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Research papers

Stratified drought analysis using a stochastic ensemble of simulated and in-situ soil moisture observations

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ABSTRACT

This study proposes a multi-wavelet Bayesian ensemble of two Land Surface Models (LSMs) using in-situ observations for accurate estimation of soil moisture for Contiguous United States (CONUS). In the absence of a continuous, accurate *in-situ* soil moisture dataset at high spatial resolution, an ensemble of Noah and Mosaic LSMs is derived by performing a Bayesian Model Averaging (BMA) of several wavelet-based multi-resolution regression models (WR) of the simulated soil moisture from the LSMs and *in-situ* volumetric soil moisture dataset obtained from the U.S. Climate Reference Network (USCRN) field stations. This provides a proxy to the *in-situ* soil moisture dataset at 1/8th degree spatial resolution called Hybrid Soil Moisture (HSM) for three soil layers (1–10 cm, 10–40 cm and 40–100 cm) for the CONUS. The derived HSM is used further to study the layer-wise response of soil moisture to drought, highlighting the necessity of the ensemble approach and soil profile perspective for drought analysis. A correlation analysis between HSM, the long-term (PDSI, PHDI, SPI-9, SPI-12 and SPI-24) and the short-term (Palmer Z index, SPI-1 and SPI-6) drought indices is carried out for the nine climate regions of the U.S. indicating a higher sensitivity of soil moisture to drought conditions for the Southern U.S. Furthermore, a layer-wise soil moisture percentile approach is proposed and applied for drought reconstruction in CONUS with a focus on the Southern U.S. for the year 2011.

1. Introduction

Drought and its impacts are not only incremental and a factor in long-term and cumulative environmental changes, but also comes into existence as a slow-onset or creeping event (Pulwarty and Sivakumar, 2014). Because it is difficult to establish a generally acceptable definition of drought for use in various water sectors, four types of droughts are defined as meteorological, agricultural, hydrological, and socioeconomic drought (Mozny et al., 2012; Wilhite and Glantz, 1985). Due to the slow onset and recovery, determining the beginning and end of a particular drought period is often difficult (Iglesias et al., 2009). In the wake of climate change, the likelihood of occurrence of extreme drought events with greater severity in the future in many regions of the globe is expected to rise significantly (Dai, 2011; Kundzewicz et al., 2010; Peterson et al., 2012; Trenberth and Fasullo, 2012). The areal extent of droughts increased more than 50% during the last century over the globe, while changes in the areal extent of wet regions were relatively small (Trenberth et al., 2004). Hence, great emphasis has been laid out worldwide on the drought strategies, with a specific focus on comprehensive drought monitoring (Hayes et al., 2011).

Many studies have established the usefulness of soil moisture anomalies for characterizing drought onset and demise (Hunt et al., 2009). Soil moisture modulates the atmospheric surface energy balance and hence has a significant impact on the vertical distribution of turbulent heat fluxes, as well as the boundary layer structure (Alapaty et al., 1997). Soil moisture is a pivotal element in the hydrological process of converting precipitation into runoff and groundwater storage. Mozny et al. (2012) used *in-situ* soil moisture dataset for drought monitoring in the Czech Republic using a Soil Moisture Index (SMI) and found soil moisture based drought index to be useful in rapid-onset drought monitoring. Ford et al. (2015) used *in-situ* soil moisture observations for developing a flash drought early warning framework for Oklahoma. Sims and Raman (2002) established strong inter-relationship of two drought indices: Palmer Drought Severity Index (PDSI) values and Standardized Precipitation Index (SPI) with soil moisture for North Carolina. Lakshmi et al. (2004) showed that the deep layer soil moisture anomaly is a good drought indicator and has a higher memory than Palmer Drought Severity Index (PDSI).

To understand the interrelationship between soil moisture and drought at a large spatial scale, long-term data of soil moisture is

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required. However, in most regions of the world, the lack of spatially extensive soil moisture monitoring networks precludes the inclusion of soil moisture in drought monitoring systems (Ford et al., 2015). While some hydrological variables like precipitation, streamflow are more frequently recorded and reported, similar long-term soil moisture observations are scarce. There has been an extensive application of near-surface soil moisture information obtained through remote sensing in agriculture and meteorology. However, in most applications the magnitudes of modeled, in situ, and remotely sensed soil moisture often do not correlate well without any posterior bias correction (Narayan and Lakshmi, 2008; Sridhar et al., 2013). Also, near surface soil moisture in not sufficient to comprehensively assess drought severity. Hence, the use of simulated soil moisture from land surface models (LSMs) has become popular and has been applied to several studies to understand the dynamics and impact of drought. With the advancements in computational power, it is now feasible to generate operational land surface hydrological data products over large scales using telemetry, remote sensing based dataset and modeled meteorological data from atmospheric forecast models (Mitchell et al., 2004b). Though, the lack of high-resolution data to perform any physically based distributed hydrological modeling remains a limitation to researchers (Sridhar and Hubbard, 2009).

Previously, Sridhar et al. (2008) used simulated soil moisture using a hydrologic model developed by Robinson and Hubbard (1990) across different land-use conditions in Nebraska, US, to develop a Soil Moisture Index (SMI) for quantifying agricultural drought. The results were compared with the SMI derived from *in-situ* soil moisture. It was concluded that developing SMI using a simulation model-based approach should be considered pragmatic considering the difficulty in establishing a soil moisture observation-based drought index over large areas on a continuous long term. Sheffield et al. (2004a) used the Variable Infiltration Capacity (VIC) model to derive a model-based drought index and evaluated its agreement with the PDSI. Zhang et al. (2016) applied Australian Community Atmosphere Biosphere Land Exchange model (CABLE) LSMs to predict near-real-time drought in China. Yuan et al. (2013) used the VIC model for obtaining simulated soil moisture for probabilistic seasonal forecasting of droughts in Africa. Xia et al. (2014) used the North American Land Data Assimilation System (NLDAS) (Mitchell et al., 2004a) dataset to derive *Objective Blended NLDAS Drought Index* (OBNDI) for Conterminous United States (CONUS). Wang et al. (2009) developed a multimodal ensemble of several LSMs for reconstruction of drought over the U.S. AghaKouchak (2014) used precipitation and soil moisture dataset from NASA Modern-Era Retrospective analysis for Research and Applications (MERRA) for probabilistic drought forecasting using a standardized soil moisture index. Sheffield et al. (2014) used the VIC model to derive soil moisture for developing a drought monitoring and forecasting framework in Sub-Sahara region of Africa. Tang and Piechota (2009) used soil moisture obtained from the VIC model for spatial-temporal evaluation of drought variability in the Upper Colorado River Basin. Mo (2008) used Noah and VIC models from NLDAS in order to estimate soil moisture percentiles and runoff indices for drought analysis over U.S. AghaKouchak (2015) proposed a multivariate approach integrating soil moisture percentiles and precipitation for a persistence based drought prediction for East Africa. Soil moisture anomalies from NLDAS were used in assessing the evolution of soil moisture and vegetation conditions in extreme flash drought in Otkin et al. (2016). Wang et al. (2011) used an ensemble of four physically-based hydrology models to obtain soil moisture percentiles which were used to estimate the severity of agricultural drought. Sohrabi et al. (2015) developed a Soil Moisture Drought Index (SODI) to characterize droughts.

It is therefore evident the scientific community is interested in exploring the application of soil moisture in drought analysis. This study points the importance of differential response of soil profile soil moisture to drought. This insight augments the current understanding of soil moisture to drought correlation. This adds to the existing literature by proposing a layer-wise soil moisture percentile based drought reconstruction approach by using shallow soil layers for short-term, low-intensity drought reconstruction and deeper soil layers for capturing long-term and severe droughts, respectively. The study of the inter-relationship between droughts and soil moisture at a large spatial scale is restricted to the use of several hydrological models which are themselves known to possess a high degree of uncertainties and biases (Mo et al., 2012). Although LSM-derived soil moisture shows encouraging consistency in the depiction of large-scale drought events, the development of a drought index based on soil moisture at a smaller scale appears to differ considerably across models (Xia et al., 2014). This is partly due to discrepancies in simulated soil moisture as well as sub-grid scale variability. Some recent studies have attempted to provide a stochastic approach to estimate *in-situ* soil moisture using hydrological models (Kim et al., 2015) but do not address the non-stationarity and multi-scale nature of the underlying process. This study utilizes an ensemble of Noah and Mosaic Land Surface Models (LSMs), obtained using a wavelet-based regression coupled with a Bayesian Model Averaging (BMA) approach (termed as WBR in this study) to simulate and evaluate soil moisture and its correlation with drought indices. The proposed wavelet-based multi-resolution modeling addresses to the non-stationarity and multiscale variability of soil moisture dataset by modeling the inputs in their sub-time series domain at multiple time-frequency resolutions. BMA is used to counter the subjectivity in the choice of mother wavelet function for time series decomposition into its sub-time series and uncertainty related to the ability of the selected wavelet to satisfactorily represent the process dynamics at the chosen level of time-frequency resolution.

The objectives of this study are as follows:

(a) To develop an adjusted, high-resolution soil moisture dataset for carrying out drought sensitivity and reconstruction analysis for Contiguous United State (CONUS) using the proposed multi-resolution regression of Noah and Mosaic LSMs against *in-situ* soil moisture dataset obtained from U.S. Climate reference network (USCRN) stations.
(b) To perform a layer-wise correlation analysis to understand the response of soil moisture to drought indices (DIs) representing short term (Palmer Z index, SPI-1 and SPI-6) and long term (PDSI, PHDI, SPI-9, SPI-12 and SPI-24) predictability of drought.
(c) To highlight the difference in the spatial and inter-layer patterns in the persistence of the soil moisture pertaining to different soil layers, thus establishing a need for multi-layer perspective in drought analysis and reconstruction using soil moisture.
(d) To propose a new layer-wise drought reconstruction approach and apply to recent drought occurrences, for capturing drought in the Southern US (from April 2011 to December 2011) as a case study.

Section 2 of the paper provides a short description of the dataset used in this study. An overview of the Wavelet analysis and Bayesian Model Averaging is provided in Section 3. Development of the WBR models is explained in Section 4. Results are provided in Section 5 whereas Section 6 provides a detailed discussion on the observed results. The paper is concluded in Section 7.