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Causes and Predictability of the 2012 Great Plains Drought

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Abstract

Central Great Plains precipitation deficits during May-August 2012 were the most severe since at least 1895, eclipsing the Dust Bowl summers of 1934 and 1936. Drought developed suddenly in May, following near-normal precipitation during winter and early spring. Its proximate causes were a reduction in atmospheric moisture transport into the Great Plains from the Gulf of Mexico. Processes that generally provide air mass lift and condensation were mostly absent, including a lack of frontal cyclones in late spring followed by suppressed deep convection in summer owing to large-scale subsidence and atmospheric stabilization.

Seasonal forecasts did not predict the summer 2012 central Great Plains drought development, which therefore arrived without early warning. Climate simulations and empirical analysis suggest that ocean surface temperatures together with changes in greenhouse gases did not induce a substantial reduction in summertime precipitation over the central Great Plains during 2012. Yet, diagnosis of the retrospective climate simulations also reveals a regime shift toward warmer and drier summertime Great Plains conditions during the recent decade, most probably due to natural decadal variability. As a consequence, the probability for severe summer Great Plains drought may have increased in the last decade compared to the 1980s and 1990s, and the so-called tail-risk for severe drought may have been heightened in summer 2012. Such an extreme drought event was nonetheless still found to be a rare occurrence within the spread of 2012 climate model simulations.

Implications of this study's findings for U.S. seasonal drought forecasting are discussed.

1. The Drought's Morphology and Impacts

Central Great Plains' rains, occurring mostly during May-August, failed in 2012. Absent was the usual abundance of slow soaking precipitation-bearing systems and evening thunderstorms that characterize Great Plains climate, and as a result surface moisture conditions greatly deteriorated. The U.S. Drought Monitor estimated that over three-quarters of the contiguous U.S. experienced at least abnormally dry conditions by summer's end with nearly half of the region, especially the Great Plains, experiencing severe-unprecedented drought. Conditions were comparable to those of a quarter-century earlier during 1988, and the combination of rainfall deficits and high temperatures even rivaled those observed during the Dust Bowl era of the 1930s.

Daily rainfall time series from observations taken at weather stations across the Great Plains (Fig. 1) illustrate the timing of drought onset. After a period of near to above normal winter and early spring precipitation at most stations over the central Great Plains, rains abruptly halted in May. For instance, there were virtually no rainy days at Cedar Rapids, IA during May, a signature of the paucity in migratory cyclones and frontal systems that have been previously identified as drought-causing mechanisms for spring and some summer droughts (e.g. Dole 2000). Neighboring stations also experienced prolonged stretches of rain-free days, with no measurable precipitation at Omaha, NE during July consistent with an absence of rain-producing thunderstorms that typically account for the bulk of mid-summer rainfall in the U.S. heartland (e.g., Dai 2001). Likewise, the western Plains stations of Goodland, KS and

Cheyenne, WY saw only infrequent rains of light intensity during July and August. By contrast, Dallas-Fort Worth, which was near the center of the prior year's southern Plains drought, accumulated above normal rainfall for the prior 6-month period through summer 2012. This greatly improved their soil moisture balance, and the U.S. Drought Monitor estimated that northeast Texas was drought-free by May 2012. Oklahoma City also showed strong signs of recovery from the 2011 drought with above average rains falling through May 2012, but then skies abruptly cleared and June through July was virtually rain-free attesting to the dearth of thunderstorm activity that also plagued other Great Plains areas.

Various measures of drought intensity paint a consistent picture of widespread and severe surface moisture deficits that spanned the central Great Plains during May-August 2012. The summer-averaged precipitation was nearly 2 standardized departures below normal from the Rockies to the Ohio Valley (Fig. 2a) indicative of meteorological drought. Surface temperatures were likewise about 2 standardized departures above normal over this region (Fig. 2b), consistent with the strong inverse relationship between summer rainfall and surface air temperature (e.g. Madden and Williams 1978; Hoerling et al. 2013). Severe agricultural drought occurred throughout the region as affirmed by estimated soil moisture anomalies that were in the lower decile of the historical distribution (Fig. 2d). And, as expected from the deficient rainfall and depleted soil moisture, estimated surface runoff was also in the lower decile, especially in the western Missouri and lower Ohio River drainage basins (Fig. 2c).

Impacts from the drought emerged swiftly. Loss estimates by the end of July 2012, were $12B (http://www.kansascityfed.org/publicat/mse/MSE_0312.pdf). The USDA estimated that corn yield (per acre of planted crop) was only 123 bushels. (http://www.nass.usda.gov). This is 26% below the 166-bushel yield expectation that the USDA had at the commencement of the growing season. Figure 3 shows the time series of U.S. corn yield since 1866, the most prominent feature of which is the growth in yield since about WWII as a consequence of improved agricultural practices and more productive and heartier strains of seed. However, 2012 corn yield fell strikingly below the recent trend line. The 2012 crop yield deficit and the implied climatic impact was a *historic event*. In terms of absolute loss in bushels of corn production, no single year since 1866 experienced so large a curtailment as occurred during 2012.

It was mostly via extrapolation of the recent historical yield time series that the USDA offered its initial expectation in spring 2012 that annual corn yield would be about 166 bushels per acre. This is a reasonable prediction given that year-to-year variations are mostly small relative to the trend “signal” of unabated improved yields. Of course, these variations----relative to trend --- are mostly the result of climate variability. The question is thus whether this drought could have been anticipated, and if actionable prediction of climate impacts on agriculture (among many other sectors vulnerable to drought) might have been rendered.

2. Historical Context and Relationships to Antecedent Conditions

By measures of rainfall deficits, the summer of 2012 was an unprecedented year. Figure 4 shows the 1895-2012 time series of May-August rainfall departures averaged over the multi-state region (WY, CO, NE, KS, MO, IA) that experienced the most severe drought conditions in 2012. The deficit in rainfall in 2012 was -34.2 mm, which was about 53% of the region's long-term mean rainfall (73.5 mm). This deficit broke the record of -28.4 mm observed in 1934, and corresponds to a departure of 2.7 standard deviations.

The 2012 event would not have been anticipated from simple considerations of central U.S. rainfall behavior in the recent past. The 1930s droughts lay in distant memory, and though not forgotten, may have resulted from unique conditions of that era (Schubert et al. 2004; Seager et al. 2005; Cook et al. 2009). These included remote effects of tropical sea surface temperatures, land use practices and the potential feedbacks that abundant soil-related aerosols may have exerted on rainfall. An important role for random atmospheric internal variability has also been proposed (Hoerling et al. 2009). However, since the 1930s, summer rainfall has shown less severe declines in the 1950s and 1970s, while the last 2 decades were noted mostly by abundant summer rainfall (e.g. Wang et al. 2009). Looking at the whole time period, there is no clear long-term trend towards either drying or wetting. The 2012 drought thus appears to be a climate surprise from such empirical considerations alone.

But did early warning signs exist based on other information, for instance in the sequence of seasonal events that immediately preceded the 2012 drought? Much of the southern and central Great Plains experienced near normal precipitation during the period October 2011 thru April 2012 (not shown), and this situation significantly improved soil moisture conditions over the southern Plains by spring 2012 (Fig. S1), and was responsible for the amelioration of agricultural drought severity over this region that had developed in prior years. Precipitation was thus mainly driving a recovery in soil moisture through spring 2012 over the southern Plains, and surface moisture conditions over the central Plains were not severely stressed despite a very warm early spring.

Is there empirical evidence that droughts over the southern Plains, such as occurred during 2010-11, tend to migrate northward as part of a life cycle? Here the instrumental record dating to 1895 is examined to explore how Great Plains droughts typically evolve. From the historical time series (Fig. 4), the prior driest May-August periods are identified. The 10 driest years (including 2012), ranked in order of their rainfall deficits, were: 2012, 1934, 1936, 1901, 1976, 1913, 1988, 1953, 1911, and 1931.

For these 9 historical cases, composite averages of precipitation for the 12 months preceding peak central Great Plains May-August rainfall deficits were calculated and are shown in Fig. S2. No evidence for appreciable dryness in the prior summer over Texas is found in this composite; suggesting that southern Plains drought such as occurred in 2011 is not a necessary condition for subsequent central Great Plains drought. There is some indication for prevailing dryness in the antecedent conditions across the central Great Plains as a whole, however. This dry signature is partly related to the fact that several of the individual driest central Plains summers in the composite were immersed within dry epochs that spanned much of the 1930s and also from the late-1940s through the mid-1950s.

4. Proximate Causes for the 2012 Drought

Why did the 2012 drought happen the way it did? This is meant as a simple starting query towards interpreting the drought, though recognizing that answers to this question alone may not provide predictive understanding. As is common with droughts, atmospheric moisture in both absolute and relative measures is typically deficient, and 2012 was no exception. A second, and often inexorably linked factor is the absence of processes that produce rainfall over the central Plains. These include springtime low pressure systems and their attending warm and cold fronts that act to lift air masses and produce widespread rains. During summertime, the key process involves thunderstorms that normally occur with considerable frequency and from which the majority of precipitation falls in July and August. Both of these mechanisms were largely absent or inoperative to considerable degree in 2012 over the central Great Plains.

Diagnosis of 500-hPa height anomalies during summer 2012 reveals considerable monthly variability (Fig. 5), implying that such a sustained and extreme drought was not a consequence of some steady sustained forcing. Yet each of these monthly anomaly patterns in their own manner squelched rainfall-inducing processes over the central Plains. In May and June (Fig. 5, top panels), a zonal ridge of high pressure anomalies inhibited the typical southward push of cold fronts from Canada that often serve to organize widespread rains. July (bottom left) saw a somewhat different pattern, though no less effective in inhibiting rainfall. An intense anticyclone was centered over the northern Plains region, preventing frontal incursions while also stabilizing the atmosphere and inhibiting deep convection that typically contributes appreciably to mid-summer rainfall totals. The August 500 hPa height pattern (bottom right), though also drought producing, was yet different again from May, June and July. A deep Ohio Valley trough acted to inhibit Gulf of Mexico moisture inflow, while subsidence over the western Great Plains was enhanced on the western edge of this low pressure system.

Together, these conditions conspired to create a 4-month sequence of record rainfall reduction over the central Great Plains. The impression is rendered of a sequence of unfortunate events given the considerable monthly variability in the upper level circulation over North America. There were nonetheless indications of more persistent planetary scale features of atmospheric circulation during summer 2012 that consisted of zonally averaged positive height anomalies in middle latitudes and negative anomalies in subtropical latitudes (not shown). Previous studies have found such distinct zonally symmetric features of the Northern Hemisphere summertime circulation to be at least weakly controlled by sea surface temperature anomalies (e.g. Schubert et al., 2002; Kumar et al., 2002; Ding et al. 2011). Such a global pattern entails widespread poleward shift of the prevailing westerlies, and is consistent with the fact that the Eurasian grain belt also experienced record heat and drought beginning in May 2012. These reduced harvests together with the impacts on U.S. production resulted in substantial wheat price increases world-wide (http://www.businessweek.com/news/2012-08-23/russia-may-run-out-of-exportable-grain-surplus-in-november).

Over the U.S., the aggregate consequence of these various drought inducing circulation features was that the principal source of water vapor in summer over the central U.S. from the Gulf of Mexico region was greatly impaired. The spatial distribution of climatological 700 hPa meridional (north-south component) wind (Fig. S3) exhibits a peak 2 m/s southerly flow immediately on the coast of southwest Texas, a feature related to the clockwise air motion around the mean subtropical high of the Atlantic Ocean. This climatological influx of Gulf air masses is also a signature of the integrated effects of migratory mid-latitude storm systems, especially in the late springtime when they exhibit a geographically preferred cyclogenesis in the lee of the southern Rocky Mountains. The southerly flow was 50% reduced during May-August 2012, with a seasonal anomaly of about -1 m/s along the Gulf Coast region (Fig. S3). Consistent with this, the summertime 700 hPa specific humidity was anomalously low throughout the Great Plains.

5. Underlying Causes for the 2012 Drought

Why did drought occur over the central Great Plains during summer 2012 (and what caused the proximate conditions discussed above)? We have already surmised, from empirical analysis, that the central Plains drought was unlikely part of a single multi-year drought life cycle having its incipient stage over the southern Plains in late 2010 and subsequently spreading northward. Although large portions of the U.S. are experiencing a third year of drought, it is plausible that various phases may have had different causes (see Hoerling et al 2013; Seager et al. 2013 for studies of the 2010-2011 drought). Here we explore whether particular forcings, including sea surface temperature (SST) and sea ice conditions, and also the trace gas composition of the atmosphere, may have contributed to the occurrence of a drought over the central Plains in summer 2012.

Concerning SST forcing, it is useful to first assess the evidence for recurrent patterns of ocean conditions attending the prior nine severe summer droughts in the historical record. For these events, 3 cases (1910/11; 1933/34; 1975/76) experienced moderate La Niña conditions the prior winter season, two occurred after wintertime El Niño conditions (1930/31; 1987/88), while the remaining 4 cases were neutral with respect to ENSO's phase. Consistent with this weak evidence for a coherent *precursor* SST condition, at least in the equatorial east Pacific, evidence for a strong *simultaneous* SST effect is not found either. An analysis of the linear correlation between the index of central Great Plains summer precipitation with summertime global ocean surface temperatures for the entire

1895-2011 period (Fig. S4) reveals no statistically significant relationship. The lack of such relationships between summer US precipitation and sea surface temperatures has thwarted efforts at successful seasonal forecasting.

Global SSTs have appreciably changed, however, since the occurrence of past major central Plains droughts. Figure 6 presents two analyses for the SST anomalies of May-August 2012, one calculated relative to a 1901-1990 climatology (top) that brackets the era in which the prior nine historical droughts occurred, and the other relative to a conventional modern 1981-2010 30-year climatology (bottom). A key point is the indication for an appreciable warming of most ocean basins as revealed by the much larger warm ocean anomalies during the 2012 summer when calculated relative to the long historical reference. The implication is that the prior severe Great Plains droughts occurred when global oceans, and climate overall, was appreciably cooler. Nonetheless, several regional features of SST conditions in 2012 are robust to choice of reference, including the presence of anomalous warmth in the North Atlantic and an enhanced east-west contrast in equatorial SSTs between the climatological warm pool of the Indo-west Pacific and typically cooler waters of the central to east Pacific.

Given such non-stationarity in climate, and in particular the change in global SSTs, it becomes important to examine the particular attributes of climate forcings that operated during 2012 and assess how they may have conditioned the probability for severe drought over the central Great Plains in 2012. The warm SSTs in the Atlantic basin during 2012 are noteworthy, and recent studies point to a summertime U.S. climate sensitivity to Atlantic forcing (e.g. Schubert et al. 2009; Findell and Delworth. 2010; Kushnir et al. 2010). Also, the tropical-wide SST anomalies of the past year have attributes of the so-called "perfect ocean for drought" pattern, with an enhanced west-east contrast in ocean temperatures between the Indo-Pacific and central Pacific. Land precipitation was found to be sensitive to this structure, especially for the cold-season over the southern U.S. (Hoerling and Kumar 2003).

Retrospective climate simulations in which the variations of ocean surface conditions and atmospheric trace gas composition during 1979-2012 have been specified are next diagnosed (see Appendix 1 for model details and an assessment of model climatology). Two particular aspects of the simulated sensitivity are of interest. First is the average response to the specified forcings, and here we diagnose the ensemble mean response of 30 simulations based on 2 different climate models. Second is the so-called “tail response”, an assessment exploring how the probability of a particular threshold exceedance (e.g., the odds of eclipsing a prior record value) changes as a consequence of the specified forcing.

Figure 7 compares the observed May-August 2012 anomalies for rainfall (left), soil moisture (middle), and surface air temperature (right) with the ensemble mean signal of the fully forced climate model simulations. A forced signal of reduced rainfall is apparent in the models, though geographically focused over the Southwest and intermountain West rather than over the central Great Plains region (outlined in the black box), and having magnitudes much weaker than those observed. For the central Great Plains region, the area-averaged simulated rainfall is -0.5 standardized departures, a dry signal appreciably smaller than the -2.0 standardized departures observed, and there is virtually no dry signal simulated east of the Missouri River where observed drought was quite severe. A similar assessment holds for soil moisture, though the standardized departure of the model's soil moisture deficit is somewhat greater than that of its simulated rainfall deficit. This reflects two factors. One is the long memory of soil moisture, and the effect of a simulated signal of reduced rainfall over the Southwest during prior seasons and into 2011 (not shown). The other is the strong contemporaneous warming of surface air temperature during summer 2012 (right side panels) that may have also contributed to land surface drying via increased evapotranspiration. For the central Great Plains region, the area-averaged simulated warmth is 0.8 standardized departures compared to the 2.3 standardized warm anomaly observed,

Perhaps more compelling is the indication for an increase in the probability for an extreme drought event having the intensity observed in 2012. The box-whisker display in Fig. 8 shows the model distribution of its 30 simulations for summer 2012 (far right), and also for each summer during 1979-2012 for both rainfall (top) and surface air temperature (bottom). The overall distribution for various rainfall anomaly thresholds within the 30 realizations shifts toward drier states in 2012, consistent with the simulated mean signal of reduced rainfall. Interestingly, for summer 2012, the extreme driest model member (red asterisk) is also the single driest simulation occurring in any year during 1979-2012.

It is difficult to reliably determine the change in extreme drought event probability for 2012 from such a small 30-member simulation suite. However, inspection of the full 33-yr time series of such distributions suggests that the recent drought may have occurred during a climate regime supporting increased likelihood for severe Great Plains drought events. There is, for instance, a roughly 4-fold increase in the frequency of occurrence for a 2 standardized rainfall deficit in the 17-yr period after 1996 compared to 17-yr period before. Once again, this is consistent with an ensemble mean dry signal in the model in virtually all years in the recent period, and not due to increased variability per se. The increased probability, nonetheless, represents the risk of an event that remains rare within the model spread.

It is reasonable to propose, based on analysis of these model experiments that the fact that a drought of such severity did occur in 2012 was largely coincidental, and that such an occurrence was almost as likely during any prior year since the late 1990s, but more likely than in the years prior to the mid-to-late 1990s. To be sure, event likelihood is seen as a low probability in any given year. Yet, it is an intriguing conjecture that, while perhaps unbeknownst and undetectable from the observations, the recent 10-15 year period may have been one of heightened risk for the occurrence of a record setting summer drought over the central Great Plains.

The indication from the model simulations is of an abrupt shift to a warmer (Fig. 8, bottom) and drier (Fig. 8, top) climate in the late 1990s over the Great Plains, at least relative to the climate of the preceding decade. (This is hard to discern based on the observational record alone as seen in Figure 4.) There are at least two candidate mechanisms that may explain the model behavior, both associated with known patterns of natural variability. One is a tropical Pacific shift with no large El Niños but an abundance of strong La Niñas in the period since the 1997/98 El Niño. A second is a sudden shift in North Atlantic SST conditions from a persistent cool state during the 1980s to late 1990s, followed by a persistent warm state of the North Atlantic thereafter, consistent with North Atlantic multi-decadal variability (e.g. Delworth and Mann 2000). Analysis of model sensitivity experiments by Schubert et al. (2009) found that a combination of warm Atlantic and cool tropical Pacific SST patterns produced substantial precipitation deficits and surface warming for annual mean responses over the continental U.S. The model sensitivity is supported by empirical evidence for a relationship between natural multi-decadal states of the Pacific and Atlantic Oceans and multi-decadal drought frequency over the U.S. (McCabe et al. 2004).

An additional question these results pose is whether the simulated change in extreme drought risk is a symptom of climate change forcing related to global warming. There are several indications that this behavior is largely unrelated to the model's sensitivity to gradually increasing anthropogenic forcing. One indication is the rather sudden character of change in model simulations toward dry conditions in the late 1990s. Though one cannot dismiss the possibility that a steady forcing (for instance increasing CO_2) may provoke an abrupt change in responses, there are other plausible physical explanations for the shift in model behavior in the 1990s including natural swings in ocean states as mentioned above. A second issue concerns the lack of any appreciable long-term change in seasonal mean climate during summer over the central Great Plains since 1895 (see Fig. 4). Nor has there been an indication for an increasing trend in the occurrences of severe summer droughts over the region, with the last severe drought happening a quarter century earlier. Additional analysis will be required to assess the role of global warming on recent precipitation variability over the Great Plains using the full suite of Climate Model Intercomparison Project (CMIP5) models.

6. Predictions of the 2012 Drought

The summer 2012 central Great Plains drought developed without an early warning. NOAA's operational seasonal drought outlook, issued 17 May 2012 for the subsequent June-August period (Fig. 9, top), did not predict a tendency toward increasing drought over the central Great Plains. Instead, surface moisture conditions were expected to improve over Iowa and western Nebraska. Otherwise, the majority of the central Great Plains was forecast to experience near normal moisture conditions. Only over the interior West was drought expected to persist or intensify.

The drought outlook reflected three primary considerations. One was the initial monitored state of drought, for which the U.S. Drought Monitor revealed surface moisture over the Great Plains had appreciably recovered during winter/early Spring. The second was the seasonal rainfall forecast, which did not yield strong guidance on the summer rainfall pattern. For instance, the May 2012 initialized predictions for June-August based on the composite of 12-centers' seasonal forecast systems showed no appreciable rainfall signal (Fig. 9, bottom left), although it did indicate a widespread large amplitude warm signal (Fig. 9, bottom right).

A third consideration for the drought outlook was the expectation for rainy season onset. The climatological normal rainy season over the Great Plains is May-August. Since empirical and dynamical tools gave no strong reason to suspect it wouldn't arrive as usual, those rains were expected to alleviate existing surface moisture deficits. In many ways, the drought outlook and the results from initialized coupled model predictions are thus consistent with the retrospective climate simulations presented in Section 5, though there may be additional useful information in the ensemble spread of the retrospective climate simulations that were not readily available to the forecasters.

7. Summary Comments on the 2012 Drought and Implications for Forecasting

a. Overall Assessment of Origin and Cause

The 2012 drought developed rapidly over the central Great Plains during May and reached peak intensity by August. In many ways, the event was a "flash drought", owing to the unusual speed and intensity with which it developed and became entrenched over the Great Plains in summer. The 4-month cumulative rainfall deficit, averaged over a 6-state area of the central Great Plains, was the greatest since record keeping began in 1895, ranking this event as the most severe summertime seasonal drought over the central Great Plains in 117 years, eclipsing 1988, 1934 and 1936. The immediate cause for the drought was predominately meteorological in nature. This involved reduced Gulf of Mexico moisture transport and reduced cyclone and frontal activity in late spring. It also involved an inhibition of summer convection resulting from increased subsidence and atmospheric stabilization that accompanied an anomalous upper tropospheric high pressure over the region. The drought can thus be seen as the symptom of classical meteorological conditions that control the region's warm season rains.

The 2012 summertime central Great Plains drought resulted mostly from natural variations in weather. The assessment did not find substantial evidence for underlying causes associated with the effects of long-lived boundary forcings. Retrospective climate simulations identify a mean dry signal during 2012 summer having a magnitude 4 times weaker than that observed for an area-average of the Great Plains region. Indicated hereby is that neither the variations in ocean states nor in greenhouse gases played significant roles in determining the intensity of the rainfall deficits in summer 2012. Furthermore, analysis of the retrospective climate simulations found virtually no dry signal over major corn producing regions of the eastern Great Plains including most of Missouri, Iowa, southern Wisconsin, Illinois, and Indiana where severe drought occurred and resulted in major curtailment of corn crop yields, indicating that neither the variations in ocean states nor in greenhouse gases played significant roles in determining the precise location of rainfall deficits during summer 2012. The simulations did reveal, however, a more substantial drying over the Southwest U.S and the far western Great Plains especially New Mexico, Colorado, western Nebraska, western Kansas, and Wyoming. These areas also suffered severe drought in 2012.

A few words are in order concerning the model suggestion of a regime shift to warmer and drier summers over the last 10-15 years, especially over the Southwest U.S. and western Plains. The underlying tendency since the late 1990s for drought conditions over the U.S. has a plausible physical basis, being likely linked to natural states of the Pacific and Atlantic Oceans. In this sense, while the 2012 drought was not well predicted, it perhaps should not be a surprise that a drought of some severity occurred (see also McCabe et al. 2004). Large portions of the U.S. are experiencing a third year of drought, although the Central Plains drought of 2012 was not a simple progression or northward creeping of the prior year's Southern Plains drought event. Further, the southwestern U.S. has been overwhelmingly in a state of abnormally dry or drought conditions since 1998. This widespread state of dryness appears at least qualitatively consistent with a longer time scale climate control associated with natural oceanic variability. In the Southwest it is also consistent with the expected climate response to rising greenhouse gases (e.g., Seager and Vecchi 2010), though that influence on precipitation is likely smaller at the current time than the influence of natural long term variability. However, despite the role of these ocean and radiative boundary conditions in tilting the odds towards a dry state, the peculiar severity of summer 2012 can only be explained by an additional heavy role for random weather variability.

b. Implications for Drought Prediction

What are some of the lessons learned in this assessment concerning U.S. drought forecasting? On the one hand, the appraisal offered herein paints a picture of an extreme event that apparently had limited potential for skillful prediction. This conclusion would thus appear to be consistent, and furthermore offer an explanation for, the poor performance of both official forecasts of drought and numerical predictions of rainfall that were rendered in late May 2012 for the subsequent June-August 2012 season. On the other hand, our diagnosis of the spread among an ensemble of retrospective climate simulations indicates an increased probability for an extreme Great Plains drought event in 2012. For instance, the single driest simulation for Great Plains summer conditions, among the sample of 990 summer simulations during the entire 1979-2012 period analyzed herein (30-members for each year of the 33-year period), occurred in the suite of 2012 runs. The models thus reveal that so-called tail-risk was heightened in summer 2012. Furthermore, these same simulations indicate that the statistical likelihood for a severe summer drought occurring over the Great Plains during the last decade may have been several-fold greater than the odds of occurrence during the prior period spanning the 1980s and 1990s. The retrospective analysis thus argues for elevated risk of an extreme drought event, even though the precise timing of any single event was uncertain, and the overall strength of the signal on *seasonal mean rainfall* was quite small.

Given the existing practices of operational drought prediction, what might have been the impact on the forecast process if various information contained in this assessment had been available in early 2012? It is useful to frame that question in the context of expected skill. The history of operational seasonal forecast performance reveals little or no skill for U.S. summer rainfall since routine forecasts were issued beginning in the mid-1990s . Furthermore, an assessment of U.S. drought hindcast skill over a longer period since 1982 recently concluded that dynamical seasonal predictions did not materially increase summer skill over the Great Plains beyond a persistence forecast benchmark (Quan et al. 2012). The reason given for the limited overall skill was small SST sensitivity of that region's summer rainfall and a small impact of antecedent soil moisture conditions, on average, upon the region's summer rainfall.

A pathway forward for summer drought prediction might thus be to consider conditional skill, and to identify so-called "events of opportunity". There are ample examples of those for rainfall and drought during the cold season in the southern U.S. associated with the strong conditioning by the El Niño/Southern Oscillation phenomenon. For instance, there was considerable skill in the seasonal forecasts of the 2010-11 southern Plains drought, especially during the winter and spring season (e.g. Hoerling et al. 2013). The current study builds upon a body of climate sensitivity studies and physical reasoning that a conditioning of U.S. summer rainfall by particular large-scale oceanic conditions may also exist (e.g. Schubert et al. 2009; Findell and Delworth 2010). Yet, contrary to ENSO effects, the magnitude of that conditioning is still highly uncertain and requires further investigation before it can be quantitatively incorporated into seasonal forecasts.

One of the opportunities for improving seasonal drought predictions is to move toward expressing the outlooks in a probabilistic manner, as is done currently for seasonal forecasts of precipitation and surface temperature. The current drought outlook product is deterministic, notwithstanding some subjective language that attempts to express the most probable tendency of drought conditions over the upcoming season. The full information of ensemble prediction systems, in particular the spread information contained in such tools, can thus not be readily incorporated into current practices for U.S. drought forecasting. Further research is also required on evaluating the spread information on drought statistics from such ensemble modeling systems. Much has yet to be learned about the robustness of spreads across multi-models, and how those spreads differ when examined in simulation mode (using uninitialized models) versus prediction mode (using initialized models). In the case of the 2012 drought, for instance, it remains to be determined if the particular event's probability was materially conditioned by antecedent soil moisture.

A related issue is the need to reconcile the identification of a modest Great Plains dry signal in the retrospective climate simulations studied herein with the lack of any dry signal in the summertime 2012 predictions of the WMO GPC multi-model ensemble. It is unclear if this was a consequence of errors in the SST predictions. Did the process of averaging 12 different models and merging them in producing the GPC forecast cause large cancellation among appreciably different signals occurring in individual models? Or was the ensemble mean prediction for drier than normal conditions in these models simply too small in amplitude, and thus perhaps deemed unreliable to include in the forecasts?

One might reasonably wonder, given the suggestion from the rainfall time series produced in the retrospective climate simulations, whether the risk of a severe Great Plains drought is once again elevated in 2013 or beyond. Clarification will require better knowledge of the factors controlling the low frequency variability of Great Plains moisture conditions. The analysis presented here has mainly proposed the roles of long time scale natural variability in sea surface temperatures. And, while this study is not intended to be a comprehensive assessment of the possible effects of global warming on the 2012 central Plains drought, the results here are inconclusive on that specific question. Here we merely note the conclusion of the U.S. Climate Change Science Program Synthesis and Assessment Products (SAP 1.3, 2008) that SST anomalies have been important in forcing some multi-year severe droughts over the U.S. during the last half-century, whereas short-term droughts ("flash droughts" having monthly-seasonal time scales) were judged to be mostly due to atmospheric variability, in some cases amplified by local soil moisture conditions. The report assessed that it is unlikely that a systematic change has occurred in either the frequency or area-coverage of drought over the contiguous US from the mid-20th century to the present. Subsequently, in 2012, the Special Report of the Intergovernmental Panel on Climate Change (IPCC) regarding extreme events expressed only medium confidence in a *projected* increase in drought in some regions by end of the 21st Century, including the southern Great Plains and Mexico, but not the northern Plains and Midwest regions. How Great Plains drought will respond under global warming therefore continues to be a key unresolved question and a matter of future research.

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Appendix 1: Climate Model Simulations

Two global atmospheric models are run over the period 1979-2012. The only constraining information representing observed conditions in these simulations is the sea surface temperature, sea ice, and external radiative forcing which are specified in the model as monthly time evolving boundary conditions from January 1979- December 2012. Climate simulations of this type are referred to as 'AMIP (Atmospheric Model Intercomparison Project)' experiments, and are designed to determine the sensitivity of the atmosphere, and the extent to which its temporal evolution is constrained by known boundary forcings.

Key to this modeling technique for assessing the impact of boundary conditions is an ensemble approach, whereby the period of simulation is repeated a multitude of times. Here simulations that have been repeated 30 times (a 30-member ensemble), and which differ from one another only in the initial atmospheric conditions in January 1979 but in which identical time evolving forcings are specified, are analyzed. The strategy is to average the monthly variability across the 30 members in order to determine the mean response to specified forcings. The process of averaging eliminates the random internal variability of the atmosphere, and facilitates identifying the coherent signal from the forcing.

One model used is the National Center for Atmospheric Research (NCAR) CAM4 global climate model (Gent et al. 2011), with the simulations performed at a 1° (~100 km) resolution and 26 atmospheric, and for which a 20-member ensemble is available. The second global climate model is the European Center Hamburg model version 5 (ECHAM5; Roeckner et al 2003), with simulations performed at T159 (~80km) resolution and 31 atmospheric levels, and for which a 10-member ensemble is available. In both models, monthly varying SSTs and sea ice and the external radiative forcings consisting of greenhouse gases (e.g. CO_2, CH_4, NO_2, O_3, CFCs) are specified. CAM4 runs also specify varying anthropogenic aerosols, solar, and volcanic aerosols. The model output has been interpolated to U.S. climate divisions to facilitate comparison with observations.   Ensemble means are computed by doing simple equal weighted averages of the CAM4 and ECHAM5 20-member and 10-member averages, respectively.

For the May-August period and for a spatial average of 6-state Central Great Plains region, the combined GCMs' climatological mean precipitation (temperature) is 302 mm (22°C) versus 298 mm (20°C) observed. The standard deviation of May-August precipitation (temperature) in the combined GCM is 12 mm (0.9°C) versus 13 mm

(0.7°C) observed.

Figure Captions

Figure 1. Daily precipitation (mm) time series during 2012 for indicated stations. For each station, top portions show the climatological precipitation (smooth curve), the actual 2012 precipitation, and their difference (color shading; brown denotes a deficit, green a surplus). Lower portions show the occurrences of daily precipitation events. Data source is NOAA Climate Prediction Center.

Figure 2. Standardized anomalies averaged over May-August 2012 for a) precipitation, b) surface air temperature, c) 3-month accumulated runoff, and d) soil moisture. Precipitation data were taken from the CPC unified precipitation analysis. Temperature data were taken from the surface temperature analysis from the University of Washington. The May-August mean and standard deviation were

computed using the base period 1979-2011. The contour intervals are given by the color bar. (b) same as (a). The runoff index and soil moisture are shown as percentiles, with those data taken from the ensemble mean NCEP North American Land Data Assimilation (four land surface models: Noah, Mosaic, VIC and SAC).

Figure 3. Historical U.S. corn yields from 1866 to 2012 (bushels/acre). Linear fit to different segments of the time series shown in solid lines, including regression formula. The 2012 yield is plotted in the blue circle, based on August estimates. Subsequent data revised the 2012 yield downward to about 123 bushels. Data source is USDA.

Figure 4. 1895-2012 time series of May-August central Great Plains rainfall departures (mm, top) and surface air temperature departures (°C, bottom). Reference period is 1895-2011. Black curve is a 9-point Gaussian filter. The area is comprised of the 6-State region of WY, CO, NE, KS, MO, and IA. Data source is the NOAA U.S. Climate Divisions.

Figure 5. Observed monthly 500 hPa geopotential height anomalies (m) for May, June, July, and August 2012. Data from the NCEP/NCAR reanalysis, and anomalies are relative to a 1981-2010 climatology.

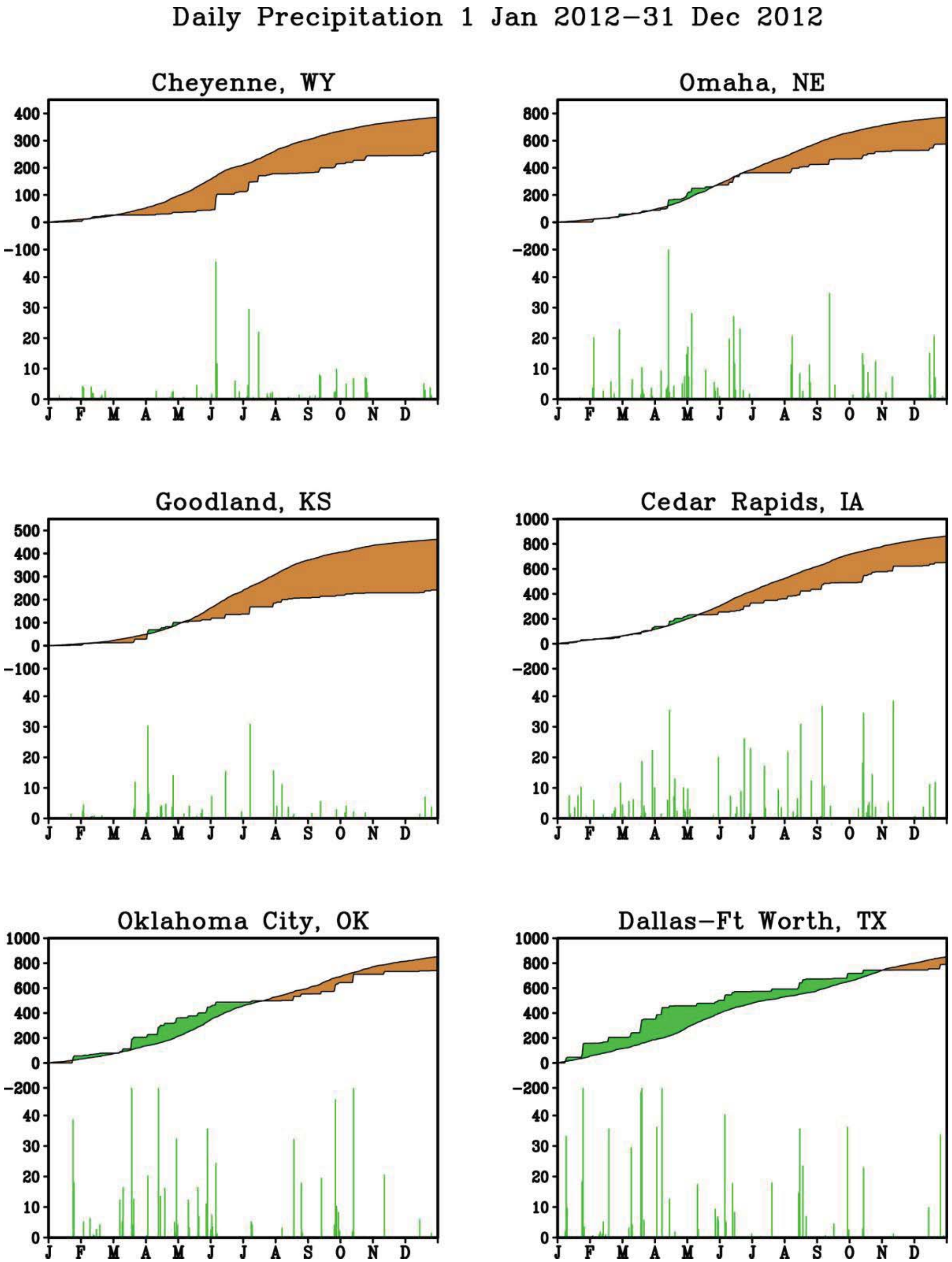
Figure 6. The May-August 2012 sea surface temperature anomalies (°C) calculated relative to a 1901-1990 historical reference period during which the prior nine

severe Great Plains droughts occurred (top) and relative to a modern 1981-2010 reference period (bottom).

Figure 7. The May-August 2012 standardized anomalies of precipitation (left), soil moisture (middle), and surface air temperature (right) for observations (top) and general circulation model (GCM) simulations (bottom). Observed soil moisture estimated from the CPC a one-layer bucket water balance model driven with observations of monthly temperature and precipitation. The GCM is based on a 30-member multi-model ensemble simulation forced with the observed SSTs, sea ice, and greenhouse gas conditions for 2012. For the model data, the standardization is calculated for each separate run, and the standardized anomalies are then averaged across all 30 realizations. Period of reference is 1981-2010.

Figure 8. Box-whisker plots of the May-August simulated central Great Plains rainfall anomalies (top, mm) and surface temperature anomalies (bottom, °C) for 1979-2012. The distribution summarizes the statistics of 30 simulations for each summer. Red (blue) asterisk denote the extreme dry (wet) ensemble member for each summer, and the dashed red lines are the model's 1-standardized departures of May-August precipitation and temperature. Green circles plot the observed values. The region consists of the 6-state average of WY, CO, NE, KS, MO, and IA. Anomalies are relative to a 1981-2010 reference.

Figure 9. (top) The NOAA official seasonal drought outlook for the contiguous U.S. issued on May 17 2012 and valid for the period May17 – August 31 2012. (bottom) The equal-weighted composites of 12 operational centers' seasonal predictions for June-August 2012 for North American sector precipitation departures (mm, left) and for North American sector surface temperature anomalies (°C, right). Forecasts are based on May 2012 initializations. Data source is the WMO GPC project. (https://www.wmolc.org/).



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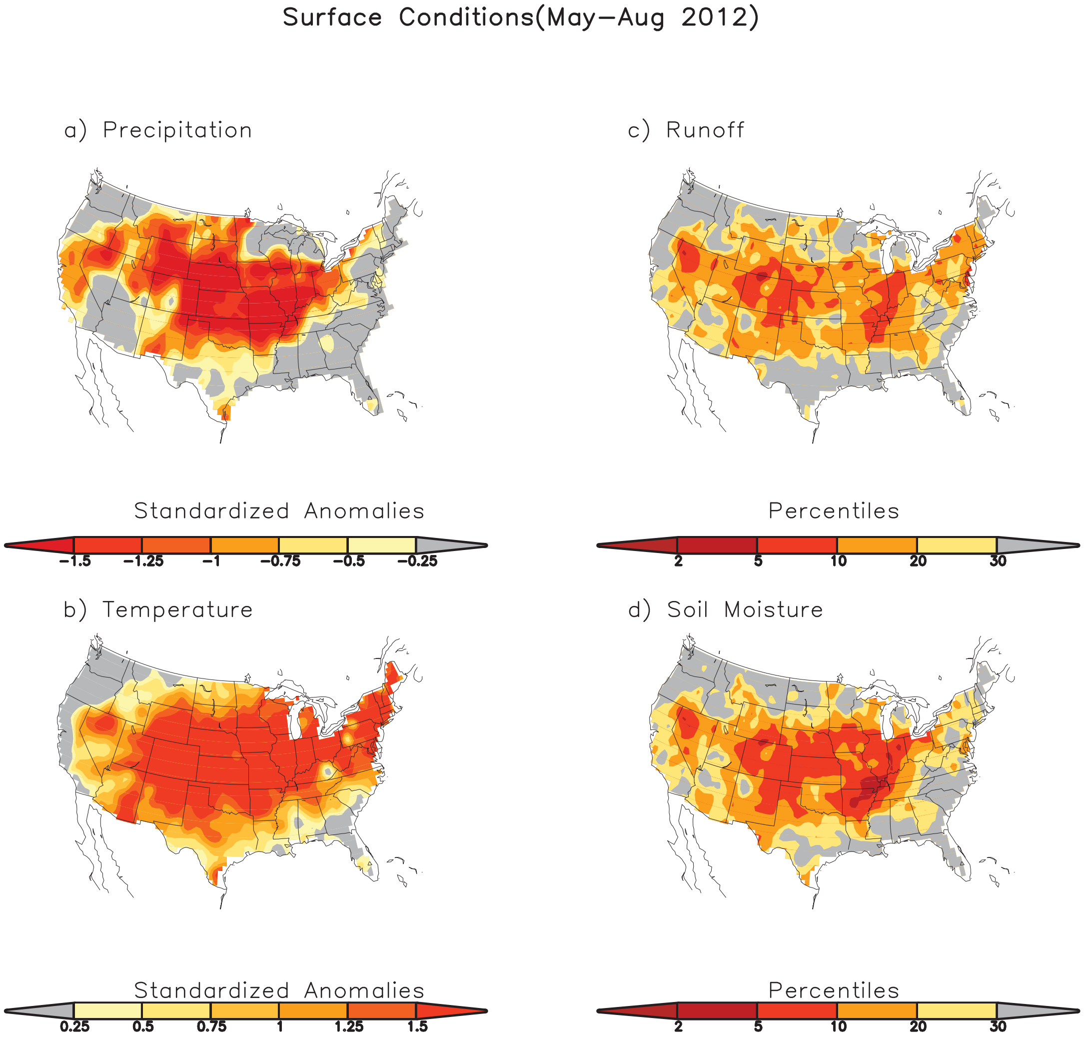

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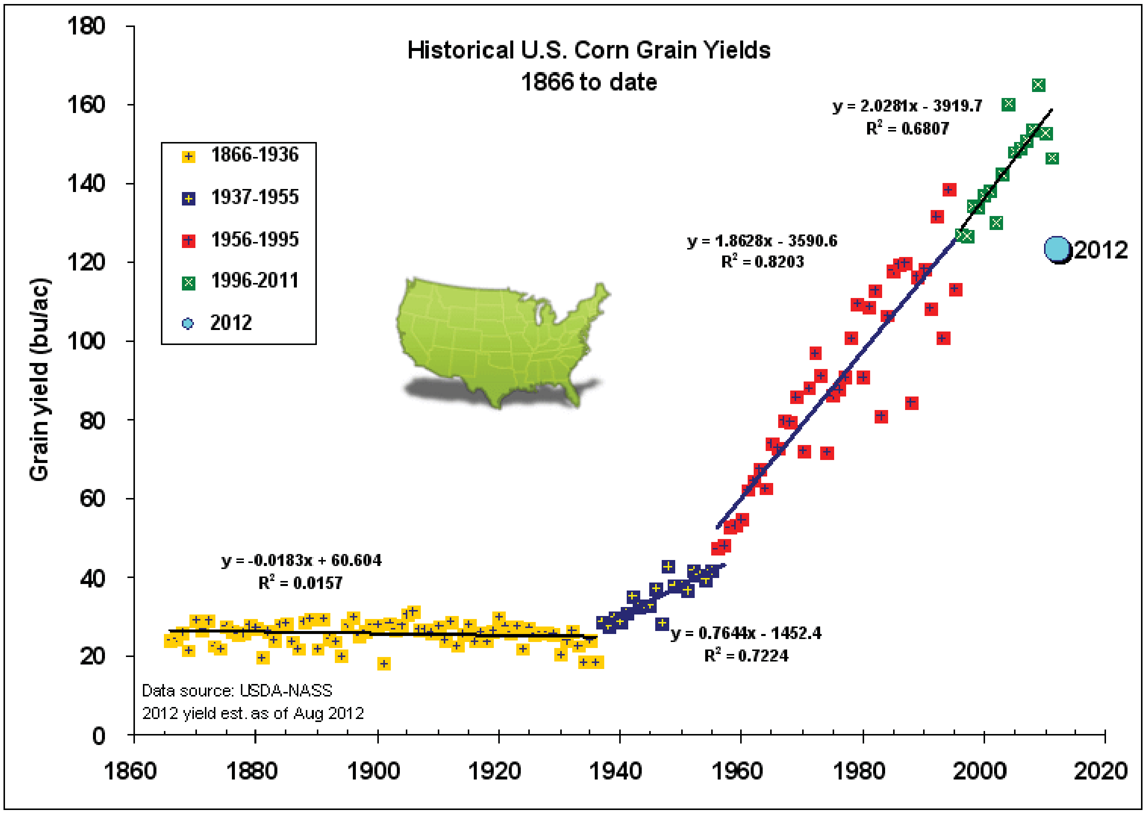

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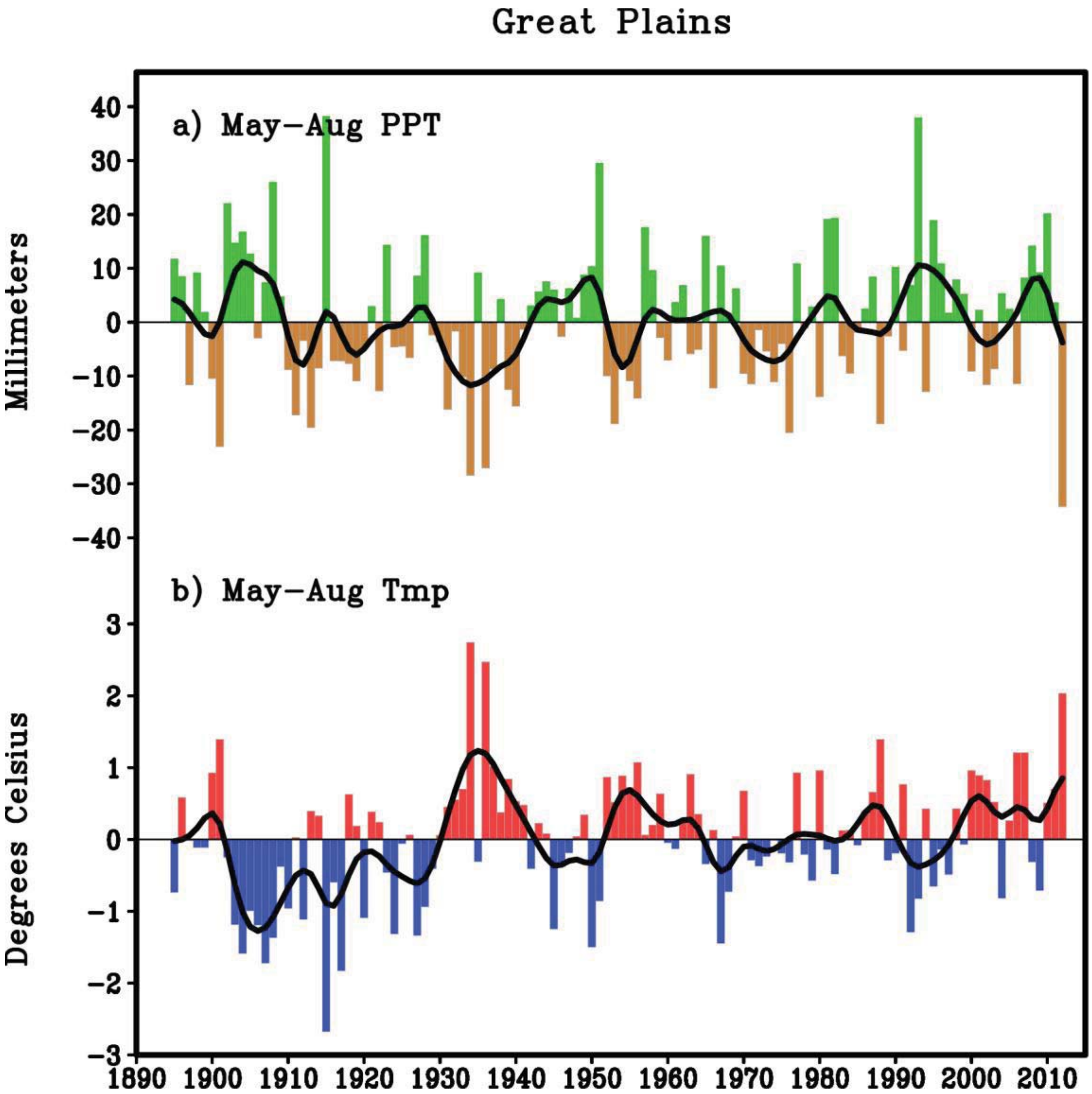

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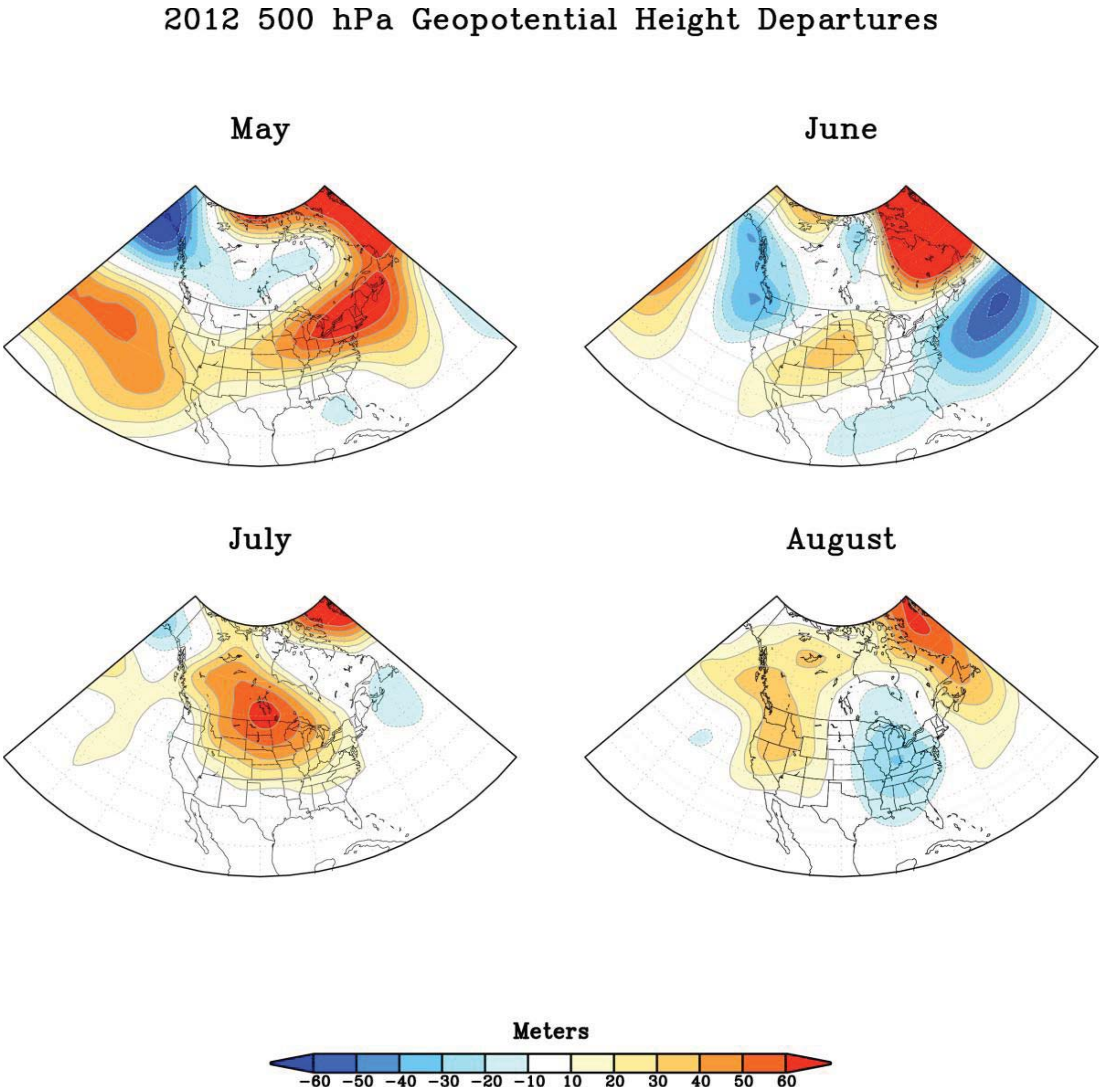

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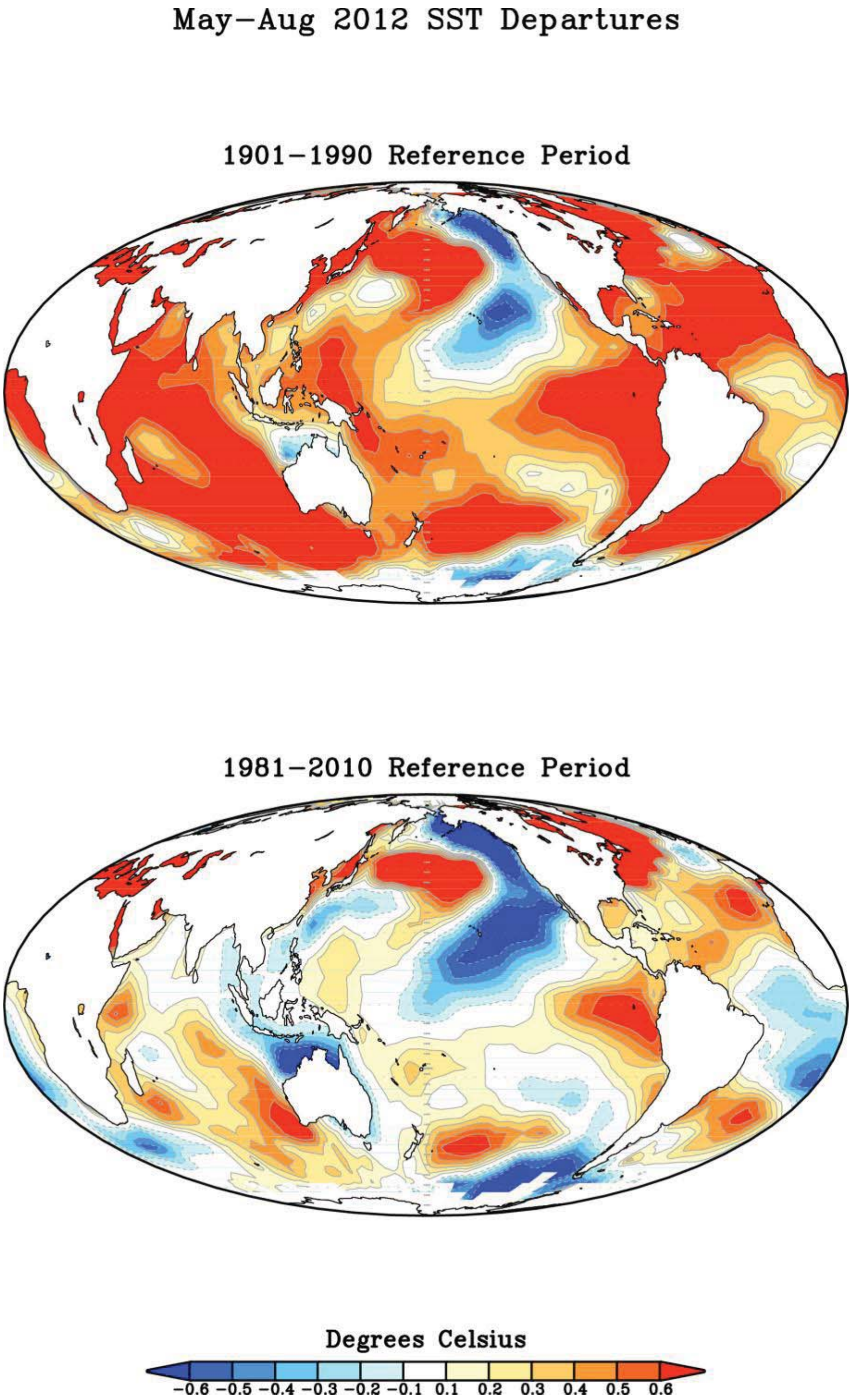

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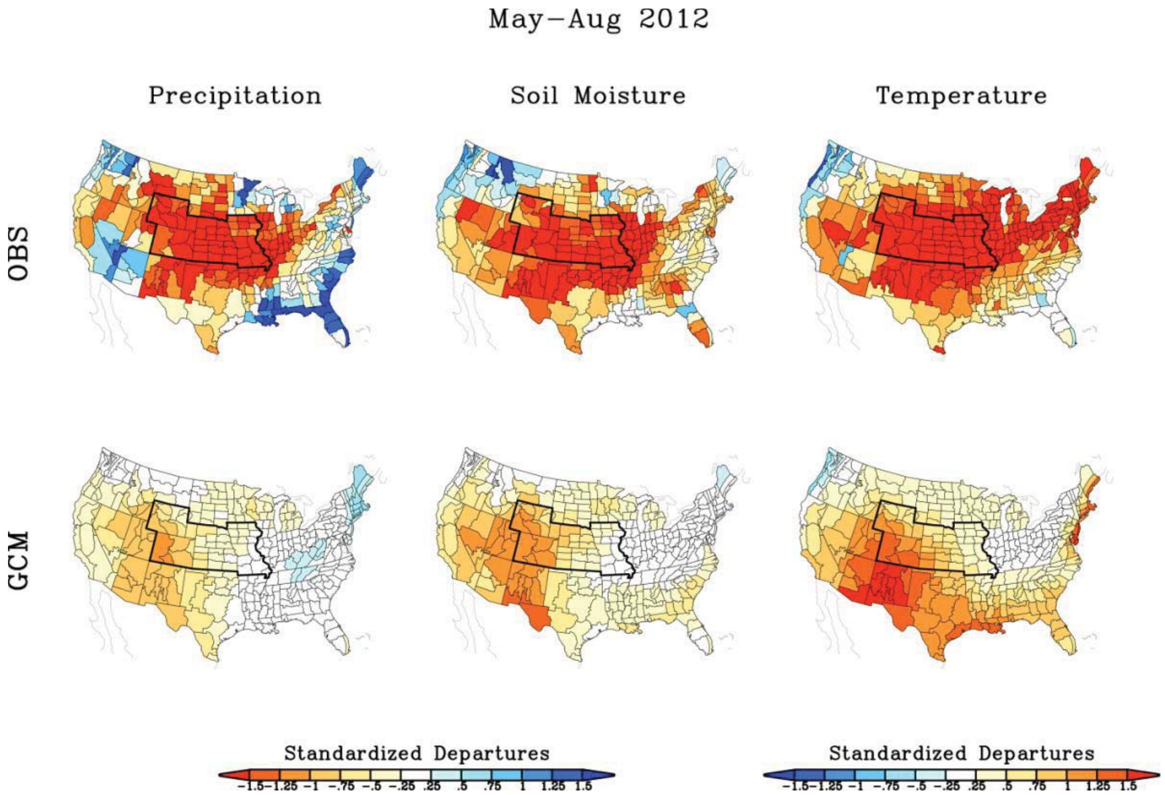

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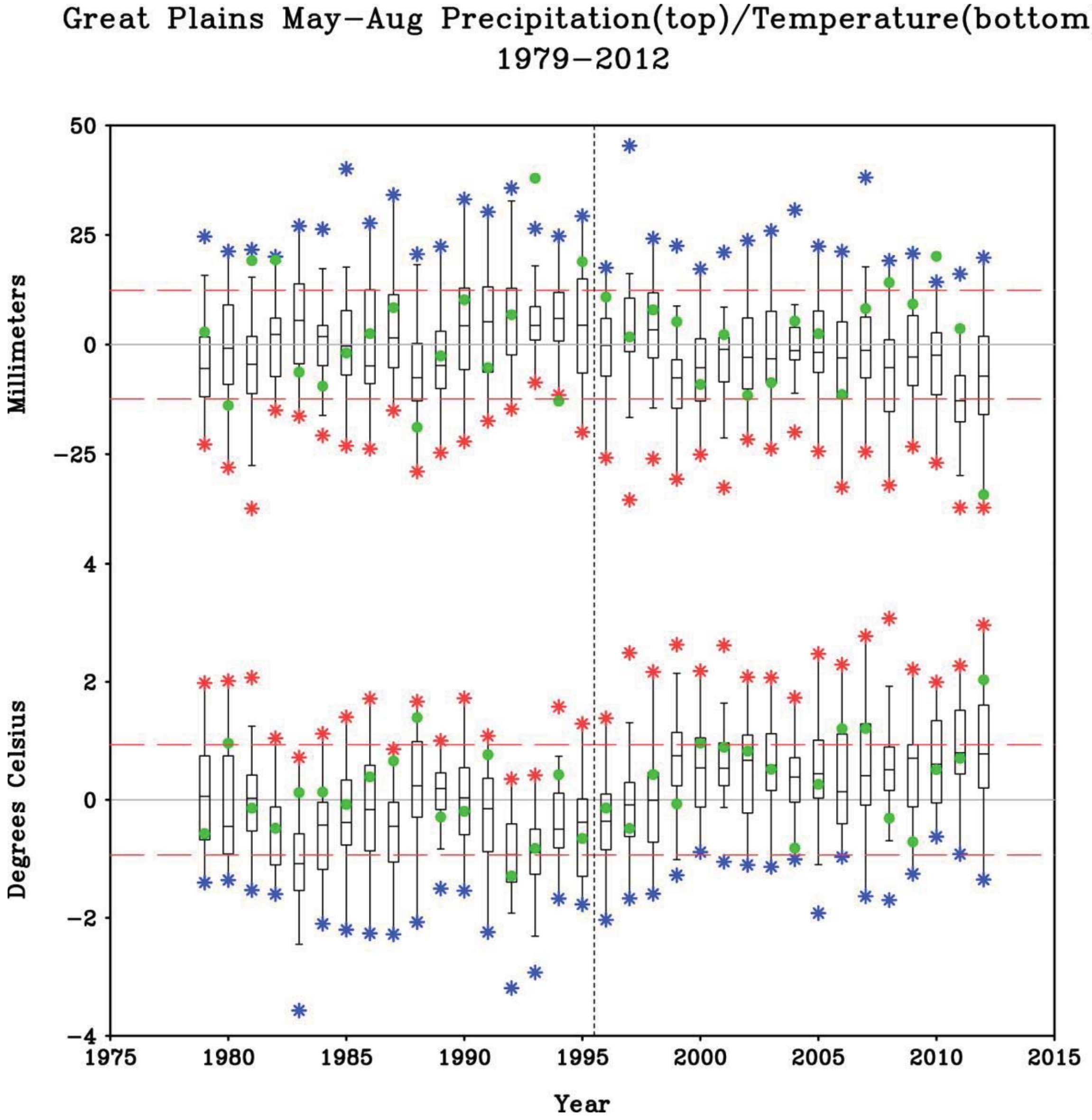

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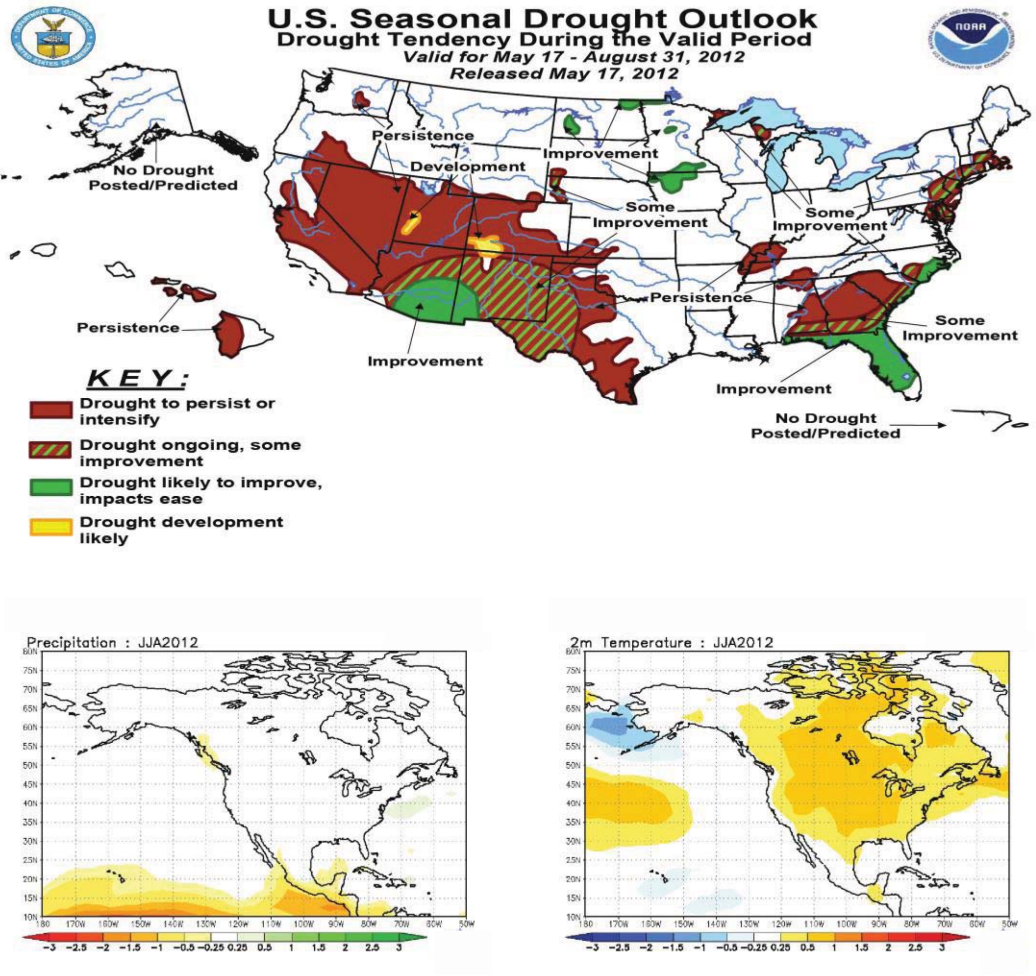

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