Is a Transition to Semi-Permanent Drought Conditions Imminent in the U.S. Great Plains?

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ABSTRACT

How Great Plains climate will respond under global warming continues to be a key unresolved question. There has been, for instance, considerable speculation that the Great Plains is embarking upon a period of increasing drought frequency and intensity that will lead to a semi-permanent Dust Bowl in coming decades. This view draws on a single line of inference of how climate change may affect surface water balance based on sensitivity of the Palmer Drought Severity Index (PDSI). A different view foresees a more modest climate change impact on Great Plains surface moisture balances. This draws on direct lines of analysis using land surface models to predict runoff and soil moisture, the results of which do not reveal an ominous fate for the Great Plains. Our study presents a parallel diagnosis of projected changes in drought as inferred from PDSI and soil moisture indicators in order to understand causes for such a disparity, and to shed light on the uncertainties. PDSI is shown to be an excellent proxy indicator for Great Plains soil moisture in the 20th Century; however, its suitability breaks down in the 21st Century with the PDSI severely overstating surface water imbalances and implied agricultural stresses. Several lines of evidence and physical considerations indicate that simplifying assumptions regarding temperature effects on water balances especially concerning evapotranspiration in Palmer's formulation compromise its suitability as drought indicator in a warming climate. We conclude that projections of

acute and chronic PDSI decline in the 21st Century are likely an exaggerated indicator for future Great Plains drought severity.

1. Introduction

The future trajectory of climate change in the U.S. Great Plains (30°N-50°N, 105°W-95°W) and in particular the frequency and intensity of future drought is a matter of continuing interest and debate given its past history of severe drought episodes such as the 1930's "Dust Bowl". While some have raised the specter of a shift to semi-permanent 1930's type drought conditions on the Great Plains due to human-induced global warming, the Special Report of the Intergovernmental Panel on Climate Change regarding extreme events (IPCC 2012) expresses only low confidence in a projected change in drought over the U.S. Great Plains as a whole, and medium confidence for some increased dryness across the southern portion of the domain.

Why such substantial differences in expectations for drought in the Great Plains, and why the overall low level of confidence in drought projections for this region as a whole? A possible explanation is an inconsistency in trends for surface water balances among analyses that use different drought indices. One approach has been to examine the sensitivity of the Palmer Drought Severity Index (PDSI; Palmer 1965) to projected changes in monthly temperature and precipitation (e.g., Rind et al. 1990; Jones et al. 1996; Burke et al. 2006; Burke and Brown 2008; Dai 2011, 2012; Burke 2011; Wehner et al. 2011). Results from these studies, though derived from widely different generations of climate models, share the common feature that

PDSI quickly approaches severe drought values with increasing greenhouse gas forcing.

Rind et al. (1990) suggested that increasing drought over the U.S. would become apparent in the 1990s, while Dai (2011) argues that the U.S. might see persistent droughts in the next 20-50 years. The spatial pattern of U.S. drought increase was found to be highly reproducible among the 19 models contributing to CMIP3, largely because the response of PDSI to future temperature increase is very robust (Dai 2011, 2012; Wehner et al. 2011). Wehner et al. demonstrate that climate models having the largest projected temperature increase yield the largest increase in drought severity due to the strong dependency of evapotranspiration on surface air temperature in PDSI. Although this temperature sensitivity depends qualitatively on the formula used to compute potential evapotranspiration (e.g. Chen et al. 2005; Burke et al. 2006), Wehner et al. (2011) surmise that the rapid and severe decline of PDSI under the influence of future warming should be indicative of decreases in soil moisture, regardless of how mean precipitation may change. However, their supposition has not been confirmed by analyses of projected soil moisture changes simulated directly by climate model land surface schemes.

Alternatively, annual mean soil moisture in CMIP3 models is projected to decline in some areas by the end of the 21st century, though not significantly so over the northern Great Plains (Sheffield and Wood, 2008; Orlowsky and Seneviratne 2011). In some regions, such as the northern Great Plains, soil moisture does not change

because projected increases in precipitation are offset by a warming-induced increase in evapotranspiration. Consistent with these changes, surface runoff projections do not exhibit appreciable change (2041–60 compared to 1901–70) for the Missouri and upper Mississippi River drainage basins in CMIP3 models (Milly et al. 2005). For the Great Plains as a whole, Sheffield and Wood's (2008) diagnosis of simulated soil moisture reveals no statistically significant change in the frequency of short-term drought (4-6 month duration) for any emissions scenario (B1, A1B, A2) through 2100, and the earliest year for detecting a statistically significant change in the frequency of long-term (>12 months) drought is about 2050. More recently, Winter and Eltahir (2012) analyzed regional climate model projections for the Midwest U.S. (an area slightly east of the Great Plains region considered herein) and found no reductions in future summer soil moisture, with increased evapotranspiration balanced by increased precipitation. Thus, questions remain on how Great Plains drought will respond to global warming. To better understand uncertainty sources, we present a side-by-side analysis of projected changes in drought using both a PDSI and soil moisture metric.

2. Data and Methods

a. Climate model simulations

We use historical simulations and climate projections based on the fourth version of the Community Climate System Model (CCSM4; Gent et al. 2011). CCSM4 is one of numerous models that comprise the Coupled Model Intercomparison Project-Phase 5 experiments (CMIP5). We analyze monthly output from an ensemble of three

CCSM4 simulations forced with variations in greenhouse gases, aerosols, time-varying solar irradiance, and the radiative effects of volcanic activity for 1850–2005 (Taylor et al. 2012). Projections of climate conditions for 2006–2100 are based upon the Representative Concentration Pathway 8.5 for individual greenhouse gases and aerosols (Moss et al. 2010).

The Community Land Model Version 4 (CLM4) used in CCSM4 represents a significant advance over prior versions (Lawrence et al. 2011; Lawrence et al. 2012). Advances include improved canopy treatment, a plant functional type dependency on soil moisture stress function, improved surface hydrology and runoff, and improved representation of evapotranspiration that provides more realistic treatment of plant transpiration, evaporation from soils, and canopy evaporation. The land model includes a prognostic carbon-nitrogen cycle with time varying vegetation phenology. Soil water is predicted from a multi-layer model in which time variability in soil moisture is a function of infiltration, runoff, gradient diffusion, gravity, canopy transpiration through root extraction, and interactions with ground water (Oleson et al. 2010). Over the U.S. Great Plains region, the land model resolves 10 soil layers to ~3m, with five additional bedrock layers to a depth of ~35m.

b. Drought indices

The monthly Palmer Drought Severity Index (PDSI, Palmer 1965) is calculated from the CCSM4 archive of monthly temperature and precipitation. The potential

evapotranspiration (PET) is calculated using the Thornthwaite (1948) formulation, which depends upon only temperature and latitude. Similar approaches were used in the recent studies of Dai (2011, 2012) and Wehner et al. (2011). Burke et al. (2006) and Dai (2011, 2012) also calculated PET using the Penman-Monteith equation (Shuttleworth 1993), which while providing a more realistic estimate of the meteorological control on PET, continues to be strongly temperature driven (Fennessey and Kirshen, 1994). A recognized limitation of PDSI as an index for drought over semi-arid regions including portions of the Great Plains is its non-Gaussian distribution with a tendency to yield more severe negative PDSI values. We used the statistical normalization method of Wells et al. (2004) to re-calibrate the PDSI which has the effect of altering the statistical distribution of extreme wet and dry occurrences in some areas so as to be more consistent with the expected frequency of rare events, to allow for more accurate comparisons of the index across regions, and to facilitate intercomparison with other standardized drought indices. Here, the parameters for calculating the PDSI values and the subsequent calibrations are determined from the monthly model output of 1901–2000 for each of the three simulations separately, and the calibrated PDSI values are obtained for the entire 1850-2100 period for each run using the respective set of parameters.

The second drought index is derived from the CCSM4 monthly column integrated soil moisture for 3 model layers having a total of ~10 cm depth, normalized, also using the standard deviation of its annual mean during 1901-2000. Sensitivity

analyses indicated that our results do not differ materially when using a shallower 1 cm or deeper 1 m soil layer.

3. Results

Individual PDSI traces averaged over the Great Plains (30°N–50°N, 105°W–95°W) for the period 1850–2100 for each of three model integrations (gray curves) and the 3-run ensemble average (yellow curve) are shown in Figure 1. Two significant features of these time series are: i) a progressive reduction in PDSI commencing in the late 20th Century and accelerating in the 21st Century occurring in all simulations due to increasing GHG forcing, and ii) a randomly occurring decadal-long drought event during the late 19th Century in one simulation due to internal model variability.

The randomly occurring severe drought in the late 19th Century simulation has many of the meteorological characteristics of severe drought over the Great Plains during the 1930s. Figure 2 (left panels) shows the spatial patterns of decadally averaged climate and land surface conditions, a period during which the simulated PDSI (1865-1875) was consistently indicating drought. Negative index values of the PDSI span the Great Plains region from North Dakota to Texas (top panel, left), similar to the observed 1930s pattern (e.g. Hoerling et al. 2009). The pattern of soil moisture deficits (second panel, left) largely mimics the indications for drought provided by PDSI. Further, the spatial pattern and intensity of drought given by both

indicators appear largely determined by the simulated precipitation deficits (third panel, left). Widespread reductions in rainfall with average annual deficits of 1 standardized departure span much of the Great Plains, similar to the magnitude of precipitation deficits observed during the decade of the Dust Bowl (e.g. Schubert et al. 2004; Hoerling et al. 2009). Figure 2 (lower left) also indicates that the drought region experienced elevated surface temperatures, though generally less than +0.5°C. While such warmth is consistent with an overall inverse relationship between rainfall and temperature in CCSM4 (not shown) analogous to that occurring in observations (e.g. Madden and Williams 1978), neither the pattern of PDSI nor soil moisture indicators of this simulated drought event were determined strongly by the temperature conditions. Overall, this randomly occurring moisture deficiency over the Great Plains is well described by PDSI using only monthly temperature and precipitation.

In contrast, under projected future climate change, modeled soil moisture and PDSI respond very differently. Spatial maps of conditions by mid-21st century (Fig. 2, right panels) reveal a North American-wide pattern of much reduced PDSI (top panel) implying that drought conditions exceed both the scale and intensity of that occurring during the Dust Bowl era. The PDSI pattern deviates radically from the spatial pattern of projected soil moisture departures (second panel). Whereas the soil moisture departures are more coherent with the simulated pattern of rainfall change (third panel), the PDSI values are more coherent with the simulated pattern

of temperature change (bottom panel).

In addition, the simulated time series of Great Plains meteorological and land surface conditions (Fig. 3) reveal that soil moisture exhibits a decline during the 21st century, but the magnitude of land surface drying is less than a standard deviation of typical interannual variability. By contrast, PDSI declines on order of 5 to 10 times its standard deviation by the latter decades of the 21st century. The comparatively modest amount of Great Plains soil moisture depletion in CCSM4 is consistent with the multi-model results based on the land surface models of CMIP3 (e.g. Sheffield and Wood 2008). This relatively small signal of soil moisture reduction is consistent with the limited detectability for a change in drought frequency over the Great Plains until the latter portions of the 21st Century as noted in other studies and assessments (Sheffield and Wood, 2008; Orlowsky and Seneviratne 2011; IPCC 2012). Nonetheless, such soil moisture deficits sustained over a long period could have appreciable consequences.

A physically based understanding for these dramatic differences in drought projections is provided by comparing Palmer and CCSM4 projected evapotranspiration (ET) changes. The ET in Palmer's formulation (Fig. 3, yellow curve) initially increases rapidly with the projected warming, with the moisture loss determined largely by the increase in PET-driven demand, the latter being a close proxy for the magnitude of projected temperature rise (compare red and orange

curves in Fig. 3). Since ET's upper bound is dictated by precipitation and available soil moisture, a decline in the rate of ET rise in Palmer's model ensues in the latter half of the 21st century as the bucket model's soil moisture becomes substantially depleted. At this point in Palmer's projections, PDSI falls to unprecedented negative values. By contrast, ET in CCSM4 (Fig. 3, purple curve) does not increase nearly as much as ET in Palmer's model. The overall modest positive ET departure in CCSM4 projections is consistent with its projected modest soil moisture decline, whereas higher frequency variability of ET in CCSM4 is mostly driven by fluctuations in precipitation.

Finally, the simulations indicate that co-variability of annual departures in Great Plains PDSI and soil moisture drastically changes in the warming 21st Century climate. Figure 4 compares the relationship during the 20th Century (blue circles) with that during the 21st Century (red circles) based on diagnosis of all three CCSM4 simulations. PDSI explains about 40% of the inter-annual variations in soil moisture during the 20th Century, but explains only about 20% of the variance during the 21st Century. A -1 PDSI value (an indication for mild drought) corresponds to about a -1 standardized departure of soil moisture during the 20th Century; however, a -6 PDSI value (which is far beyond the range of the most extreme PDSI value during the calibration period) also corresponds to a -1 standardized departure of soil moisture during the 21th Century. The magnitude of the PDSI during the projection period of a warming climate thus ceases to be a reliable indicator of land surface water

deficiencies and implied drought severity, at least within the simulations of CCSM4.

4. Conclusions and Discussion

Assessments of how climate change may affect the frequency and severity of drought need to consider various drought indicators (e.g., IPCC 2012). Two such indicators, PDSI and the soil moisture anomalies each present very different views of how surface water balances may evolve over the Great Plains under global warming. To understand these differences, we analyzed both drought indicators using CCSM4 simulations. Our analysis reproduces disparate outlooks for Great Plains drought—projections using the PDSI suggest that the Great Plains will be in a semi-permanent state of severe Dust Bowl-like drought in coming decades, whereas soil moisture projections reveal modest drying and comparatively low detectability for changes in Great Plains drought frequency. Our analyses illustrate that the PDSI exaggerates future drought severity over the Great Plains due to unrealistic sensitivity to the projected warming of surface temperatures.

Scale analysis by Hu and Wilson (2000) shows the PDSI is about equally affected by temperature and precipitation anomalies having similar magnitude, but that the temperature sensitivity during the 20th Century is generally masked by the strong negative correlation between temperature and rainfall variability. A GHG-forcing change in surface temperature without a corresponding change in rainfall leads to

projected values of PDSI that are effectively proxies for the projected increases in temperature, but are not suitable indicators for soil moisture. The simple parameterization of potential evapotranspiration using a Thornthwaite formula is not appreciably remedied using a more sophisticated Penman-Montieth formulation (e.g. Dai 2011, 2012). Estimates of evapotranspiration based solely on temperature have been regarded as problematic (e.g. Lockwood 1999; Burke et al. 2006; Burke 2011). Palmer's formula for how PET relates to a specific location's radiation climate, as inferred from temperature alone, becomes violated in the presence of appreciable warming and leads to unrealistic extreme drought indications (Lockwood 1999). Additionally, the sensitivity of the PET calculation is strongly affected by the choice of the calibration period (Karl 1986).

The PDSI was developed to define drought using a minimum number of widely observed variables and provides a good snapshot of observed drought conditions in a variety of climates. However Dai's (2011) review of factors affecting drought raised several limitations of PDSI under global warming. Dai noted that the Palmer formula overestimates potential evapotranspiration under a warming climate, and, "the fact that they [the PDSI index] may not work for the 21st century climate itself is a troubling sign". While past performance has been useful in appreciating the value of the PDSI, it is no guarantee for future success, especially when applied to the non-stationary climate system currently unfolding.

Our result for severe drought indication over the Great Plains based on PDSI is entirely consistent with a host of prior PDSI-based drought projections but derived from an earlier generation of climate models (e.g., Dai 2011, Wehner et al. 2011). The similar results are due to the robustness in projected surface warming combined with the strong dependency of PDSI on temperature, rather than the soundness of Palmer's formulation of the complex surface water balance. Palmer's drought index avoids the complicating biological factors and the complex processes of soil-vegetation–atmosphere transfer, which are essential in representing how land surface moisture balances evolve in a warming climate. With the advent of model-based reanalyses, and the need to examine the GHG-forced climate response of drought, it is clear that drought indices need to be developed that incorporate all relevant variables at the proper time resolution to consistently define drought conditions across the full range of climates.

An extensive comparison of the Thornthwaite method with pan-based estimates of evapotranspiration in China (Chen et al. 2005) illustrates severe deficiencies that are only somewhat alleviated by properly calibrated Penman-Monteith (PM) estimates. However, we stress the fact that while the use of the PM formulation to estimate PET reduces the bias associated with the strong temperature dependence in Palmer's formulation (see e.g., Burke et al. 2006), the impact of other simplifications remain. For instance, the PM formulation lacks a land surface model with plant phenology from which transpiration is physically derived, and still uses

simple accounting assumptions of how ET balances either precipitation or PET in Palmer's water balance calculations.

In the context of our study, it is important to consider the implications that a non-stationary, warming climate has for misinterpreting drought severity based on model projections of PDSI. The limitations are: 1) the absolute value of PDSI should be viewed as an unreliable measure of drought severity in a warming climate (and for these same reasons in an extreme heat wave event like over the Great Plains in 2012), and 2) inferences of possible amplifying effects of temperature alone (separate from precipitation effects) on drought severity derived from analysis of Palmer's model should likewise be viewed as unreliable. For real-time drought monitoring the first limitation could be mitigated by annually updating the calibration of the Palmer equations and their coefficients using the latest data. By updating to include the data through 2011–12, one can derive a more representative estimate of the "climatological water balance", given the known appreciable variability and emergent trends; however, the problem in using PDSI for assessing future drought conditions in climate model projections remains.

So is a transition to semi-permanent drought imminent for the Great Plains? While our results cannot rule out the possibility of a Dust Bowl like-period in the near future, the physical processes for such an occurrence are likely to be related to prolonged deficiencies in Great Plains precipitation, rather than to the local temperature effect of projected surface warming alone.

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Figure Captions

Figure 1. Annual time series of PDSI averaged over the Great Plains (30°N–50°N, 105°W–95°W) for 1851–2100 (the calibration period is 1901–2000). Individual traces correspond to each of the three CCSM4 model integrations (gray curves) while the 3-run ensemble average is shown by the yellow curve. The time series are smooth with a 9 point Gaussian filter.

Figure 2. Spatial patterns of decadally averaged land surface conditions for PDSI (top row), 10cm soil moisture (second row), precipitation (third row), and temperature (bottom row) for 1865–1875 (left panel) and 2045–2055 (right panel) for the CCSM4 model integrations. Anomalies are computed from the 1901–2000 reference period. The 1865–1875 results are based on a single model run, and the results for 2045–2055 are based on the 3-run ensemble average. Box in lower left panel denotes the Great Plains domain over which spatial averages are computed for time series analysis in Figs. 1 and 3, and scatter plot relationships in Fig. 4.

Figure 3. Standardized annual time series of Great Plains surface temperature (red curve), evapotranspiration (purple), precipitation (green), soil moisture (blue), and PDSI (yellow) as simulated in the ensemble of CCSM4 forced integrations. Also shown are the Palmer-model derived annual time series of evapotranspiration (yellow) and potential evapotranspiration (orange). The reference period for the

standardization is 1901–2000 and each of the curves is smoothed with a 9 point Gaussian filter.

Figure 4. Comparison of the relationship between annual 10-cm soil moisture and PDSI for the 1901–2000 period (blue circles, R=+0.61) with that of the 2001–2100 period (R=+0.48) based on the diagnosis of all three CCSM4 simulations.

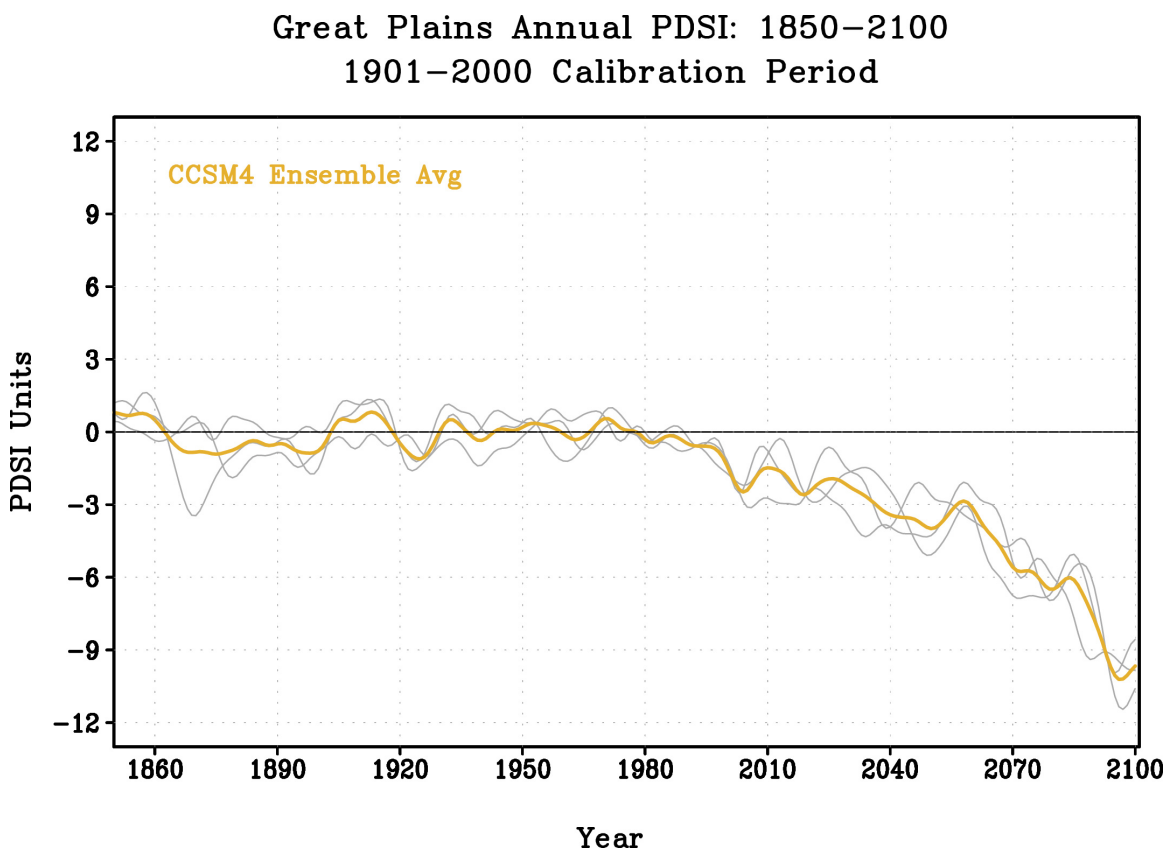
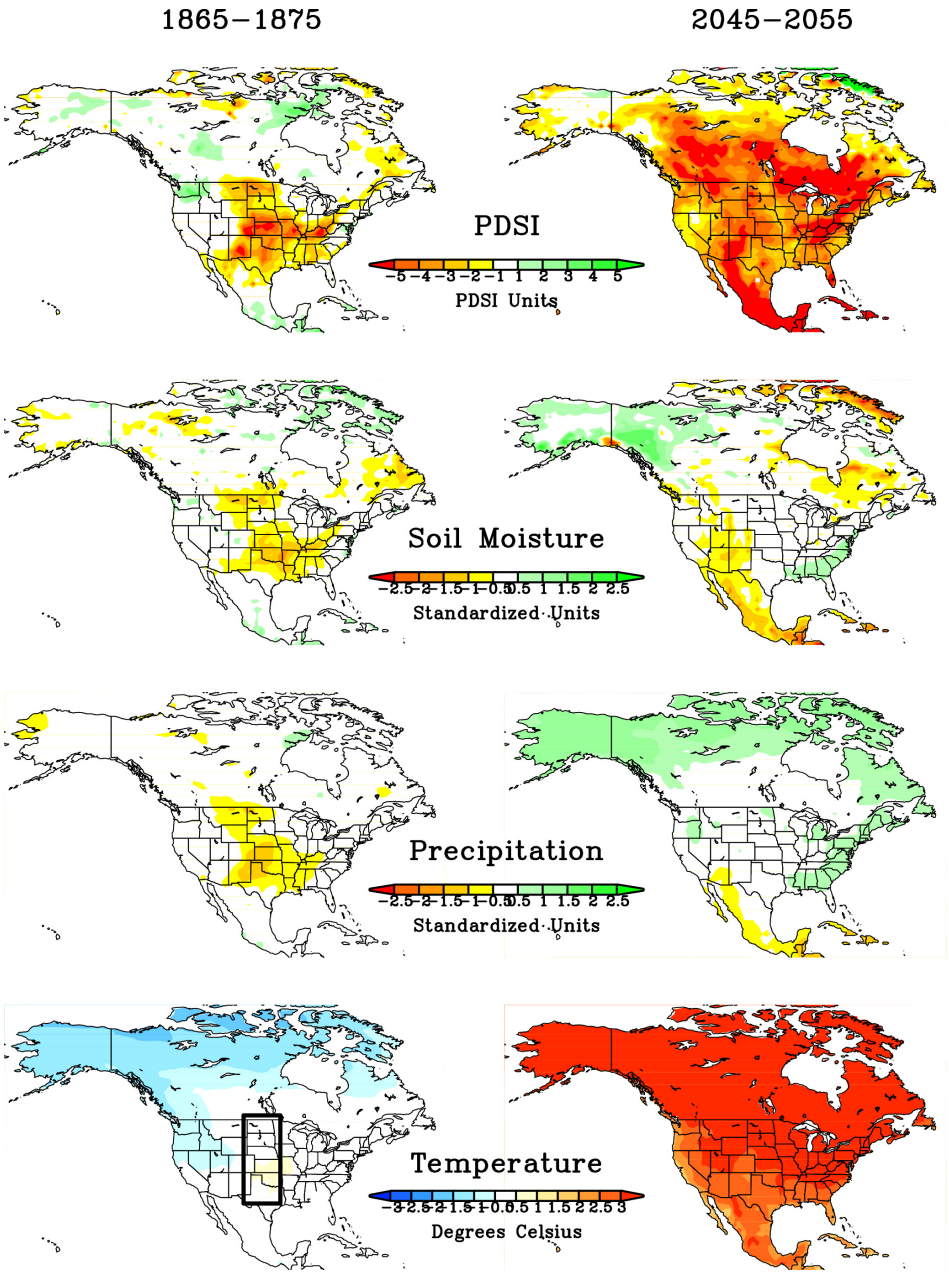


Figure 1. Annual time series of PDSI averaged over the Great Plains (30°N–50°N, 105°W–95°W) for 1850–2100 (the calibration period is 1901-2000). Individual traces correspond to each of the three CCSM4 model integrations (gray curves) while the 3-run ensemble average is shown by the yellow curve. The time series are smooth with a 9 point Gaussian filter.



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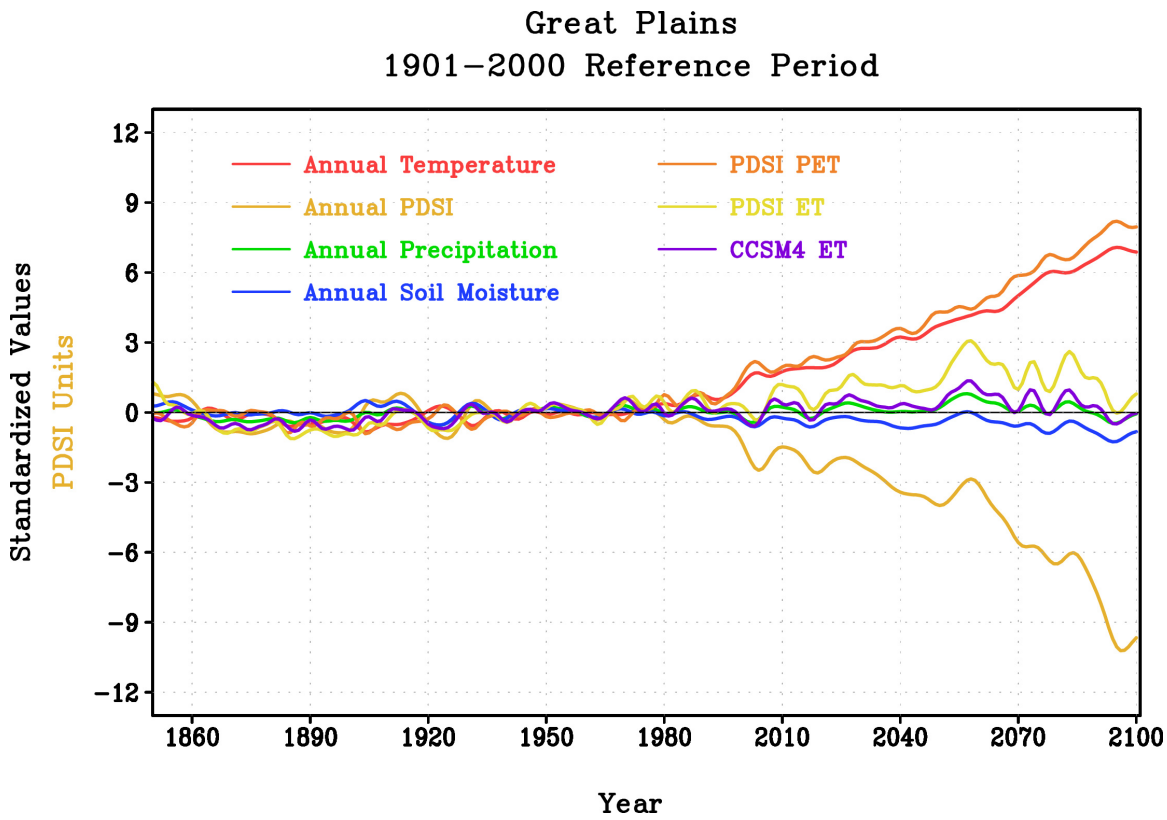

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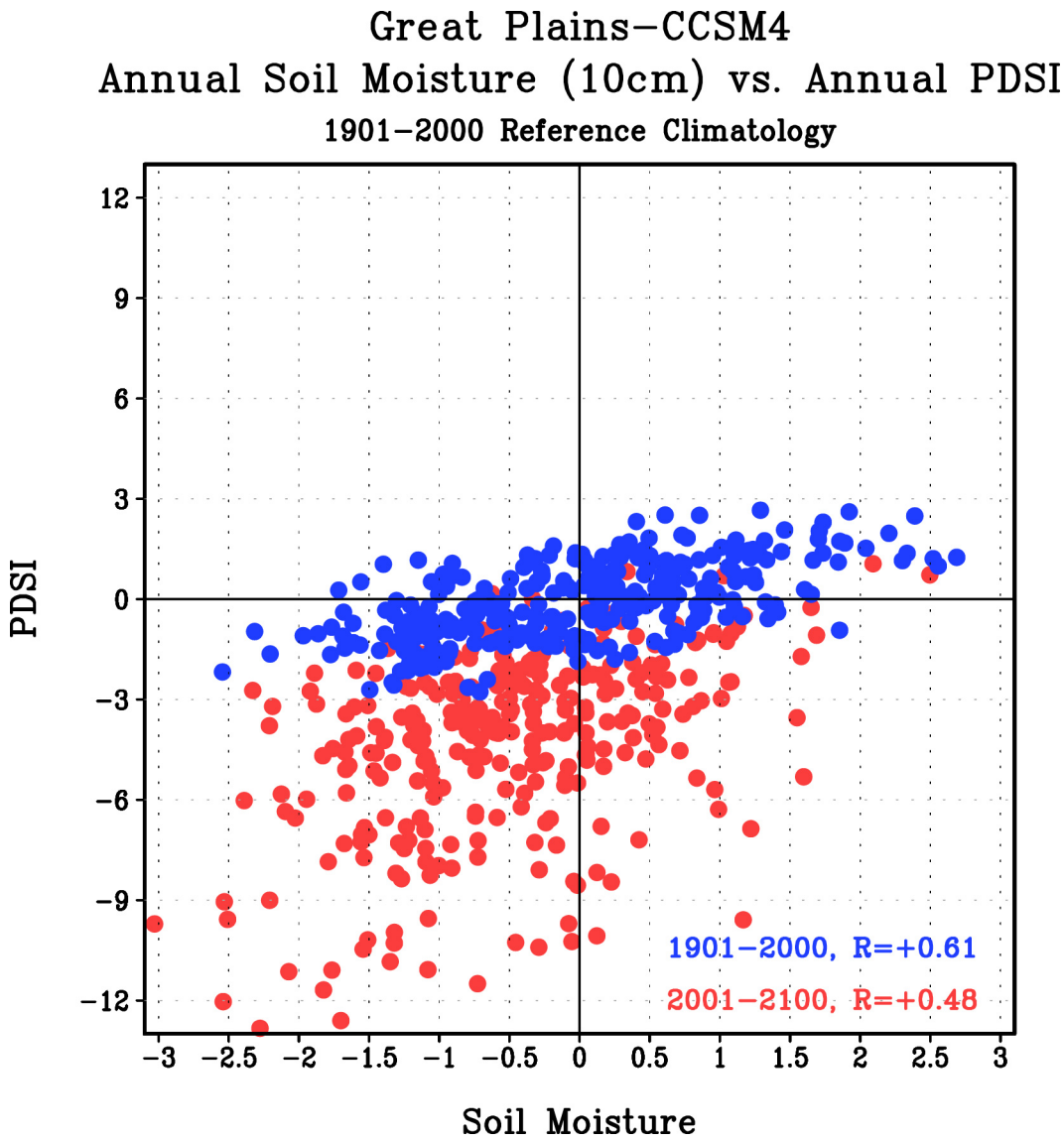

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