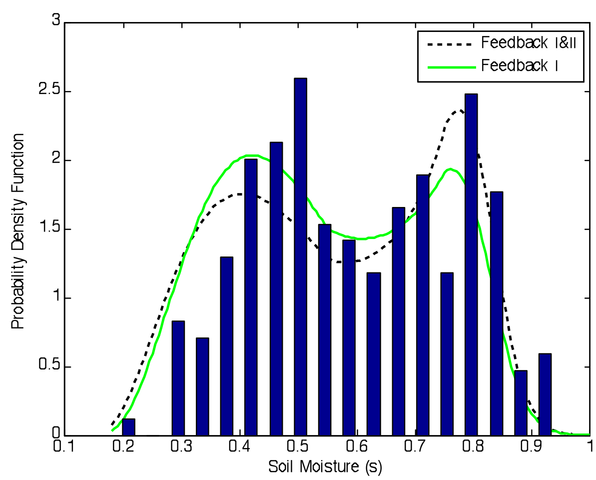


Figure 6 Probability density function of soil moisture with Feedback I and Feedback I&II. The histograms show top 50cm soil moisture frequency for May to September from 1982 to 2004 at Peoria, Illinois.

When Feedback I and I&II (dashed and solid lines) were taken into effects, inter-arrival time has higher probabilities in long and short periods. As shown in the left side of Figure 7, Feedback I tends to have drought periods while Feedback II has little impacts on the drought states. On the right side, Figure 7 shows Feedback I itself has little impacts on the persistent wet states while Feedback II combined with Feedback I has larger impacts. However, these differences are sensitive to the choice of parameters, such as the calibrated coefficients of Feedback II. These two Feedbacks, soil moisture's feedback on rainfall frequency and PET, both trend to change the system's preferential states.

Although the Feedback II itself can not change rainfall inter-arrival time, it can change the time through Feedback I. What is more, Feedback II itself tends to generate bimodality in pdf of soil moisture, and the combining two Feedbacks can emphasize the character of the bimodality as shown in Figure 4.

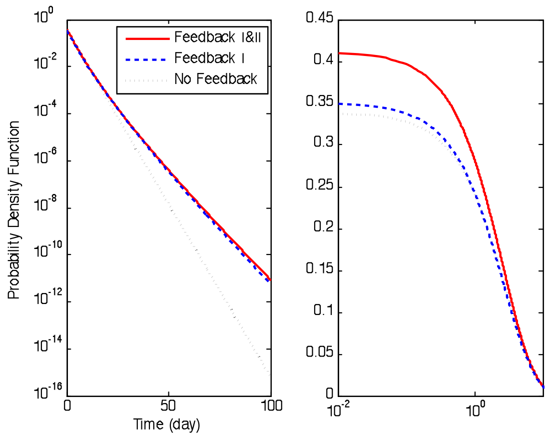


Figure 7 Probability Density Functions of inter-arrival Time when considering Feedback I and/or II (Left graph has logarithmic scale on the y axis, and Right graph has logarithmic scale on the x axis)

*2. Climate Impacts on Precipitation in the SGP*

To investigate the precipitation change in Southern Great Plains by large scale GCM outputs, we extend the study area to a region with latitudes 25.8-41°N and longitude 93.5-109°W (Figure 8). According to (Koster, Dirmeyer et al. 2004) Central and Southern Great Plain is a hotspot for land-atmosphere interaction. Various researches focus on the feedbacks of land surface properties to the local climates. It is interesting to study how the local recycling would be change in the global warming scenarios.

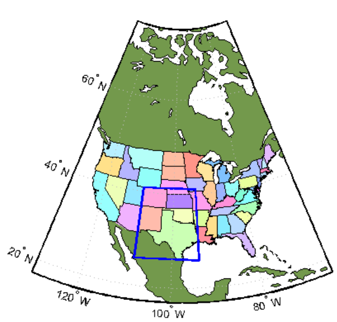


Figure 8 Study area of Extended Southern Great Plains

Output of HadCM3 prepared for IPCC Fourth Assessment climate was used in this analysis. We found that in spring (March, April, and May) and winter (December, January, February) HadCM3 overestimated the region's precipitation, but in summer (June, July, August) and fall (September, October, and November) HadCM3 can simulate the precipitation within reasonable accuracy.

We examined the fraction of precipitation resulting from convective events,

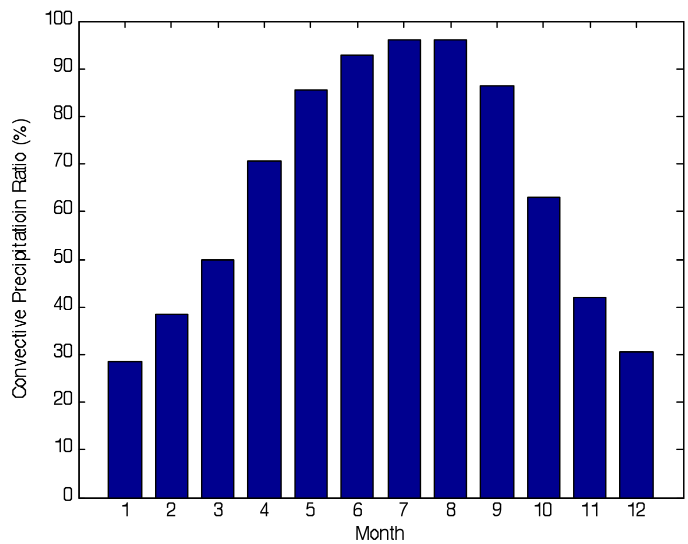


Figure 9. Ratio of Convective Precipitation to total Precipitation from HadCM3 1950-1999 Monthly outputs

Figure 9 compares precipitation changes between current (1950-1999) and future (2050-2099) from HadCM3 A1B scenario. It shows that precipitation changes very little in winter and early spring, but decreases late spring and summer and increases in fall. Precipitation uncertainties also vary in each month. As the error bar in Figure 9 shown, precipitation uncertainties increase when the total precipitation changes (either increase or decrease), while keep relative constant in winter and early spring.

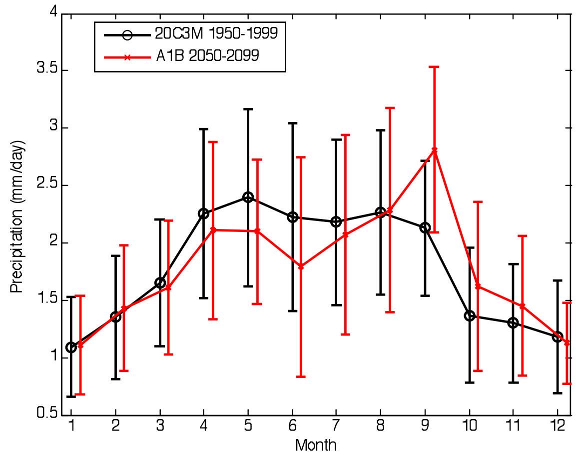


Figure 9 Precipitation Changes from HadCM3 A1B scenario 2050-2099

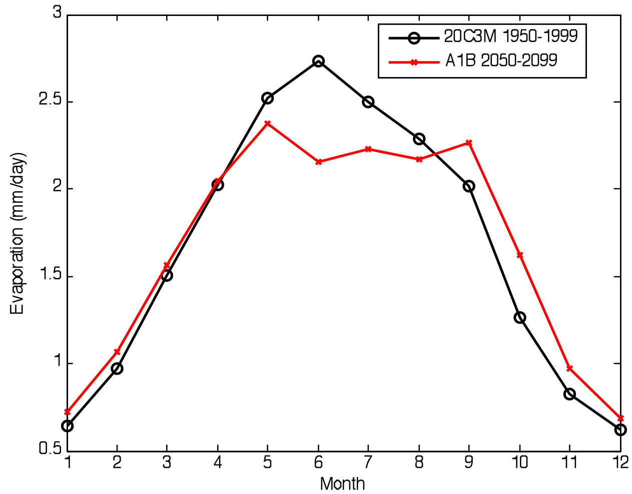


Figure 10 Evaporation Changes from HadCM3 A1B scenario 2050-2099

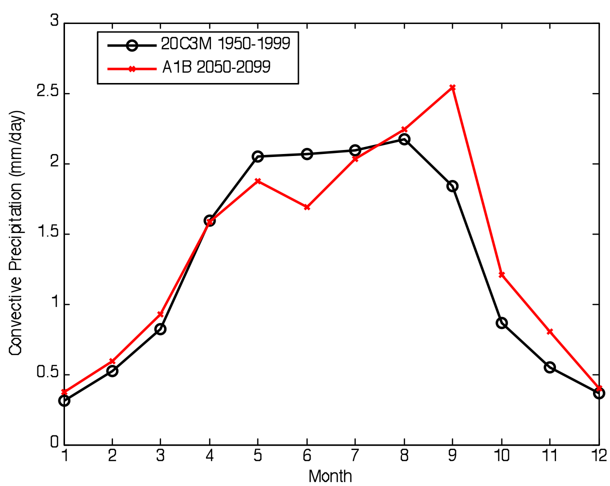


Figure 12. Convective Precipitation Changes from HadCM3 A1B scenario 2050-2099

Convective available potential energy (CAPE) and Convective inhibition energy (CINE) were calculated and plotted in Figure . The decrease of CAPE and increase of CINE in late spring and summer may lead to the difficulty of forming convective precipitation.

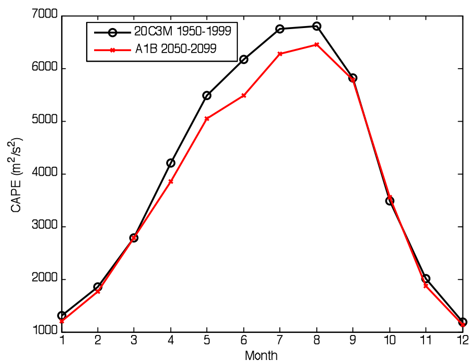


Figure 13 Convective Available Potential Energy Changes from HadCM3 A1B scenario 2050-2099

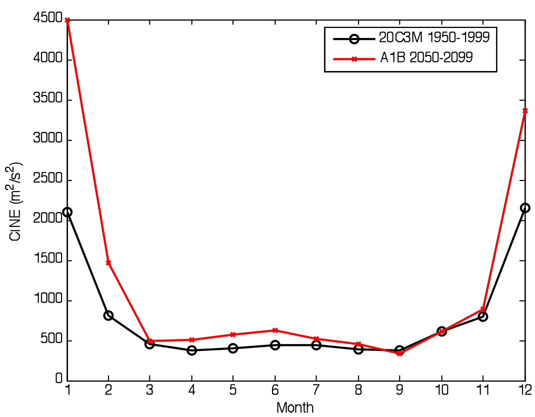


Figure 11 Convective Inhibition Energy Changes from HadCM3 A1B scenario 2050-2099

*3. PBL Height Dynamics*

The PBL feedback elements of this project will require objective means to estimate true PBL heights from radiosonde data. Many methods, such as temperature and humidity gradients are often used to determine Boundary layer height. However, the gradient methods is very sensitive to the local perturbation (Hennemuth and Lammert 2006). PBL heights from Southern Great Plains determined by gradient method were tested through a slab model, and considerable large root mean square errors of PBL heights indicate the gradient method may be not suitable for determining boundary layer height. A more stable and accurate method is therefore needed.

One alternative testing criterion is the comparison of boundary layer heights determined from profiles of different variables, such as potential temperature and specific humidity.

If the method is stable and accurate, it should have similar results for different profiles. Figure 12 shows the mixing layer heights that were determined from potential temperature and specific humidity profiles at CF-SGP. Since the specific humidity vertically varies more drastically than potential temperature does, mixing layer heights determined by these two kinds of profiles have some differences. Sometimes, it is difficult to judge which height is accurate just by radiosonde profiles.

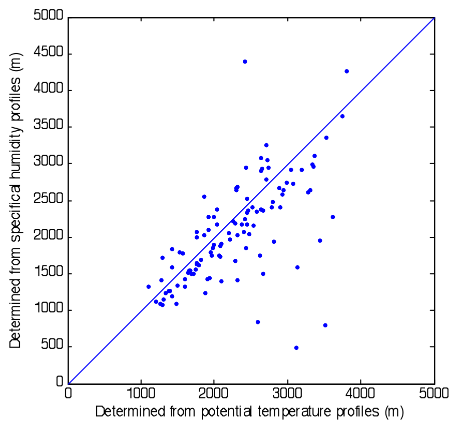


Figure 12 Comparison of mixing layer heights determined by different profiles

The traditional gradient method yielded greater scatter than our proposed multivariate approach, suggesting that the proposed method is more stable and would be more accurate.

The proposed method can determine the not only the mixing boundary layer but also top and bottom of entrainment zone. The entrainment zone may have something to do with the mixing layer depth, potential temperature and the change crossing the entrainment zone. So, it is important to recognize the EZ for the study of ABL.

Some of the profiles may have ambiguous boundary layers such as the one shown in **Error! Reference source not found.**. These ambiguous boundary layers may influence the study of entrainment zone depth, so they are expected to be exempted from the study samples. Under the proposed method framework, it is easy to recognize whether the determined layer is ambiguous. If the angle between the referential line and the line from minimal/maximal range to the tangent point is small, the boundary layer trends to be ambiguous. The angle, then, can be used as a criterion for selecting samples for studying boundary layer.

The slab model simplifies the entrainment zone as an instant jump and assumes the potential temperature is constant crossing the mixing layer. However potential temperature of early morning residual layer sometimes has a slope, and more turbulence kinetic energy is needed to fill the slope before reach the top of residual layer. This period can be simulated by thermodynamic method. After the residual layer is encroached, slab model can be used. This may improve the traditional slab model, but still keep the simplicity. It may also have analytical solution if the outer heat flux is simplified as certain functions. Further study and testing are needed to test the combination of the models.

The proposed method also provides measurements of residual layer and entrainment zone depths. These variables may help to determine mixing layer height empirically. (Santanello, Friedl et al. 2005; Santanello, Friedl et al. 2007) study some empirical relationships for mixing layer height. If residual layer height and entrainment zone were added into the relation function, more variance of mixing layer height may be explained. Similarity theory can be used to help find the relation between these variables.

## Publications and Presentations.

In this first year the project led to three invited presentations:

- AGU Fall Meeting 2009, San Francisco, Invited Talk: "Hydrology-Vegetation Interactions Under Climate and Population Pressures: Bridging Ecology, Turbulence, and Water Resources", John D. Albertson and Nicola Montaldo

- AGU Fall Meeting 2009, San Francisco, Invited Talk: "Vegetation Dynamics and Soil Water Balance Interactions in a Water-limited Mediterranean Ecosystem on Sardinia Under Climate Change Scenarios", Nicola Montaldo and John Albertson.

- NASA Energy and Water Cycle Workshop, Invited talk, December 2009: "Drought Persistence in the Southwestern US: A Preliminary Analysis", John D. Albertson.

We expect journal article submissions to begin in the second half of year 2.

## Direction in Year 2.

In this coming year we will be examining the land surface remote sensing data in concert with PBL dynamics to develop a clear view of 'observed' coupling and its role in drought persistence.

In particular we will focus on the effect of inversion strength and entrainment processes at the ABL top as conditioning the strength of persistence.

We will extend out feedback analysis to consider the role of vegetation cover status (including heterogeneity) on the feedback strength.

We will continue a close interaction with Dr. Joe Santanello and his LoCo efforts at NASA Goddard and begin to involve Dr. William Kustas of the USDA's Hydrology and Remote Sensing lab.

## Training Progress.

Duke Ph.D. Student Jun Yin is being trained on this grant. He has completed much of his course work in the first year, begun a collaborative relationship with Dr. Joe Santanello at NASA Goodard on this project, and played a primary role in performing the above analysis.

## References


D'Odorico, P. and A. Porporato (2004). "Preferential states in soil moisture and climate dynamics." Proceedings of the National Academy of Sciences of the United States of America **101**(24): 8848-8851.

Daly, E. and A. Porporato (2007). "Intertime jump statistics of state-dependent Poisson processes." Physical Review E (Statistical, Nonlinear, and Soft Matter Physics) **75**(1): 011119-011116.

Durre, I., J. M. Wallace, et al. (2000). "Dependence of extreme daily maximum temperatures on antecedent soil moisture in the contiguous United States during summer." Journal of Climate **13**(14): 2641-2651.

Entekhabi, D., I. Rodriguez-Iturbe, et al. (1992). "Variability in large-scale water balance with land surface-atmosphere interaction." Journal of Climate **5**(8): 798-813.

Findell, K. and E. Eltahir (1997). "An analysis of the soil moisture-rainfall feedback, based on direct observations from Illinois." Water resources research **33**(4): 725-735.

Hennemuth, B. and A. Lammert (2006). "Determination of the Atmospheric Boundary Layer Height from Radiosonde and Lidar Backscatter." Boundary-Layer Meteorology **120**(1): 181-200.Hollinger, S. and S. Isard (1994). "A soil moisture climatology of Illinois." Journal of Climate **7**(5): 822-833.

Hollinger, S. E. and S. A. Isard (1994). "A soil moisture climatology of Illinois." Journal of Climate **7**(5): 822-833.

Huang, J., H. M. van den Dool, et al. (1996). "Analysis of model-calculated soil moisture over the United States (1931–1993) and applications to long-range temperature forecasts." Journal of Climate **9**(6): 1350-1362.

Porporato, A. and P. D'Odorico (2004). "Phase Transitions Driven by State-Dependent Poisson Noise." Physical review letters **92**(11): 110601-110601.

Santanello, J. A., M. A. Friedl, et al. (2007). "Convective Planetary Boundary Layer Interactions with the Land Surface at Diurnal Time Scales: Diagnostics and Feedbacks." Journal of Hydrometeorology **8**(5): 1082-1097.

Santanello, J. A., M. A. Friedl, et al. (2005). "An Empirical Investigation of Convective Planetary Boundary Layer Evolution and Its Relationship with the Land Surface." Journal of Applied Meteorology **44**(6): 917-932.

Stull, R. (1988). An introduction to boundary layer meteorology, Springer.