Hydroclimatic Anomaly Propagation with Increasing Depth of the Soil Profile in Illinois – Implication for Land Memory Processes

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Abstract

In this study we investigate the patterns of hydroclimatic anomalies (drought and flood) at the regional scale of Illinois, based on a comprehensive data set covering 25-year (1981-2005) monthly precipitation, soil moisture, groundwater depth, and streamflow. The focus is on the vertical (downward) propagation of hydroclimatic anomalies with increasing soil depths as well as the associated anomaly amplification or dissipation, at the monthly, seasonal, and inter-annual timescales. The characteristics of persistence and downward propagation of droughts and floods through the soil profile and unconfined aquifer are analyzed by using analytical crossing theory.

Introduction

In this study, we investigate the patters of hydrological droughts and floods in Illinois as they propagate from the atmosphere into the soil and down to the groundwater aquifer. The average climatology as well as the corresponding anomalies in several hydrological variables will be investigated. These variables include the flux of atmospheric water vapor, precipitation, soil moisture, groundwater level, and river flow. Specifically, we focus on the statistical properties of anomalies as they propagate through the soil profile and groundwater. The analytical crossing theory is used as an analytical tool for analysis.

The scientific questions attempted to answer in this study include:

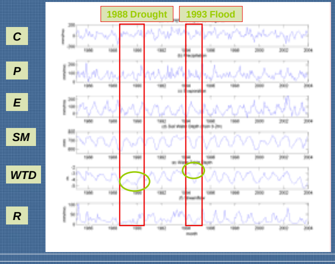
- How meteorological anomalies propagate through the hydrologic cycle and form hydrologic anomalies?
- How similar (different) do soil moisture and groundwater experience a dry (wet) anomaly?
- How soil moisture and groundwater dissipate, perpetuate, or amplify anomalies? How similar are their recovery or amplification mechanisms?
- What are the important time scales associated with the propagation or delay of anomalies?
- How different are groundwater recharge and discharge anomalies under flood and drought conditions? How do they affect groundwater depth itself, streamflow, and evapotranspiration?

Data

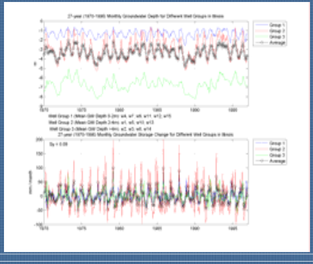
The Illinois data set (Eltahir and Yeh, 1999) used in this study describes the following variables: atmospheric vapor convergence, precipitation, soil moisture (SM), water table depth (WTD), and river flow (R). The data on SM was collected by the Illinois State Water Survey (ISWS). Weekly (March ~ October) and biweekly (November ~ February) measurements were taken at 11 different soil layers with a resolution of about 20 centimeters down to 2 meters below the surface. The WTD data consists of monthly groundwater level at 18 wells scattered throughout Illinois for monitoring unconfined aquifers. These aquifers are relatively shallow and the average depth to the water table ranges between 1 to 10 meters below the surface. We investigate the propagation of hydroclimatic anomalies (flood and drought) for each of the 11-layer soil moistures, as well as for each of the three groups of groundwater wells: shallow (0-2m), intermediate (2-4m), and deep (>4m) groundwater, which were divided from the total 18 wells in Illinois based on their climatological mean WTD.

Sampling Network in Illinois

1984-2004 Monthly Time Series of Water Balance Components in Illinois



Divide Wells into Three Groups Based on Ave. Water Table Depth



Magnitude and Duration of Hydroclimatic Anomalies with Increasing Depth of the Soil Profile

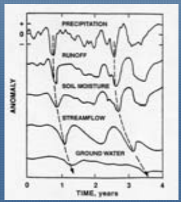
We consider standardized anomalies of the observed variables from their corresponding monthly averages. For each variable, the differences between any observed variable and the corresponding monthly average and for that month of the year were first computed, and then normalized by the corresponding monthly standard deviations.

The autocorrelation function and spectrum of each water balance components in Illinois have been analyzed. The correlation timescales increase from less than 1 month for precipitation and atmospheric vapor convergence, to ~ 3, 4, and 6 months for river flow, soil moisture, and water table depth, respectively. As the soil moisture anomalies propagate downward with the increasing depth, the correlation timescales increase from ~2 months for the surface soil moisture (0-30cm) to ~10 months for the deep groundwater (average WTD > 4m).

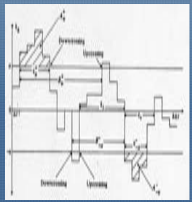
Results and Conclusion

- Relative to atmospheric forcing, soil moisture and groundwater in Illinois is characterized by long duration and great magnitude of negative (drought) anomaly, while runoff anomaly is characterized by large positive anomaly with short duration, and small negative anomaly but long duration.
- Soil moisture anomaly from the surface down to 2m has correlation timescale increasing from 2 to 4 months. Shallow (0-2m), intermediate (2-4m), deep (>4m) groundwater anomalies have correlation timescales of 3, 5, 10 months, respectively.
- Unconfined aquifer amplifies the drought climatic anomalies and dissipates the flood anomalies (but causing flood in streamflow), which results in the observed asymmetric response of the aquifers to the droughts and floods.
- Soil moisture, groundwater, and streamflow are well correlated with each other (but not with precipitation). However, they show different response to droughts and floods. Their complicated three-way interactions and feedbacks dictate the propagation of hydroclimatic anomaly within the soil profile in Illinois.

Propagation of Anomaly (Changnon [1987])

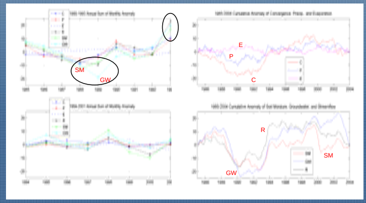


Crossing Theory (Bras & Rodriquez-Iturbe, 1985)

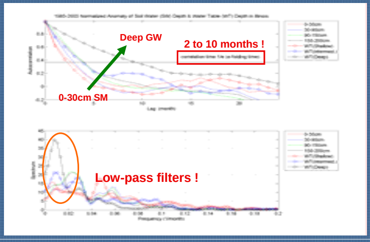


1985-2003 Annual and Cumulative Anomalies

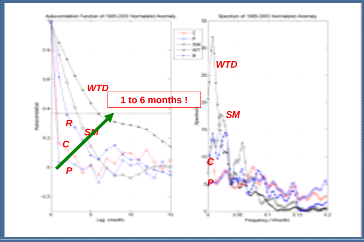
Amplification / Dissipation — Persistence



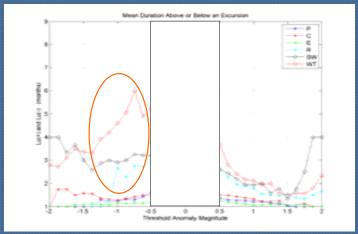
Autocorrelation & Spectrum of Soil Saturation and Water Table Depth



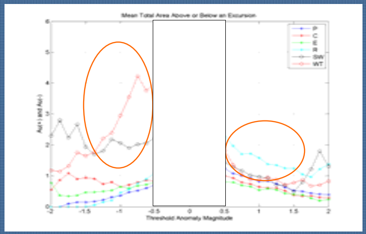
Autocorrelation and Spectrum of Hydroclimatic Anomalies



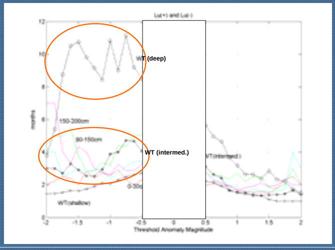
Mean Duration Above or Below a Threshold Anomaly Magnitude



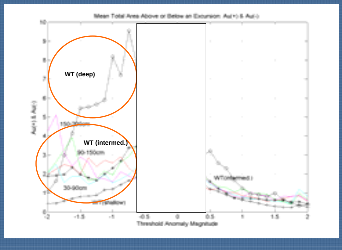
Mean Magnitude (Area) Above or Below a Threshold Anomaly Magnitude



Mean Duration Above or Below a Threshold Anomaly Magnitude



Mean Magnitude (Area) Above or Below a Threshold Anomaly Magnitude



References:

- Bras, R. L., and I. Rodriquez-Iturbe, Random Functions and Hydrology, Addison-Wesley, Reading, Mass., 1985.
- Changnon, S. A. Jr., Detecting drought conditions in Illinois, ISWS/CIR-169-87, 36 pp., Illinois State Water Survey, Champaign, IL., 1987.
- Eltahir, E. , and P. Yeh, On the asymmetric response of groundwater level to floods and droughts in Illinois, Water Resour. Res. 35(4), 1199-1217, 1999.