The Physics of Great Plains Drought:
Its Predictability and Its Changed Risk in a Warmer World

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1. Background

Drought is broadly understood to be a condition of deficient moisture in the land surface (e.g. Wilhite and Glantz 1987), a natural hazard associated with agricultural loss, water resource shortfalls, and other economic impacts. The Great Plains, a region of primary US grain production especially corn and soybeans in its central portions, has a distinct rainy season coinciding with its growing season of May through August. Grain yields are highly sensitive to the meteorological delivery of timely and abundant rains.

In this presentation on the physics of drought, based largely on the study by Livneh and Hoerling (2015), we focus on the land surface sensitivity to meteorological drivers, particularly precipitation and temperature. A set of questions regarding the nature and understanding of drought are posed, answers to which are sought via a set of land surface model (LSM) simulations driven by meteorological data derived from historical observations, climate model simulations, and scenarios of plausible future change.

Are droughts and rainfall deficits synonymous? While it is well established that summer rains are critical moisture sources for the land surface supporting agricultural productivity especially in the Corn Belt (Wallace 1920), temperature is also a critical variable particularly in late summer (Thompson 1962). Here we explore the joint influence of temperature and precipitation on the land surface response during drought, focusing initially on the 2012 Great Plains drought as a recent case.

Is the drought prediction problem merely the seasonal rainfall prediction problem? As indicated in historical LSM experiments (Livneh and Hoerling 2015), soil moisture is persistent on multi-seasonal time scales, and thus its initial value is often a useful predictor of drought regardless of subsequent meteorological conditions (see also Quan et al. 2012). Here we show the physical links between antecedent conditions and severe summertime Great Plains drought.

How will Great Plains drought change as climate warms? LSM simulations using prescribed scenarios of temperature and precipitation change are diagnosed, and inter-compared to projections of drought change in the Great Plains based on coupled climate models driven by projections of future greenhouse gas emissions (Cook et al. 2015).

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2. Discussion

a. A Case study of the 2012 Central Great Plains drought

A previous study on the meteorological causes of the 2012 drought characterized the event as a "flash drought" that developed suddenly (Hoerling et al 2014). The event was preceded by near normal antecedent precipitation during winter and spring, offering little apparent forewarning of the subsequent failed summer rains. The spring of 2012 was, however, unusually warm. Large portions of the Corn Belt from eastern Colorado to Ohio recorded their warmest March/April since record keeping began in 1895. Was the land surface materially dried by these antecedent temperature conditions, and how important were those for the drought risk in the subsequent summer as compared to the impact of failed summer rains?

Two different Land Surface Models (VIC and the Unified Land Model [ULM]) were driven by daily observed meteorological forcing at a ~ 50 km scale from 1950-2013. The 1-meter depth soil moisture variability during 2002-2013 over the Central Plains agrees well among the two models and also with independent satellite estimates using the terrestrial water anomalies of the Gravity Recovery and Climate Experiment (GRACE) satellites.

A key finding from the land models is that the high spring temperatures did not materially reduce antecedent soil moisture. The subsequent summer drought, and severe soil moisture deficits, were largely the result of diminished rains. The summer temperatures were also near record highs, and the VIC simulations indicate that while approximately 70% of the Great Plains soil moisture was precipitation driven, 30% was related to evapotranspiration resulting from increased atmospheric demand owing to the heat (ULM indicated even greater relative precipitation sensitivity).

The nature of summer drought in the Great Plains is typically one in which low rainfall and high temperatures coexist. Diagnosis of the physics of that link indicates that most of the Great Plains summer temperature variability is itself a consequence of how rainfall alters the surface energy budget. As such, the net effect of failed rains in 2012 on the drought was found to be larger than the 70% estimated from the LSM simulations.

b. General Characteristics of Central Great Plains drought

To overcome the limited sample size of observed Central Plains droughts, the meteorological and land surface variations occurring in large ensembles of historical atmospheric model simulations (AGCM) are diagnosed. A total of 1050 years of model data for the climate conditions spanning the post-1979 period are studied. The AGCM's daily meteorology is also used to drive VIC simulations for this same 1050 years of data to explore uncertainties in land surface response to meteorological forcing.

The presentation explores the role of initial land surface conditions for the AGCM 1% simulated driest, and also for the 1% of AGCM simulated hottest summers (May-August), totaling 10 events for each (e.g. 1% of 1050 years). Consistent with case study results of 2012, the summers having lowest rainfall also exhibited among the lowest soil moisture by summers end, affirming again the prominence of precipitation control on the land surface and the associated drought severity. Antecedent soil moisture was found to be quite variable, and of limited predictive value for the summer rainfall.

By contrast, the hottest summers exhibited somewhat more variable soil moisture deficits in summer, though all were below normal. The result indicates that hot summers are usually linked with low rainfall in the central Plains (as in 2012), with the rainfall mainly driving the soil moisture deficits rather than the temperatures driving the soil moisture deficits. Interestingly, the antecedent conditions for these hottest summers were much more constrained than for the driest summers--- large spring soil moisture deficits occurred in all of the 1% hottest summers. This indicates the important effect of soil moisture on the surface energy balance that largely dictates the intensity of heat waves in general, and during droughts in particular.

Results of the surface energy balance, based on the model data, provide insight on the physics of drought, and clarify the link between summer droughts and heat waves over the Central Plains. We find a linear relation between soil moisture and rainfall deficits in summer over the Great Plains. By contrast, a nonlinear relation exists between soil moisture and surface temperature, with a rapid escalation in the magnitude of heat waves for incrementally drier land surface conditions as one progresses from moderate to severe drought. This is a symptom of the nonlinear relation between surface sensible and latent heat flux, or more generally between soil moisture and the Bowen ratio, which becomes asymptotically large (i.e. sensible heat flux exceeding latent heat flux) as soil moisture progressively dries.

c. How Will Great Plains Drought Change as Climate Warms?

The projected effect of increasing greenhouse concentrations is to warm the Central Plains and the planet overall (IPCC 2013). Summer temperatures are expected to increase by more than 4°C by the end of the century under an aggressive RCP8.5 emission scenario, though the magnitude of the warming varies among models. The projected change in rainfall is far less certain for the Central Plains, with even the sign of mean summer rainfall change uncertain. Cook et al. (2015) analyzed the result of a subset of the CMIP5 climate models subjected to RCP8.5 emissions scenarios, and determined that high future emissions would lead to unprecedented drought conditions during the last millennium. Their diagnosis of the climate models suggests a high risk of multi-decadal droughts occurring over the Central Plains during the last half of the 21st Century exceeding persistent droughts of the Medieval era. The physics of this is argued to result from an acute land surface drying resulting from the high surface temperature. It is important to note, however, that not all models used in their study (17) yielded such a strong sensitivity of drought risk, even though all models warm---indicating that open questions remain on the physics of land surface responses to meteorological forcing.

In this presentation, we show 1-m soil moisture responses of VIC to a range of surface warming scenarios from +1°C to +4°C. Also shown are the results for changes in precipitation from -20% decline to a +20% increase. These roughly capture the range of projected Central Plains climate changes and also the range of multi-decadal variability in historical rainfall. The results indicate that a 10% change in mean rainfall has a greater effect on soil moisture than even a +4°C warming. A warming of +4°C alone, in the absence of rainfall change, is found to reduce soil moisture, but with a magnitude that is appreciably less than 0.5 standardized departure of the historical soil moisture variability over the Great Plains. This sensitivity is considerably less than implied by the results of Cook et al. (2015).

3. Conclusions and Next Steps

Land surface model simulations indicate precipitation explained in excess of 70% of soil moisture depletion during the 2012 summer Great Plains drought, and drove most of the Central Plains soil moisture variability since 1950. Physical considerations and energy balance calculations reveal that growing season temperature variability is strongly driven by precipitation, indicating that the net effect of rainfall on soil moisture is appreciably greater than 70%.

A nonlinear relationship between soil moisture and the Bowen ratio of sensible to latent surface energy flux indicates an amplifier of heat waves during severe drought conditions. The record hot summer in 2012 is thus seen as largely consistent with the record low rainfall and resulting dry soil moisture conditions. Antecedent wintertime-spring soil moisture conditions affect growing season drought probabilities, and appreciably affect summer temperature though having less of an effect on summer rainfall.

Within a paradigm where precipitation deficits are the principal underlying cause for drought in the Great Plains region, near-future semi-permanent drought conditions, as suggested by Cook et al. (2015) are unlikely given the intrinsic variability in precipitation. The analysis presented herein finds that under various scenarios of future warming, the land surface response of our land surface models is appreciably smaller than the effect of interannual and decadal rainfall variations, implying low detectability of drought changes for the foreseeable future.

Next steps will involve better understanding the physical reasons for differences among climate model projections of Great Plains drought change. It was also noted in the presentation that Great Plains summer temperature have not warmed during the last century, a situation that appears inconsistent with that expected from effects of GHG forcing to date. Detailed study is needed to explain this "warming hole", and determine whether it has been a climate surprise of a highly variable Great Plains climate, or may be an artifact of changes in forcing including land use and land cover that may not be well represented in climate models at this time.

4. References

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