Seasonal Predictability of Drought and the Importance of Land-Atmosphere Interactions

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Abstract

Hydrologic extremes in the form of flood and drought have large impacts on society. The ability to predict such extreme events at seasonal timescale allows for preparations that can reduce the risk of these events. However, seasonal prediction skill of global climate models varies seasonally and spatially, which severely limits their practical use. In this thesis a framework for assessing and attributing the seasonal predictability through a probabilistic predictability metric based on model skill across temporal and spatial scales; i.e. for the canonical events was developed and demonstrated. The attribution of predictability specific to land-atmosphere interactions and drought is also developed through a new classification of land-atmosphere interactions that includes the Coupling Drought Index (CDI). The CDI was used to understand the current predictability in NCEPs Climate Forecast System version 2 (CFSv2) and the new classification of coupling is used to develop statistical models to isolate attributes of predictability relevant to land-atmosphere interactions and drought. The results show clear seasonal and spatial patterns of predictability that vary with each forecast variable and provide a better understanding of when and where to have confidence in model predictions. The new classification of coupling indicates strong persistence and the CDI shows good agreement with the temporal and spatial variability of drought and highlights the role of coupling in drought recovery. The CDI in the CFSv2 forecasts indicates climatological bias toward the wet coupling regime that precludes the forecast model from consistently predicting and maintaining drought over the continental US. The attribution of the CFSv2 forecasts skill in the summer indicates that the local persistence of initial conditions provides some predictability over the hindcast period and for specific drought events, however the skill is greatly enhanced by the inclusion of spatial interactions. Furthermore, the statistical model based on correcting coupling bias in CFSv2 provides an unbiased prediction and maintained a similar level of skill and provided better precipitation predictions during the 1988 drought. This argues that the wet bias in the coupling limits the precipitation predictability during drought events. The synthesis and extension of the results is also discussed.

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To my wife and daughters.

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Chapter 1

Introduction

1.1 Motivation and Background

In many parts of the world, extreme hydrologic events in the form of floods and droughts are a significant source of social and economic damage. In recent years there have been several of these events such as the heavy rainfall that caused record flooding throughout large segments of Iowa in 2008 (Smith et al. 2013) and more recently the drought of 2011 and 2012, which have affected a historically large fraction of the country including the primary growing regions (Karl et al. 2012). Although, the average US precipitation during these events was not as low as previous years, the record high temperatures caused an intensification and expansion of drought that greatly impacted some regions, particularly during the summer months (Karl et al. 2012). In the United States, the average annual damage due to drought alone is estimated at \$6.8 billion (Wilhite 2000). The acute impacts of drought are also further amplified due to increasing populations and crop production that adds stress to a limited water supply (Seager et al. 2009). The ability to have a warning of such extremes would allow for the resulting impact on society to be reduced through preparation. One such preparation is the ability of water managers to make decisions to ensure sufficient water supply during droughts and ample reservoir storage during flood events. In order to achieve the intended benefit, these preparations require sufficient warning on a seasonal time scale.

The prospect of seasonal predictability of hydrologic drivers, such as precipitation and temperature, to aid in reservoir management has motivated water managers and forecasters to develop prediction models. Historically these models were statistically based and incorporated a large array of predictors based on observations (Goddard et al. 2001). As computational resources and our understanding of the climate has improved, the use of physically based Global Climate Models (GCMs) to make seasonal predictions has become available. However, using the forecasts from GCMs is not always straightforward due to the coarse resolution and inherent model biases associated with their predictions. Even with these limitations, there have been many examples of using GCM for seasonal hydrologic prediction (Wood et al. 2002; Luo et al. 2007) which have shown predictability for some areas and events (Luo and Wood 2007). There have also been many studies that have compared the use of statistical methods against GCM for hydrologic forecasts, however the hydrologic forecast is greatly dependent on the skill of the precipitation forecasts (Yuan et al. 2011, 2013).

Individual storms that cause hydrologic extremes cannot be predicted due to the chaotic nature of the atmosphere, however some extremes are the result of a seasonal persistence into a wet or dry state. The 2008 flooding and the 2012 drought are examples of such extremes caused by a seasonal persistence (Karl et al. 2012; Smith et al. 2013) and not a single event. The source of predictability of the atmosphere on a seasonal time scales lies in the slowly varying boundary conditions (i.e. sea-surface temperatures and land surface characteristics) and can provide skillful seasonal forecasts to the extent that the boundary conditions are predictable

(Palmer and Anderson 1994; Goddard et al. 2001). There have been several studies that have shown the potential of seasonal predictability through a connection of large-scale climate patterns and land-atmosphere interactions (Palmer and Anderson 1994; Trenberth and Guillemot 1996; Goddard et al. 2001; Koster et al. 2010; Villarini et al. 2013). In particular, the cold season predictability of the atmosphere in the extratropics comes from the slowly varying ocean boundaries that play a role in circulation patterns (i.e., teleconnections) (Palmer and Anderson 1994). However, during the summer the teleconnections between tropical Pacific SST and precipitation across the US are weakened, which limits the predictability (Lavers et al. 2009; Seager et al. 2009; Quan et al. 2012). Even though the warm season teleconnections are weak and provide no means of predictability, there is still a potential of predictability via soil moisture-precipitation feedbacks (Koster et al. 2000b). The land-atmosphere interaction (hereafter coupling) impacts the diurnal precipitation cycle through the surface heat and moisture fluxes, which impact the growth and attributes of the atmospheric boundary layer. Modeling studies have shown that soil moisture conditions contributed to drought intensification in the case of the 1988 Great Plains drought (Atlas et al. 1993; Sud et al. 2003). Likewise, Trenberth and Guillemot (1996) argue that soil moisture played a role in perpetuating the drought of 1988 but also played a role in perpetuating the wet conditions in 1993 over the Mississippi River basin. In particular, the parameterization of the land surface plays a crucial role in the heat flux partitioning that contribute to the growth and attributes of the boundary layer that produces convection and can provide a feedback mechanism (Ek and Mahrt 1994; Findell and Eltahir 2003a).

There has been a great deal of work over the last decade to quantify land-atmosphere interactions and feedbacks over a variety of scales and for observations and prediction models. Working groups as part of the Global Energy and Water

Cycle Experiment (GEWEX) initiative have done much of this work. One such effort focuses on the local land-atmosphere coupling through diagnosing the interactions between the lands surface and the planetary boundary layer for models and observations using high-resolution test beds (Santanello et al. 2009, 2011). Other analyses have looked at the land-atmosphere interactions of models at the scale of GCMs (Dirmeyer et al. 2006) including the Global Land Atmosphere Coupling Experiment (GLACE) phase one (Koster et al. 2006; Guo et al. 2006) and phase two (Koster et al. 2011). A promising addition to these studies is the use of satellite remote sensing to classify and understand land-atmosphere interactions at the GCM scale (Ferguson and Wood 2011; Taylor et al. 2012).

1.2 Dissertation Goals

Although there are two distinct sources of seasonal predictability of the atmosphere through the boundary conditions (i.e. sea-surface and land surface), the seasonal and spatial variations of the predictability is not well understood, particularly in respect to the attribution of land-atmosphere interactions on seasonal predictions of drought. As a result of not knowing the attribution and the seasonal and spatial variation of skill of the forecasts from GCMs, the forecasts are often under utilized and do not provide the maximum benefit to society. The aim of this thesis is to provide a framework for understanding the spatial and seasonal variability of predictability and its attribution, with a particular focus on land-atmosphere interactions and the prediction of drought. The driving science questions in this thesis are, *What is the seasonal and spatial variation of predictability over the U.S.* and *What portion of this predictability is associated with land-atmosphere interactions*? Answering these key questions will provide the needed information to allow for a more effective use of seasonal forecasts and provide a framework for model assessment that can lead to improvements in modeling techniques and ultimately better forecasts.

1.3 Thesis Overview

The remaining chapters of this thesis are organized as follows. In Chapter 2 the formation of a probabilistic predictability metric based on multiple temporal and spatial scales is used to understand the seasonal and spatial variability of predictability and its attribution to sea-surface temperature. In Chapter 3 the foundations for understanding the seasonal predictably of land-atmosphere interactions is established by developing a new classification of land-atmosphere interactions and its importance to drought through the Coupling Drought Index (CDI). In Chapter 4 the CDI is used as the primary measure of coupling to assess the seasonal predictability of a GCM and its implications to drought prediction. In Chapter 5 the attribution of land-atmosphere interactions on the summer time predictability, with an emphasis on drought prediction, is established through the use of statistical, hybrid and GCM models. Chapter 6 gives a summary of the findings and a synthesis and extension of the results.

1.4 Publications and Presentations

The core chapters of this dissertation (Chapters 2 through 5) have been published or submitted for publication. Below are the full references:

- Chapter 2: Roundy, J. K., X. Yuan, J. Schaake and E. F. Wood, 2014: A framework for analyzing seasonal prediction through canonical event analysis. Submitted to *Monthly Weather Review*.