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Analyzing the sensitivity of drought recovery forecasts to land surface initial conditions

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SUMMARY

Droughts are complex hydro-meteorological phenomena, which are challenging to both quantify and predict. From the perspective of drought quantification, knowledge of the land surface conditions is vital for determining the impacts a drought event is having on both the environment and society. Although such land surface information is essential for quantifying drought in real-time, the precise effect of land surface moisture deficits on future drought conditions is unknown. Forecasting of recovery from drought events is undoubtedly reliant on its intensity, yet the lead time at which a drought can be expected to recover is poorly understood. Due to this gap in knowledge, this study attempts to quantify the expected lead time for drought recovery, and the rate of drought recovery, by examining the loss of sensitivity to initial conditions within a climatological forecast. From this perspective, the expected recovery time from a specific drought event is quantified, based on a case study in the Upper Colorado River Basin in Southwestern USA for two initialization dates in years 2003 through 2008. This study has ramifications for understanding the time of drought recovery, and highlights the importance of accurate land surface state estimation. With respect to recent studies, the experiments presented here suggest that forecasts can be sensitive to initial conditions at greater lead-times, and therefore drought conditions are potentially more persistent than previously thought.

1. Introduction

Forecasting of land surface states at seasonal to annual lead times is essential for drought management, providing a basis for applying mitigation measures (Pozzi et al., 2013). Through effective application of such mitigation measures, the impacts of drought may be reduced, making drought forecasts critical for reducing economic losses (Huang and Chou, 2008; Maity et al., 2013). Although these forecasts are vital to minimizing the cost of drought events, forecasts at seasonal to annual lead times are plagued with low accuracy. As a result of the spatiotemporal complexities of hydro-meteorological states, both observation and simulation of drought relevant variables are challenging (Andreadis and Lettenmaier, 2006a; Hao and AghaKouchak, 2013; Mo et al., 2012). Such a challenge has left scientist with an incomplete understanding of land-atmospheric processes, leading to persistent uncertainties. Due to the perpetuity of uncertainties, it has become widely accepted that forecasts must be framed from a probabilistic perspective (Brown et al., 2010; DeChant and Moradkhani, 2014; Demargne et al., 2013; Madadgar and Moradkhani, 2013b; Yuan et al., 2013), thus relying on statistical principles to convey the level of certainty which one can place on a forecast. From the probabilistic perspective, a forecast user may leverage a given forecast of risk to minimize potential cost of a drought event. In order to perform such risk management, reliable estimates of forecast uncertainty are essential, with increasing effectiveness as the variance of the probabilistic forecast is decreased.

Three primary sources of uncertainty are present in a drought forecasting framework: initial condition, meteorological forcing and model uncertainties. Initial condition uncertainty arises due to the difficulty of estimating land surface water storages at the initial forecast date, meteorological forcing is uncertain due to the imperfect knowledge of climatic conditions over the forecast period, and model uncertainty results from the imperfect nature of land surface models and insufficient information to precisely estimate parameters. Of these three sources of uncertainty, meteorological forcing and model uncertainties are significant at all potential lead times. Alternatively, the initial condition will only be significant up to a certain forecast lead time, with the sensitivity of the forecast to the initial condition reducing as lead time increases (Wood and Lettenmaier, 2008). This scenario makes quantifying the sensitivity of future land surface states to initial

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conditions highly valuable for forecasters and hydro-meteorologists. Two specific examples of this are highlighted in this study: (1) examining the recovery time from a drought scenario and (2) understanding the extent to which improved initial conditions will help a given forecast system.

Understanding the relationship between the intensity of drought conditions and the time to recovery is of great importance (Mishra and Singh, 2010; Pan et al., 2013; Madadgar and Moradkhani, 2013a, 2014). Since a drought is determined by some deficiency in water, that deficiency will take some amount of time to be alleviated. If the magnitude of that deficiency can be related to the expected recovery time, then mitigation measures may be focused during that expected drought recovery period. Without information about future climate, which is commonly assumed in hydrologic forecasting, it is beneficial at the basic level to quantify the recovery time under normal conditions. This provides another view to drought intensity, beyond simply explaining the magnitude of the deficiency. Such information about the typical recovery time may be more functional to the general public and water resources managers alike, and therefore is of interest to society in general. Further, information about sensitivity to initial conditions is useful in considering potential methods to improve a given forecast system as well.

Improving a forecast system involves reducing the uncertainty in initial condition, meteorological forcing, or the model itself. Among these forecast components, uncertainty related to initial condition has great potential to be reduced through recently developed data assimilation techniques. Due to a range of studies in improving estimates of land surface states through data assimilation (Clark et al., 2008; DeChant and Moradkhani, 2011b; Leisenring and Moradkhani, 2011; Margulis et al., 2002; Reichle et al., 2002), particularly with remote sensing data (Andreadis and Lettenmaier, 2006b; DeChant and Moradkhani, 2011a; De Lannoy et al., 2012; Durand et al., 2008), nearly all regions of the planet have the potential for improved land surface state characterization. Although implementation of a data assimilation system has been proven to reduce uncertainty in land surface state, and therefore initial condition, it does require significant resources to develop and maintain. Given this scenario, information about the sensitivity of forecasts in a given basin to initial conditions, at various lead times, would be highly beneficial in the development of forecast systems. If the forecast at the desired lead time is insensitive to the initial conditions, implementation of a data assimilation system may not be warranted. Alternatively, persistent influence of initial condition over the forecast at long lead times would indicate that a data assimilation system is highly beneficial.

A primary objective in this study is determining the sensitivity of drought forecasts to initial conditions, particularly the lead time at which a forecast becomes insensitive to initial conditions. Recently, several studies have analyzed the sensitivity of extended forecasts to initial condition, but have focused on the relative uncertainties in initial condition and meteorological forcing (Li et al., 2009; Mahanama et al., 2011; Paiva et al., 2012; Shukla and Lettenmaier, 2011; Shukla et al., 2013; Yossef et al., 2013). These studies either compared the Ensemble Streamflow Prediction (ESP) methodology (Franz et al., 2008) (deterministic initial conditions with climatological forcing) with Reverse Ensemble Streamflow Prediction (RESP) (stochastic initial conditions with deterministic forcing) (Wood and Lettenmaier, 2008), or examined of the ratio of the variability of initial condition and precipitation during the forecast period. Through these methodologies, it was generally shown that forecasts in snow dominated basins were controlled by initial conditions between three and six month lead times, when the initial forecast date occurred during the accumulation or ablation season, yet only forecasts for very large non-snow dominated basins were controlled by initial conditions beyond a single month. While this analysis provides a compelling argument for the use of data assimilation in short-term forecasts for all basins, and seasonal forecasts during spring and summer for snow dominated basins, such analysis falls short of determining the lead time at which initial condition provide significant information. For example, forcing may be the dominant source of forecast skill beyond the seasonal time-scale for nearly all basins, but initial conditions may still have a significant impact on forecast uncertainty at longer lead times. Due to this shortcoming, this study attempts to quantify the time at which a forecast becomes entirely insensitive to initial condition, and examines the rate at which the information from the initial condition is lost over time. By quantifying the specific lead time at which a forecast is no longer sensitive to initial condition, a forecaster can provide clear evidence of the point at which data assimilation will be of no benefit, and provide insight into the recovery time expected from certain drought events. For the remainder of this study, the term "drought recovery" will be used to describe the loss of sensitivity to initial conditions, and to specify that this study focuses entirely on the effects of land surface moisture deficits on seasonal to annual forecasting, as opposed to moisture surpluses.

2. Methods

2.1. Study area

This study is performed over the entire upper Colorado River basin (UCRB), defined as the entire basin upstream of Lee's Ferry, Arizona (Fig. 1). This basin is semi-arid, with the majority of precipitation falling in the higher elevations as snow, and interior lowlands receiving very little precipitation annually. Although this basin is semi-arid, a large population relies on its runoff. With mean yearly natural flow of 18 billion cubic meters, it supplies water for nearly 26 million people, making the resource extremely strained. In addition to water within the UCRB being a taxed resource, the basin has been prone to drought in recent years, experiencing drought through much of the 21st century. Due to the combination of water supply stress and frequent drought conditions, the UCRB is ripe for study of drought processes.

2.2. Model and data

Experiments performed in this study used the Variable Infiltration Capacity (VIC) model (Gao et al., 2010; Liang et al., 1994). The VIC model is a physically-based, distributed model that solves the energy and water balance at the land surface, which is run at spatially discretized units on a regular grid. A primary feature of VIC is the ability to model sub-grid variability in vegetation and elevation by partitioning the model discretized units into different vegetation types and elevation bands. By accounting for sub-grid variability, the VIC model is well suited for large scale applications. VIC simulations in this study were performed at a spatial resolution of 0.25°. Soil information for VIC simulations were gathered from the Natural Resources Conservation Services STATSGO dataset and vegetation data was gathered from the University of Maryland land cover dataset, derived from observations made by the Advanced Very High Resolution Radiometer (AVHRR).

The VIC model requires precipitation, maximum and minimum temperature, potential evapotranspiration, wind speed, humidity, and incoming shortwave and longwave radiation to perform land surface simulations. Observed precipitation and temperature data was gathered from the NWS Cooperative Observer Program (COOP) and NRCS SNOTEL sites, and then spatially distributed over the UCRB with the aid of Parameter-elevation Regressions on Independent Slopes Model (PRISM) monthly data (Daly et al., 1994). NCEP/