GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L11401, doi:10.1029/2004GL019930, 2004

Soil moisture as an indicator of weather extremes

Venkat Lakshmi,[1] Thomas Piechota,[2] Ujjwal Narayan,[1] and Chunling Tang[2]

Received 9 March 2004; accepted 22 April 2004; published 4 June 2004.

[1] In this paper, we investigate floods and droughts in the Upper Mississippi basin over a 50-year period (1950–1999) using a hydrological model (Variable Infiltration Capacity Model – 3 Layer). Simulations have been carried out between January 1950 and December 1999 at daily time-step and 1/8° spatial resolution for the water budget and at hourly time-step and 1° spatial resolution for the energy balance. This paper will provide valuable insights to the slow response components of the hydrological cycle and its diagnostic/predictive value in the case of floods and droughts. The paper compares the use of the Palmer Drought Severity Index against the anomalies of the third layer soil moisture for characterizing droughts and floods. Wavelet and coherency analysis is performed on the soil moisture, river discharge, precipitation and PDSI time series confirm our hypothesis of a strong relationship between droughts and the third layer soil moisture. *INDEX TERMS:* 1818 Hydrology: Evapotranspiration; 1833 Hydrology: Hydroclimatology; 1836 Hydrology: Hydrologic budget (1655); 1866 Hydrology: Soil moisture; 1878 Hydrology: Water/energy interactions. **Citation:** Lakshmi, V., T. Piechota, U. Narayan, and C. Tang (2004), Soil moisture as an indicator of weather extremes, *Geophys. Res. Lett.*, *31*, L11401, doi:10.1029/2004GL019930.

1. Introduction

[2] Extremes in weather affect the land surface hydrological cycle, namely, droughts and floods and cause large amounts of devastation each year globally. Understanding the extremes in the hydrological cycle has multiple incentives. Firstly, we can underline the mechanisms that contribute to these processes, viz., extreme flooding is caused by already saturated soils and critical droughts occur after prolonged periods of lack of rainfall coupled with warm summer temperatures that enhance evapotranspiration. Secondly, hydrological models used for simulation of the land surface conditions have to be validated against observed data in order to gain confidence for usage during periods and locations of no observations. Process validation whereby, the integrity of the entire model in reproducing the entire hydrological system in a consistent fashion is examined in the case of extreme events.

[3] We evaluate the hydrological model characterization of extreme events—droughts and flood. We do not carry out any model improvements or model development in this study but instead we focus on comparison of the soil moisture for the two extreme cases of a drought and a flood year. Using wavelet analysis, we compare the deep soil moisture to the Palmer Drought Severity Index (PDSI), precipitation, and streamflow to determine whether deep soil moisture is an indicator of climate extremes.

2. Model, Data and Simulations

[4] The land surface hydrological model used in the study is Variable Infiltration Capacity - 3 Layer (VIC-3L) model [*Liang et al.*, 1994], a macro-scale three layer (0–10 cm, 10–40 cm and 40–140 cm) hydrological model that carries out complete water and energy balance on a grid cell basis. The model has been successfully validated and implemented on a variety of climatic conditions and basins worldwide, as well as the Upper Mississippi River Basin [*Cherkauer et al.*, 1999] and the Mississippi River Basin [*Maurer et al.*, 2001a, 2001b, 2002].

[5] The three-layer VIC model simulations were carried out for the Mississippi River Basin for the water and the energy balance were carried out over a period of 50 years (1950–1999).

3. Results and Analysis

3.1. Streamflow Comparison Over a Period of 50-years (1950–1999)

[6] Comparisons between USGS measured discharge and model simulated stream-flow for the period 1950–1999, shows a reasonable R^2 of 0.74 and a bias of 1,145,385 m^3/s. The percentage difference of the mean flow for the bias (bias/mean flow) translates to around 15%. Similar comparisons at Valley city, IL gave a lower (compared to the basin outlet at Grafton, IL) R^2 value of 0.61 and a bias of 95,436 m^3/s. These results and those for the soil moisture comparisons for the three soil layers for the Illinois soil surveys are similar to those of *Maurer et al.* [2001a, 2001b, 2002].

3.2. Soil Moisture Characteristics

[7] All three layers depict distinctly lower soil moisture during the summer of 1988 and higher soil moisture during summer of 1993 in the basin (Figures 1a, 1b, and 1c respectively). As other studies [*Namais*, 1988, 1989] indicated, the late winter and spring soil moisture during 1988 are significantly lower, which could have possibly enhanced warmer dryer conditions during summer/early fall of 1988. The average soil moisture (over a 50-year period) for the basin tends to lie between these two extremes. The more sensitive top layer displays greater frequency of variation but of lower amplitudes (due to its lower capacity) when compared with the lower two soil layers. In the case of layer 2, the difference in soil moisture during summer between the drought and flood events is around 30 mm

[1]Department of Geological Sciences, University of South Carolina, Columbia, South Carolina, USA.
[2]Department of Civil and Environmental Engineering, University of Nevada Las Vegas, Las Vegas, Nevada, USA.

0094-8276/04/2004GL019930$05.00

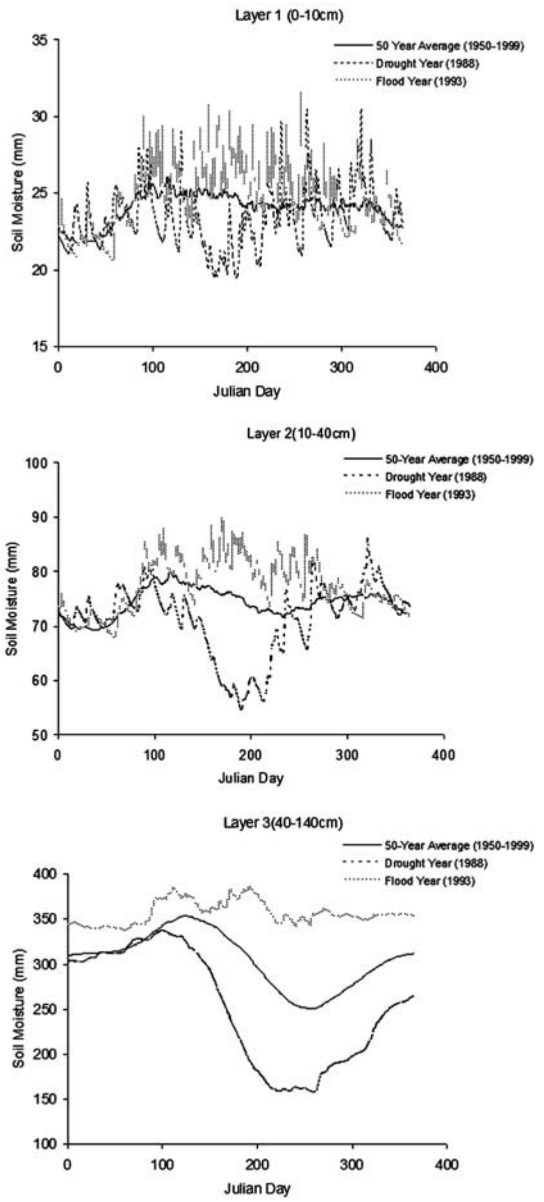

Figure 1. (a) Upper Mississippi River Averaged Soil Moisture layer 1 (0–10 cm); (b) Upper Mississippi River Averaged Soil Moisture layer 2 (10–40 cm); (c) Upper Mississippi River Averaged Soil Moisture layer 3 (40–140 cm).

with the 50-year mean being around 70 mm (Figure 1b). Whereas in layer 3, the difference for the same period is as high as 200 mm with an 50-year average soil moisture being about 250 mm (Figure 1c). VIC-3L simulated show that during the 1988 drought the average soil water content in the top 140 cm thick soil column was as low as 250 mm, as compared with a 50-year mean of about 350–370 mm during the same period. Also, during the Mississippi River floods of summer 1993, the moisture increased to around 500 mm in the 140 cm layer. This accounts for a 250 mm or more of difference in the soil water content in the 140 cm thick soil layer, between the flood and the drought year.

[8] The monthly average 3-layer aggregated soil moisture for the years 1988 and 1993 along with the 50-year average is summarized in Table 1. The annual average soil moisture of the basin during the drought year 1988 is about 346 mm as compared to 458 mm during the flood year 1993 and the 50-year average was about 403 mm. The deficit of soil moisture in the drought year of 1988 drops from its peak value (−126 mm in July) to 50% of the peak value (−62 mm) in about 4.5 months whereas the same half-peak drop in the flood year occurs in 2 months (+106 mm September to +54 mm in November). This illustrates an asymmetry in the response of the land surface state to floods and droughts.

3.3. Soil Moisture Persistence and Relation to PDSI

[9] Previous studies [*Huang et al.*, 1996; *Maurer et al.*, 2001a, 2001b, 2002] have studied various aspects of soil moisture persistence. Specifically, *Huang et al.* [1996] found that precipitation anomalies influence soil moisture anomalies and that the soil moisture anomalies have greater persistence during periods of low precipitation. *Maurer et al.* [2001a, 2002] found that the VIC modeled soil moisture auto-correlation compares well with Illinois soil moisture observations but have a higher persistence than the NCEP reanalysis data [*Maurer et al.*, 2001b] for the entire Mississippi and the Upper Mississippi River Basins.

[10] It is observed for the drought of 1988, the third layer soil moisture anomaly reacted faster to the precipitation than PDSI. In fact for most of the 50-year monthly values, the PDSI and the third layer soil moisture anomaly track each other quite well. Figure 2a depicts the autocorrelation for precipitation and third layer soil moisture anomalies and for PDSI (not anomaly) for the Upper Mississippi river basin 1950–1999. The plot shows that the PDSI has a large persistence even for a longer time period, i.e., the autocorrelation does not drop below 0.6 for up to six months lag time. On the other hand the autocorrelation of third layer soil moisture anomalies drops below 0.6 in 3.5 month lag time. This shows that the PDSI erroneously over-predicts the memory of the land surface. In addition, both PDSI and the third layer soil moisture anomalies show greater autocorrelation over longer lag times than the precipitation. In fact, this highlights an important result—the land surface (soil moisture) exhibits greater memory than the atmosphere (precipitation). However, examination of the drought period only, (May 1988–April 1989) shows that the third layer soil

Table 1. Upper Mississippi River Basin Averaged Monthly Soil Moisture (0–140 cm)

	Aggregated Basin Averaged Soil Moisture in mm				
	1950–1999	1988	1988–(1950–1999)	1993	1993–(1950–1999)
Jan	404	398	−6	436	32
Feb	408	406	−2	433	25
Mar	428	426	−2	444	16
Apr	452	433	−19	484	32
May	450	405	−45	472	22
Jun	427	332	−95	479	52
Jul	391	265	−126	485	94
Aug	357	252	−105	455	98
Sep	353	263	−90	459	106
Oct	373	289	−84	454	81
Nov	396	325	−71	450	54
Dec	406	355	−51	453	47
Average	404	346	−58	458.80	55

The table illustrates the below normal (1950–1999) for the drought year (1988) and the above normal for the flood year (1993).

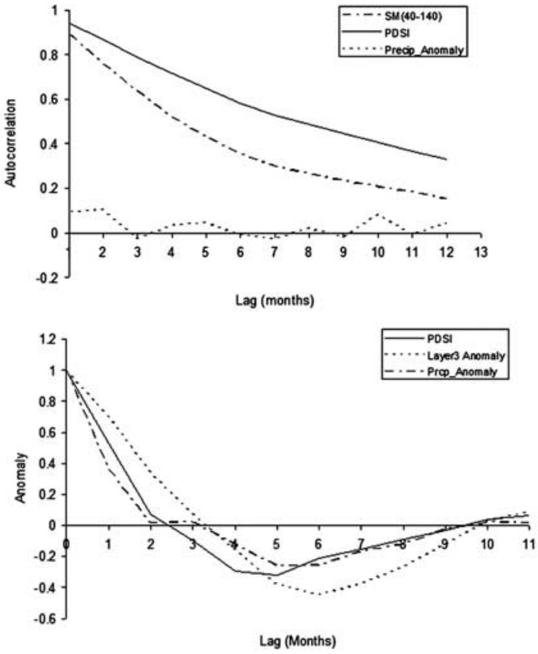

Figure 2. (a) Autocorrelation of the layer 3 soil moisture anomalies, PDSI and precipitation anomalies over the Upper Mississippi River Basin for 1950–1999. (b) Autocorrelation of the layer 3 soil moisture anomalies, PDSI and precipitation anomalies over the Upper Mississippi River Basin for May 1988–April 1989 (drought period).

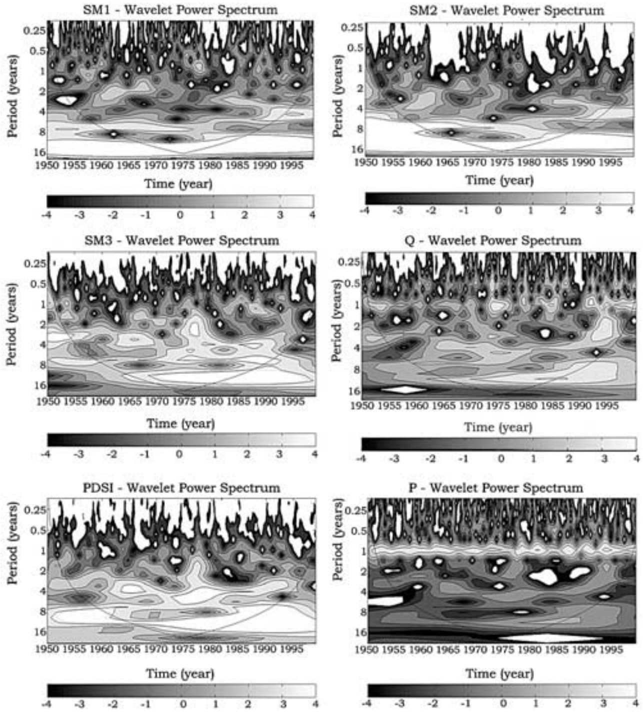

Figure 3. Wavelet power spectrum of all six hydroclimatic time series. The scale of the power spectrum is a $\log_2$ representation of the power spectrum value. Lighter values indicate regions of higher power spectrum.

moisture anomalies show greater autocorrelation than the PDSI (Figure 2b). This is a significant result when considering the fact that soil moisture is a better predictor for future monthly temperature and that soil moisture anomalies are better predictors during periods of low precipitation [*Huang et al.*, 1996].

3.4. Wavelet Analysis and Coherency Between Variables

[11] Wavelet analysis is a useful tool for evaluating the power spectrum in hydroclimatic time series and how the dominant frequencies vary over time. [*Torrence and Webster*, 1999]. Wavelet analysis decomposes a time series into time/frequency space simultaneously by using a wave-like function known as wavelets. The Morlet wavelet is used in the analysis presented here. Wavelet analysis transforms the signal into the amplitude of any period and presents how the amplitude varies with time. A comparison of wavelet analysis on two time series is made by calculating the wavelet coherence. Wavelet coherence values range between 0 and 1, and provide a quantitative representation of the co-variance between two time series as a function of frequency. A complete description of wavelet analysis can be found in several noteworthy studies [e.g., *Torrence and Webster*, 1998, 1999; *Landau and Binder*, 2000; *Addison*, 2002].

[12] In the study presented here, wavelet analysis was first performed on the six time series: soil moisture, layer 1 (SM1); soil moisture, layer 2 (SM2); soil moisture, layer 3 (SM3); Mississippi River streamflow at Grafton (Q); precipitation for the entire basin (P); and PDSI for the entire basin. Figure 3 shows the wavelet power spectrum of the six data sets. A dominant feature that is expected in precipitation for the basin is the high power spectrum for the period of one year. This represents the annual cycle in precipitation. On a longer time scale, all the soil moisture layers (SM1, SM2, and SM3), PDSI and Q all have a frequency of 8–16 years. Over the entire range of frequencies and time period, the most similar wavelet power spectrums are for SM3 and PDSI. This is expected since the PDSI is partially computed based on soil moisture values.

[13] Further investigation to better quantify the similarities of Figures 3a–3e is performed by computing the coherence between all of these data sets. Table 2 summarizes the coherency between the data sets. Similar to the observation made in Figure 3, the Q and P time series have a high coherence value that is significant at the 95% level. The SM1 and SM2 are significant at the 99% level and this probably represents the high amount of interflow between these two soil moisture layers. PDSI and SM3 are coherent at the 95% level. This suggests that SM3 could be used as an indicator of extreme climate conditions (e.g., droughts and floods). Lastly, the Q and SM3 have a moderate

Table 2. Average Coherence Values for All Combinations of Hydroclimatic Variables

	P	SM1	SM3	SM3	PDSI
SM1	0.66				
SM2	0.67	0.93***			
SM3	0.81	0.68	0.7		
PDSI	0.86	0.68	0.7	0.85**	
Q	0.85**	0.66	0.67	0.81	0.81

The coherence value show represents the average of all coherence values for each frequency and time period (*90% significant, **95% significant, ***99% significant).

coherency that further highlights the usefulness of SM3 as an indicator of hydroclimatic conditions.

4. Conclusions and Discussion

[14] The temporal dynamics of deep layer soil moisture is also investigated and wavelet analysis and coherency studies show that the third layer soil moisture is the best indicator of droughts and floods. Our results show remarkable consistency with those of *Oglesby et al.* [2002] who summarize that subsurface dry anomalies play a significant role in the perpetuation of a drought. In fact we see that the PDSI as an index for prediction of drought could be supplemented with the soil moisture anomalies of the deep layer.

[15] The salient features of the present study that distinguishes itself from prior work stems from a combination of (1) simultaneous validation of three hydrological variables, viz., point based soil moisture and a spatial integrator—streamflow and (2) provides a reliable strategy to characterize meteorological droughts and floods in a hydrologically quantifiable manner. The limitation in obtaining the lower layer soil moisture by measurements or observations suggests the use of such detailed distributed land-surface schemes as possible sources of data. This is demonstrated by autocorrelation and anomaly analysis as well as wavelet and coherency analysis of the pertinent land surface hydrological variables.

[16] **Acknowledgments.** The authors gratefully acknowledge the support of NASA Land Surface Hydrology Program, NAG5-8875 and the Program Manager Dr Jared Entin. The authors would like to thank Drs. Keith Cherkauer, Bart Nijssen, and Ed Maurer, and the hydrological modeling group at University of Washington, Seattle, WA for providing the VIC-3L model and datasets.

References

Addison, P. S. (2002), The Illustrated Wavelet Transform Handbook, Napier Univ., Edinburgh, UK.

Cherkauer, K. A., and D. P. Lettenmaier (1999), Hydrological Effects of Frozen Soils in the Upper Mississippi River basin, *J. Geophys. Res.*, *104*(D16), 19,599–19,610.

Huang, J., van den Dool, and Georgakakos (1996), Analysis of Model-Calculated Soil Moisture over the United States (1931–1993) and Applications in long-range Temperature Forecasts, *J. Clim.*, *9*, 1350–1362.

Landau, D. P., and K. Binder (2000), Guide to Monte Carlo Simulations in Statistical Physics, Cambridge Univ. Press, 398 pp.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges (1994), A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for GSMs, *J. Geophys. Res.*, *99*(D7), 14,415–14,428.

Maurer, E. P., G. M. O'Donnell, D. P. Lettenmaier, and J. O. Roads (2001a), Evaluation of NCEP/NCAR Reanalysis Water and Energy Budgets using Macroscale Hydrologic Model Simulations, Water Science and Application Volume 3, pp. 137–158, AGU series in Water Science and Applications, edited by V. Lakshmi, J. Albertson, and J. Schaake, pp. 137–158.

Maurer, E. P., G. M. O'Donnell, D. P. Lettenmaier, and J. O. Roads (2001b), Evaluation of the Land Surface Water Budget in NCEP/NCAR and NCEP/DOE Reanalyses using an Off-line Hydrologic Model, *J. Geophys. Res.*, *106*(D16), 17,841–17,862.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen (2002), A long-term hydrologically-based data set of land surface fluxes and states for the continental United States, *J. Clim.*, Vol. *15*, 3237–3251.

Namais, J. (1988), The 1988 summer drought over Great Plains: A classic example of air-sea-land interaction, *Eos, Transactions of AGU*, *69*, 1067.

Namais, J. (1988), Cold Waters and Hot Summers, *Nature*, *338*, 15–16.

Oglesby, R. J., S. Marshall, D. Erickson, J. Roads, and F. Robertson (2002), Thresholds in atmosphere – soil moisure interactions: Results from climate model studies, *J. Geophys. Res.*, *107*(D14), 4224, doi:10.1029/2001JD001045.

Torrence, C., and P. J. Webster (1998), The annual cycle of persistence in the El Niño Southern Oscillation, *Q. J. Roy. Meteor. Soc.*, *124*(550), 1985–2004, Part B, Jul.

Torrence, C., and P. J. Webster (1999), Interdecadal changes in the ENSO-monsoon system, *J. Clim.*, *12*(8), 2679–2690, Part 2, Aug.

V. Lakshmi and U. Narayan, Department of Geological Sciences, University of South Carolina, Columbia, SC 29208, USA. (venkat-lakshmi@sc.edu)

T. Piechota and C. Tang, Department of Civil and Environmental Engineering, University of Nevada Las Vegas, Las Vegas, NV 89154-4015, USA.