Science and Technology Infusion Climate Bulletin
NOAA's National Weather Service
39th NOAA Annual Climate Diagnostics and Prediction Workshop
St. Louis, MO, 20-23 October 2014

Mechanism Behind the Spring to Summer Drought Memory and Its Potential for Improving the Predictability of Summer Drought over the US Great Plains

Rong Fu[1], Bing Pu[1], Robert Dickinson[1], and Nelun Fernando[1, 2]

[1] *Jackson School of Geosciences, The University of Texas at Austin*

[2] *Texas Water Development Board, Austin, TX*

1. Introduction

Droughts in the US cause severe economic loss ($210B during 1980-2011 adjusted to 2011 dollars), making them one of the costliest of natural disasters (Smith and Katz, 2013). "Worst droughts on record" now occur frequently, such as the 2011 Tex-Mex drought, the 2012 US Great Plains drought and the 2014 California drought, enhancing the urgency for societal drought preparedness. Current climate models could not predict these droughts and have provided no more prediction skill than the persistence of rainfall anomalies (Quan *et al.*, 2012; Hoerling *et al.*, 2014), especially over the Great Plains, the "bread basket" of the US.

Strong (Severe to exceptional) summer droughts are a result of persistent rainfall deficits. Some droughts are initiated by La Niñas, and some are intensified by the sea surface temperature anomalies (SSTA) over the tropical Atlantic and Indian Ocean (*e.g.*,Trenberth *et al.*, 1988; Lau and Peng, 1990; Cayan *et al.*, 1999; Hoerling and Kumar, 2003; McCabe *et al.*, 2004; Schubert *et al.*, 2004; Hu and Feng, 2007; Mo *et al.*, 2009; Kushnir *et al.*, 2010; Nigam *et al.*, 2011). However, other strong droughts, such as those in 1988 and 2012, were intensified in absence of SSTA. The latter persists from spring to summer, leading to extreme droughts without clear forcing from SSTA (*e.g.*, Namias, 1982, 1991; Hoerling *et al.*, 2013; Seager *et al.*, 2014; Wang *et al.*, 2014). Although land surface feedbacks can contribute to the drought memory (*e.g.*,Carson and Sangster, 1981; Rind, 1982; Karl, 1983; Mintz, 1984; Oglesby and Erickson, 1989; Oglesby, 1991; Dirmeyer,

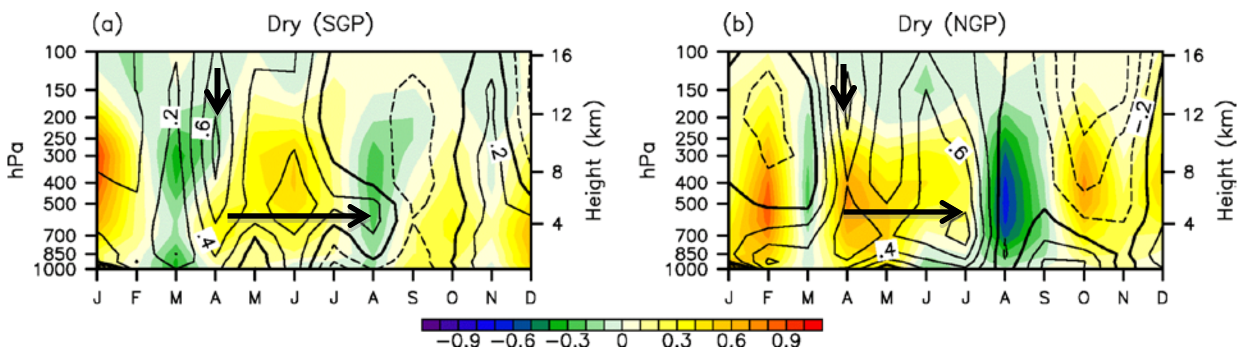

Fig. 1 Seasonal evolutions of the vertical atmospheric dynamic structure (color shades are vertical velocity anomalies, contours stream function anomalies normalized by their standard deviation) suggesting that summer droughts begin with a bartropic-like strong anomalous anticyclonic circulation in April (indicated by solid contours and the vertical arrow). This anticyclonic circulation anomaly persists in the low-middle troposphere (indicated by horizontal arrow), along with mid-tropospheric subsidence (yellow shades), from spring to summer. The seasonal and vertical distributions of the normalized streamfunction anomalies (approximately and equivalent to geopotential height anomalies) and those of anomalies of vertical velocity (unit: Pa/s) are obtained from the composite for all the severe-to-extreme droughts based on NCEP reanalysis during the period of 1979-2012 for the SGP (left) and NGP (right), respectively.

Correspondence to: Rong Fu, Jackson School of Geosciences, The University of Texas at Austin;
Email: rongfu@jsg.utexas.edu

1994; Hong and Kalnay, 2000; Schubert *et al.*, 2004; Myoung and Nielsen-Gammon, 2010), such effects cannot sustain drought for much more than one month in climate models' prediction.

Our analysis suggests that 8 out of 13 severe-to-exceptional summer droughts were developed from spring droughts during the period of 1948-2012 over the US southern Great Plains (SGP). Only 2 spring droughts were not followed by summer droughts. Thus, it is important to understand the mechanisms behind such a spring to summer drought memory and its potential for improving summer drought predictability.

2. What could cause the spring to summer drought memory?

Namias (1982, 1991) and Oglesby (1991) showed that the anomalous anticyclonic circulation or soil moisture in late spring are phase locked with the mean atmospheric circulation transition from the lower to middle troposphere westerly or cyclonic flow in spring to the anticyclonic circulation in summer. In doing so, the anomalous circulation appears to strengthen the summer anticyclonic circulation during the rest of the summer, leading to strong summer droughts. To explore the potential sources for this persistent anomalous anticyclonic circulation, we analyze the composite streamfunction anomalies normalized by their standard deviation at each height (NSFA) for all the years with strong summer droughts during the period of 1979-2012 (Figure 1). Over both the SGP and northern Great Plains (NGP), the summer anticyclonic NSFA in the middle and lower troposphere appears to directly stem from a strong deep tropospheric anticyclonic NSFA in spring following a drier winter that is then maintained in the lower and middle troposphere.

The dominant cause for such persistent anticyclonic anomalies in the middle and lower troposphere is explored in Fig. 2, which shows a comparison between the auto-correlation of the pentad 500hPa geopotential height (Z'_{500hPa}) with the lead-lag correlation between Z'_{500hPa} and soil moisture. The pentad Z'_{500hPa} is more significantly correlated with underlying soil moisture anomalies about 15-30 days earlier than with itself, evidencing that the persistent anomalous anticyclonic vorticity during the summer is caused by land surface feedbacks.

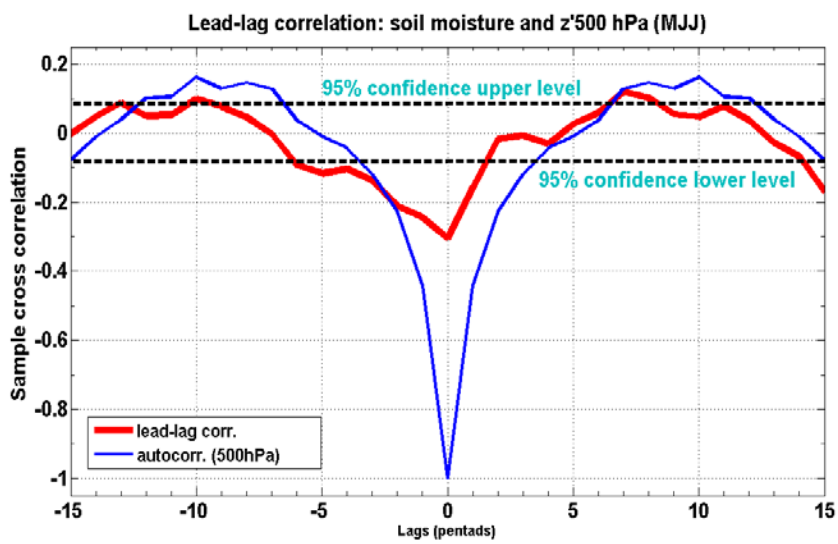

Fig. 2 The correlation coefficients between soil moisture anomalies (red curve) and the 15-30 days lagging (negative 3-5 pentads) 500 hPa geopotential height anomalies (Z'_{500hPa}) are stronger than the auto-correlation of Z'_{500hPa} of the same phase (blue curve) during May-July for the period of 1979-2012. Soil moisture is derived from NLDAS-Noah model.

In summer an extensive ridge occurs in the mid-troposphere centered over the eastern Great Plains. Hydrostatically, this ridge requires relatively cold air. Since dynamic processes are weak, the ridge is largely a consequence of relative diabatic cooling compared to the east coast with its stronger rainfall and clouds, and to the western US with elevated surface heating and deeper turbulent heat transport. This relative cooling results from relative dryness of the continental air at middle troposphere suppressing the diabatic heating from precipitation and the radiative heating from middle to high clouds, with a dynamic response of sinking motion. Thus, *we hypothesize that the persistent anticyclonic vorticity in summer is mainly a response to the sinking motions needed to balance a radiative and latent cooling spatial anomaly in the troposphere from decreases of clouds and precipitation.*

Without thermodynamic feedbacks, the adiabatic warming induced by subsidence would damp the anticyclonic anomalies associated with drought. However, the decreases of clouds, rainfall and water vapor

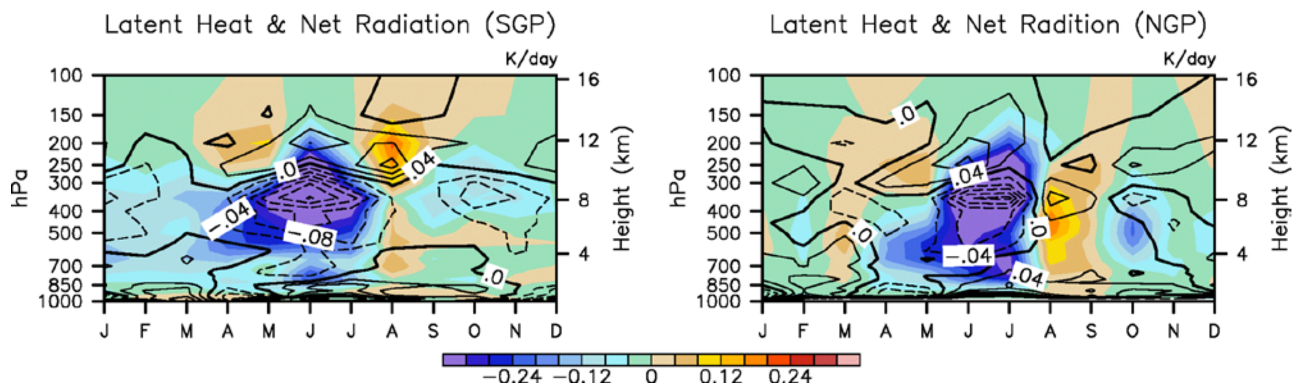

Fig. 3 Seasonal evolutions show strong reduction of latent heating (color shades, K/day) and radaitive heating (contours, K/day) due to decreased clouds and rainfall during April to July. Such anomalous diabatic cooling, initiated by land surface drying, are responsible to the sustained subsidence shown in Figure 1. The seasonal and vertical distributions of the latent and radiative heating anomalies are obtained from the composite for all the severe-to-extreme droughts based on MERRA reanalysis during the period of 1979-2012 for the SGP (left) and NGP (right), respectively.

induce anomalous diabatic cooling in the mid-troposphere to balance the adiabatic warming, thus maintain the subsidence and anticyclonic circulation (Fig. 3). The latter further suppresses convection and associated clouds, and also enhances anticyclonic circulation through friction induced divergence in the PBL and weaker northward vorticity advection. *Thus, decreases of clouds, water vapor and precipitation induced by droughts can maintain and enhance the anticyclonic circulation through anomalous diabatic cooling in the mid-troposphere and friction induced divergence in the PBL. These thermodynamic feedbacks play a critical role in sustaining spring to summer drought memory*.

Figure 4 illustrates the key processes and feedback pathways for the initiation and development of the summer drought, based on the above observational evidence and discussion. *Although SSTA and/or interannual atmospheric variability can be critical for initiating the drought anomalies in winter and spring, the positive feedbacks between land surface and atmosphere, especially through cloud/water vapor and radiative feedbacks, precipitation feedback and PBL friction induced vorticity feedback are important for re-enforcing the anticyclonic circulation anomalies and surface dryness.*

3. Could the spring-to-summer drought memory improve the summer drought predictability over the US Great Plains?

Based on the results shown in Section 2, we have identified three important pre-conditions for spring to summer drought memory over the US Great Plains. These conditions are the geopotential height anomalies at 500 hPa, the difference between temperature at 700 hPa and surface dewpoint, and percentile soil moisture anomalies. We have also developed a combined Multivariate Empirical Orthogonal Function (EOF) and a Canonical Correlation

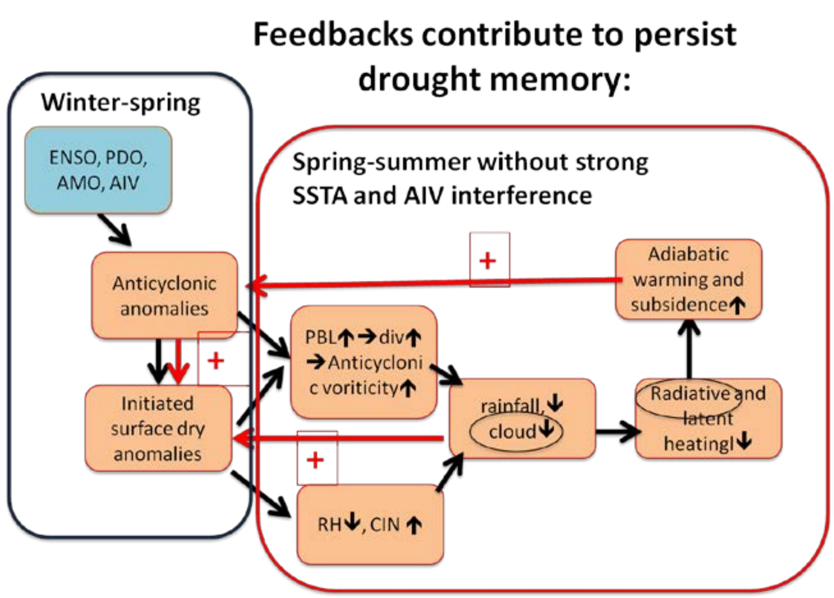

Fig. 4 Observed key processes important for drought initiation, development and intensification over the US Great Plains.

Analysis (CCA) [1] statistical prediction model to explore whether these pre-conditions provide an improved drought predictability and its potential for a summer drought early warning over the US Great Plains.

Figure 5 compares the prediction skills of this statistical drought prediction with 3-months lead time to those of the ensemble prediction of the National Mulit-model Ensemble Prediction (NMME). The overall higher prediction skills than those of the dynamic models suggest that the spring-to-summer drought memory could provide improved drought prediction over the US Great Plains. We have provided our drought early warning to the Texas Water Development Broad (TWDB) in April 2014 for its brief to the State Drought Preparedness Council. TWDB has formally introduced our drought early warning system to its stake holder (http://www.twdb.texas.gov/newsmedia/press_releases/2015/02/drought.asp).

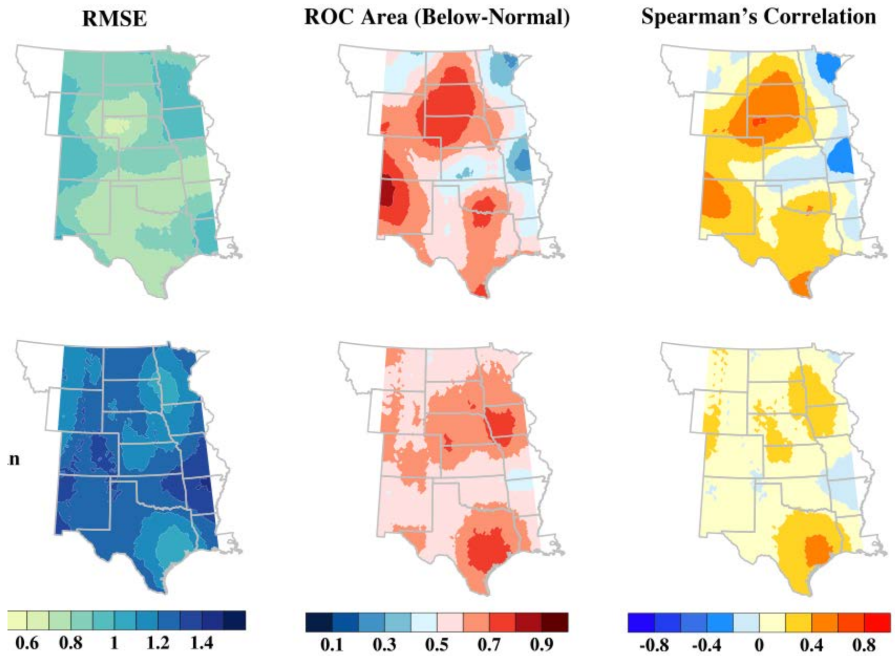

Fig. 5 The 3-months lead drought prediction by our process-based statistical model (top) showing generally higher skills than those of the NMME ensemble prediction (bottom) over the Great Plains, as measured by the Root Mean Squared Error (RMSE, left column), ROC Area (below-normal, middle column), and Spearman's correlation (right column) for July SPI6 using April initial conditions.

4. Conclusions and future works

Severe-to-exceptional summer droughts over the US Great Plains require persistent drought memory from spring to summer. Observations suggest that such persistent spring-to-summer droughts memory is initiated by a strong anomalous barotropic-like anticyclonic circulation in spring, and re-enforced by the coupled land surface, clouds and precipitation feedbacks.

The spring-to-summer drought memory could provide improved drought predictability, as demonstrated by our process-based statistical drought prediction model using three key predicting factors in spring. The drought early warning based on these predicting factors in spring and multivariate EOF statistical model has shown better skill than the dynamic prediction. It has been recommended by state water resource agency and begun to enable society to transition from emergence response to the drought preparedness.

Our results suggest that the cloud feedbacks play as important a role as the precipitation feedbacks to the land surface dryness in sustaining persistent large-scale subsidence, and spring to summer drought memory. Thus, comprehensive evaluations of the drought mechanisms in climate models, especially the impact of uncertainty in capturing the coupling between cloud, precipitation and land surface is an important first step for improving the summer drought prediction over the US Great Plains.

Acknowledgements. This work was supported by the NOAA's Climate Program Office's Modeling, Analysis, Predictions, and Projections Program (Grant Award NA10OAR4310157), the NASA Indicators for the National Climate Assessment Program (Grant NNX13AN39G) and the Jackson School of Geosciences.

[1] The CCA prediction Tool (CPT) available at http://iri.columbia.edu/our-expertise/climate/tools/cpt/ is used.

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