An Interpretation of the Origins of the 2012 Central Great Plains Drought

Assessment Report

NOAA Drought Task Force

Narrative Team

Lead: Martin Hoerling

Co-Leads: Siegfried Schubert & Kingtse Mo

20 March 2013

Composed by the “Narrative Team”[1] of the NOAA Drought Task Force[2] in partnership with the National Integrated Drought Information System (NIDIS)

Lead: M. Hoerling

Co-Leads: S. Schubert, and K. Mo

[1] A. AghaKouchak , H. Berbery, J. Dong, M. Hoerling, A. Kumar, V. Lakshmi, R. Leung, J. Li, X. Liang, L. Luo, B. Lyon, D. Miskus, K. Mo, X. Quan, S. Schubert, R. Seager, S. Sorooshian, H. Wang, Y. Xia, N. Zeng

[2] Organized by the NOAA Modeling, Analysis, Predictions and Projections Program (MAPP) of Office of Oceanic and Atmsopheric Research/Climate Program Office

Published March 2013

NATIONAL INTEGRATED DROUGHT INFORMATION SYSTEM

This report is available online at: www.drought.gov/drought/content/resources/reports

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An Interpretation of the Origins of the 2012 Central Great Plains Drought

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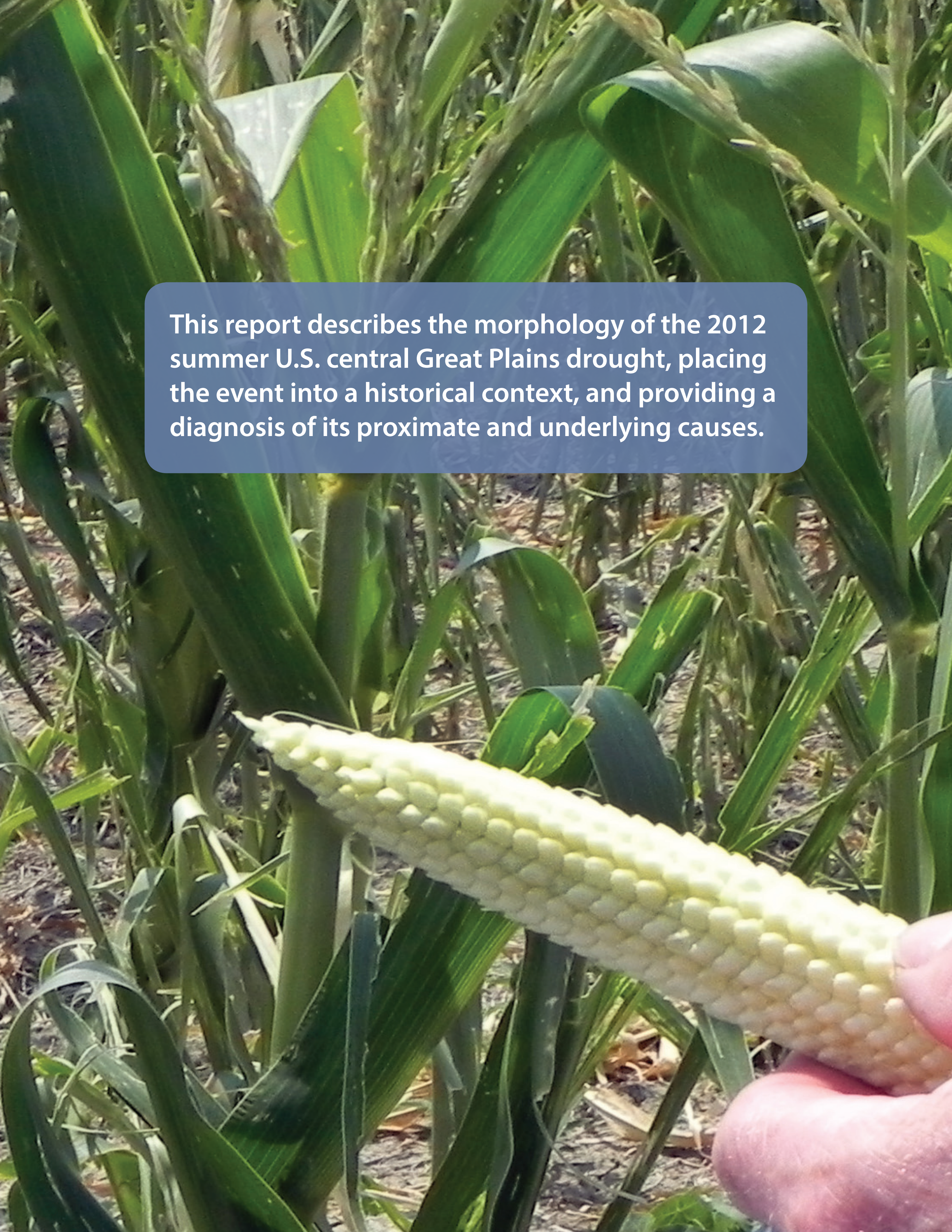

This report describes the morphology of the 2012 summer U.S. central Great Plains drought, placing the event into a historical context, and providing a diagnosis of its proximate and underlying causes.

Executive Summary

This report describes the morphology of the 2012 summer U.S. central Great Plains drought, placing the event into a historical context, and providing a diagnosis of its proximate and underlying causes. Precipitation deficits for the period May-August 2012 averaged over the central Great Plains were the most severe in the instrumental record since 1895, eclipsing the driest summers of 1934 and 1936 that occurred during the height of the Dust Bowl. The drought developed suddenly, with near normal antecedent precipitation during winter and spring over the Great Plains giving little forewarning of the subsequent failed rains. The event did not appear to be just a progression or a continuation of the prior year's record drought event that occurred over the southern Great Plains, but appeared to be a discrete extreme event that developed in situ over the central U.S. The proximate cause for the drought was principally a reduction in atmospheric moisture transport into the Great Plains from the Gulf of Mexico that normally provides the major source of water vapor for the region in summer. Processes that would provide air mass lift and condensation during the wet season over the Great Plains were mostly absent, including a lack of frontal cyclones in the early stages of drought development followed by a suppression of deep convection in mid-late summer owing to large scale subsidence and atmospheric stabilization.

Climate simulations and empirical analysis suggest that neither the effects of ocean surface temperatures nor changes in greenhouse gas concentrations produced a substantial summertime dry signal over the central Great Plains during 2012. Official seasonal forecasts issued in April 2012 did not anticipate this widespread severe drought. Above normal temperatures were, however, anticipated in climate models, though not the extreme heat wave that occurred and which was driven primarily by the absence of rain. Our integrative assessment of historical data, climate simulations, and seasonal forecasts thus paints a picture of an extreme drought event that may not have had extreme forcing as its cause. The interpretation is of an event resulting largely from internal atmospheric variability having limited long lead predictability. This is a characteristic quite different from that of the prior year's southern Plains drought that spanned October 2010-August 2011, and for which appreciable early warning capability existed owing to a strong sensitivity of that region to La Niña conditions. The outcome and value of such an assessment, beyond scientific merits of better understanding what produced the 2012 drought, is two-fold. It clarifies whether such drought could have been anticipated, and it suggests investments that may lead to better guidance on mitigating effects of future drought. Assessments of this sort help inform scientific pathways for creating more actionable information for stakeholders that are vulnerable to drought-related hazards, even when forecast skill is expected to be low.

Absent were the usual abundance of slow soaking rain systems and evening thunderstorms that characterize Great Plains climate from May through August, and as a result surface moisture conditions greatly deteriorated.

The Drought's Morphology

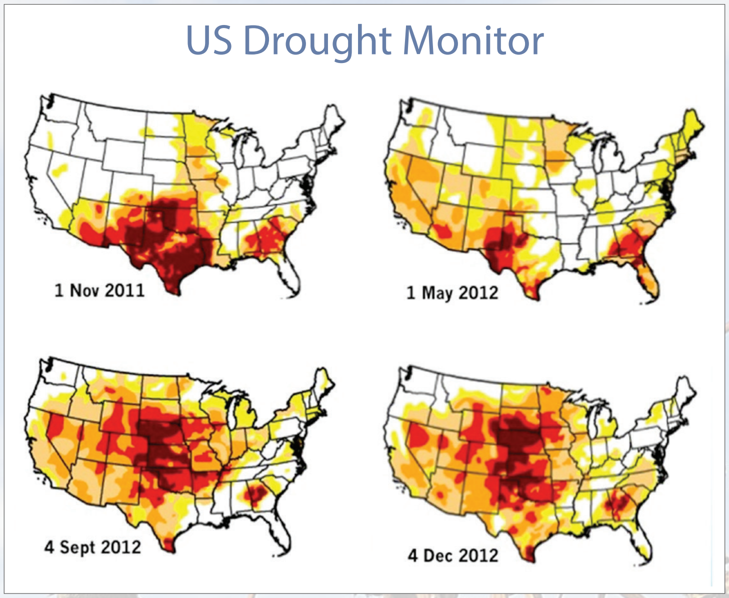

Figure 1. *U.S. Drought Monitor* maps for select periods during 2011-12. First color level (D0, yellow) denotes abnormally dry, and last color level (D4, dark red) denotes exceptional drought. See http://droughtmonitor.unl.edu for more details.

Drought conditions developed rapidly over the central Great Plains during late spring 2012, and intensified in summer. The tracking of drought severity via the U.S. Drought Monitor revealed extreme drought to be initially confined to the southern Plains in November 2011, a remnant of the record setting drought of Texas and Oklahoma that began in late 2010 (Fig. 1, top left). In Fall 2011, only a narrow swath of moderate drought extended northward thru eastern Kansas to Minnesota, and no extreme drought existed over the central Plains. While some concerns existed that the southern Plains drought might expand northward into the grain belt, little indications to this effect were initially observed. Indeed, much of the central Great Plains became drought-free by May 2012 (Fig. 1, top right), and considerable recovery was even occurring over the Southern Plains. There were also concerns about the possible effects of unusually high surface temperatures over the Great Plains during March on soil moisture conditions. Nonetheless, estimates of the monthly averaged column soil moisture[1] over the contiguous US for April did not reveal extreme soil moisture deficits over the central Great Plains, with conditions resembling the map of the 1 May U.S. Drought Monitor. But then the expected rainy season failed. Absent were the usual abundance of slow soaking rain systems and evening thunderstorms that characterize Great Plains climate from May through August, and as a result surface moisture conditions greatly deteriorated. By early September (Fig. 1, bottom left), estimates of surface moisture conditions revealed that over three-quarters of the contiguous U.S. was experiencing at least abnormally dry conditions with nearly half of the region (the central Plains in particular) experiencing severe-unprecedented drought. In this way, the comfort of having entered late spring virtually drought-free was abruptly replaced by the distress of extreme drought. Conditions became comparable to those experienced a quarter-century earlier during 1988 by a previous generation of inhabitants, and the combination of rainfall deficits and high temperatures even rivaled those observed by their forebears during the Dust Bowl.

Consistent with the Drought Monitor maps, the Palmer Drought Severity Index (PDSI; Palmer 1965) for August 2012 (Fig, 2. left) identifies the core region of the drought to be the central Plains region, with the most extreme moisture deficits occurring over the western Plains. A central U.S. epicenter for the drought is also affirmed by the May-August standardized rainfall deficits (Fig. 2, middle) with -2 standardized departures being widespread from Colorado to Missouri.

Much of the dry region also experienced hot temperatures (Fig. 2, right). The combination of low rainfall and high temperatures is typically seen during summertime droughts over the central U.S.

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[1] *Monthly averaged column soil moisture is estimated routinely at CPC using a one-layer "bucket" model driven by monthly precipitation and temperature. See Huang et al. (1996) in Additional Reading.*

Surface Anomalies
May-Aug 2012
Versus 1895-2000 Longterm Average

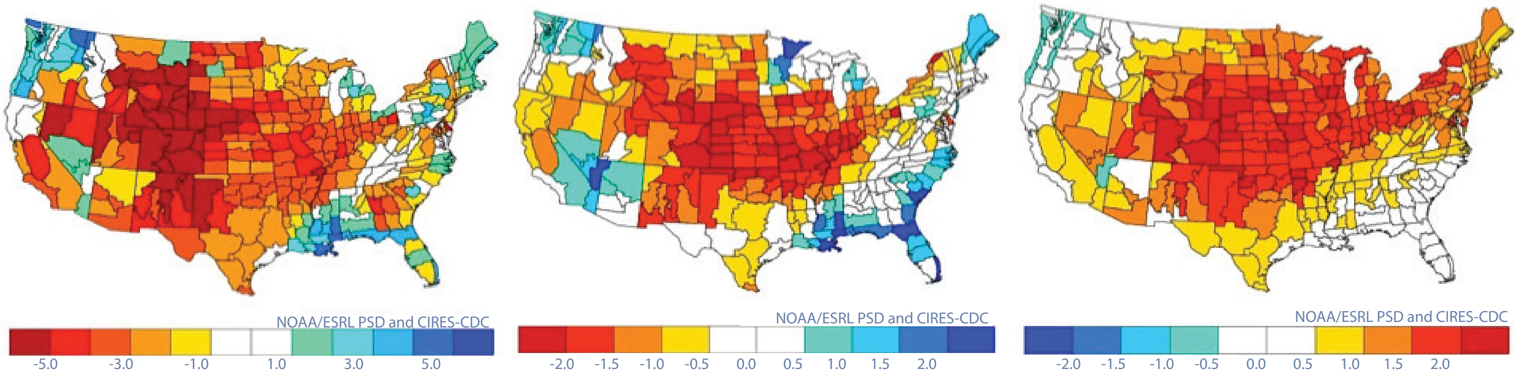


Figure 2. The Palmer Drought Severity Index (PDSI) for August 2012 (left), the standardized precipitation departures for May-August 2012 (middle), and the surface temperature departures for May-August 2012 (°C, right). Data source is the NOAA U.S. Climate Divisions.

The historical relationship between rainfall and temperature deficits (Fig. 3) suggests, however, that 2012 could have been appreciably warmer (perhaps by ~1°C) given the severity of rainfall deficits alone. The scatter plot shows that 2012 was the driest summer in the historical record (-34 mm departure), though the temperature anomaly of +2°C was exceeded by two prior summers -- 1934 and 1936. Indeed, although the 2012 summer experienced less rainfall over the central Great Plains than in either 1934 or 1936, those years were about 0.5°C warmer.

Daily rainfall time series from observations taken at weather stations across the Great Plains (Fig. 4) illustrate the timing of drought onset. Consistent with the Drought Monitor tracking, the event commenced suddenly in May. Further, the core period of the drought appears to be May-August 2012. The daily time series reveal that after a period of near to above normal winter and early spring precipitation at most stations over the central Great Plains, rains abruptly failed in May. For instance, there were virtually no rainy days at Cedar Rapids, IA during May. Likewise, July saw no measurable rain at Omaha, NE. Both are climatologically wet months, so the lack of any rain was a severe loss. Likewise, the western Plains sites 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 2011 drought, accumulated above normal rainfall for the prior 6-month period through summer 2012. This greatly improved their soil moisture balance, and the Drought Monitor indicated northeast Texas to

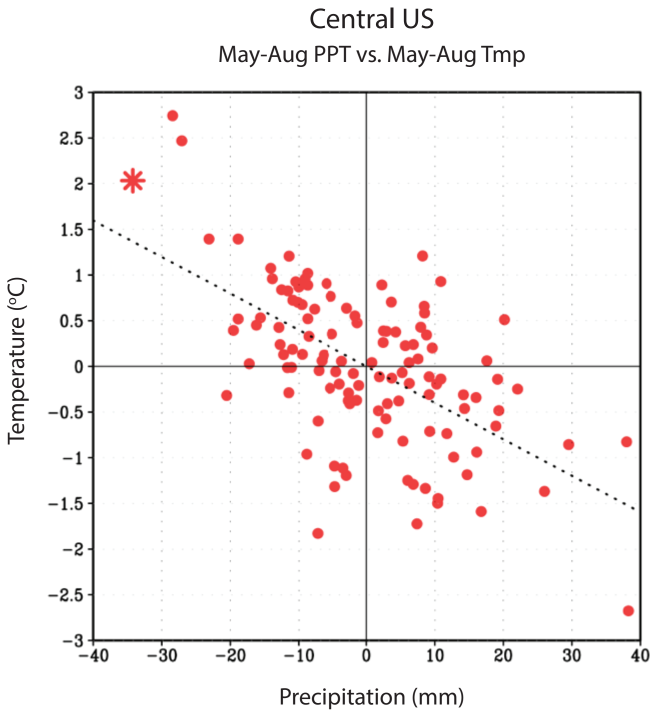


Figure 3. The observed relationship between May-August averaged rainfall departures (mm, x-axis) and surface temperature departures (°C, y-axis) over the U.S. central Great Plains. Reference period is 1895-2012. The 2012 departures are -34mm, and +2.1°C, and shown by the red asterisk. Dashed line is the linear relation between temperature and precipitation variability. Note that for extreme dry conditions, temperatures are appreciably warmer than predicted by this linear fit. May-August departures are averages over the multi-state region (WY, CO, NE, KS, MO, IA). Data source is the NOAA U.S. Climate Divisions.

be drought-free in May 2012. Oklahoma City also showed strong signs of recovery from the 2011 drought with above average rains falling through May 2012, but skies cleared and June through July was virtually rain-free.

As of this writing, drought conditions that established by the end of summer 2012 remain mostly in place. Neither the termination nor the duration of this drought is yet known. The climatological rainfall, illustrated by the smooth curves in Fig. 4, reveals the period from September thru February to be normally dry over central Plains. Thus, it is unlikely that sufficient precipitation could materialize in that period to redress the severe deficits accumulated during the normally wet season of late spring/summer. In this sense, while in hindsight we might speak with confidence about the time of drought onset, judgment on its duration must await the outcome of the 2013 wet season.

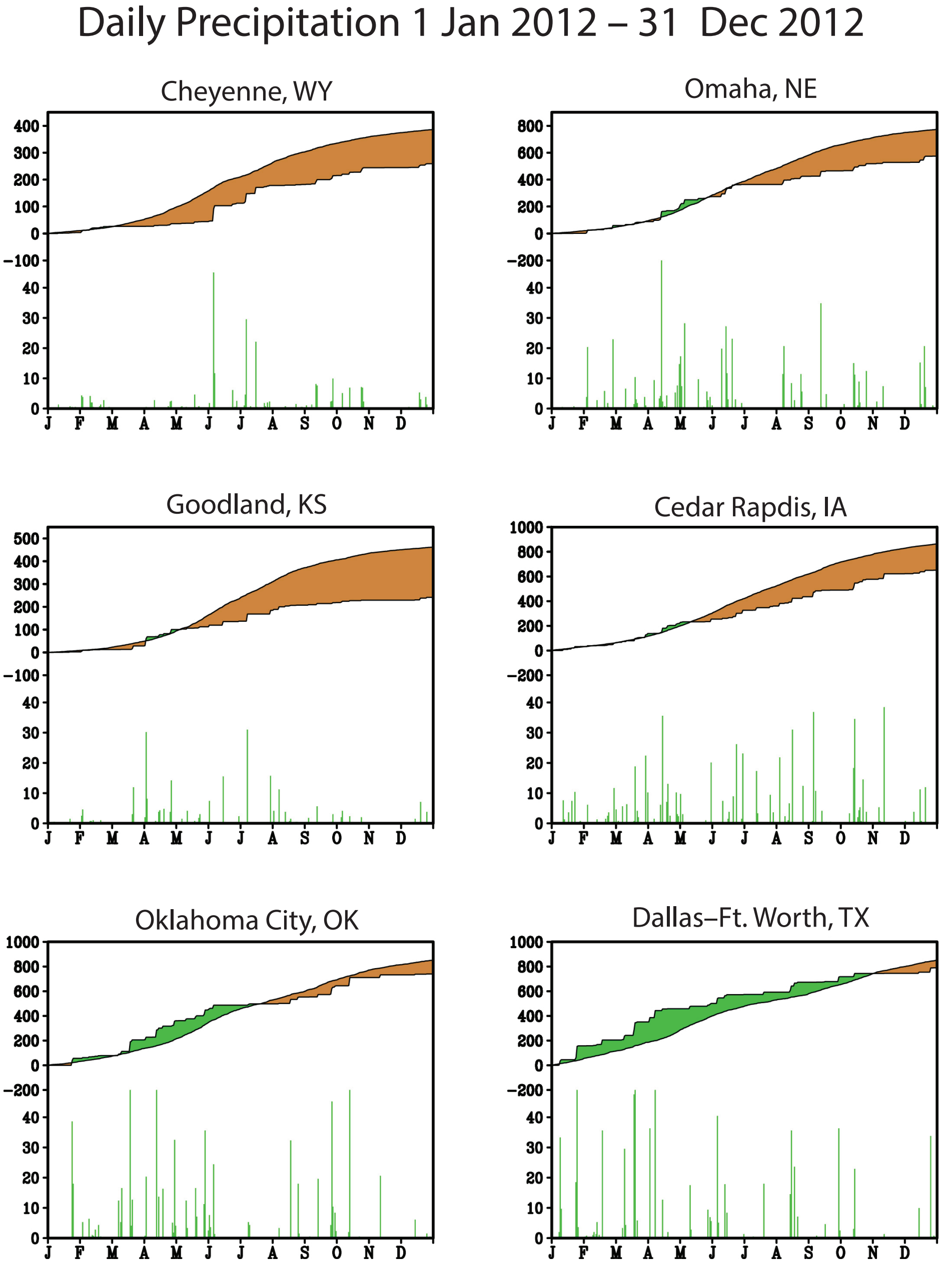
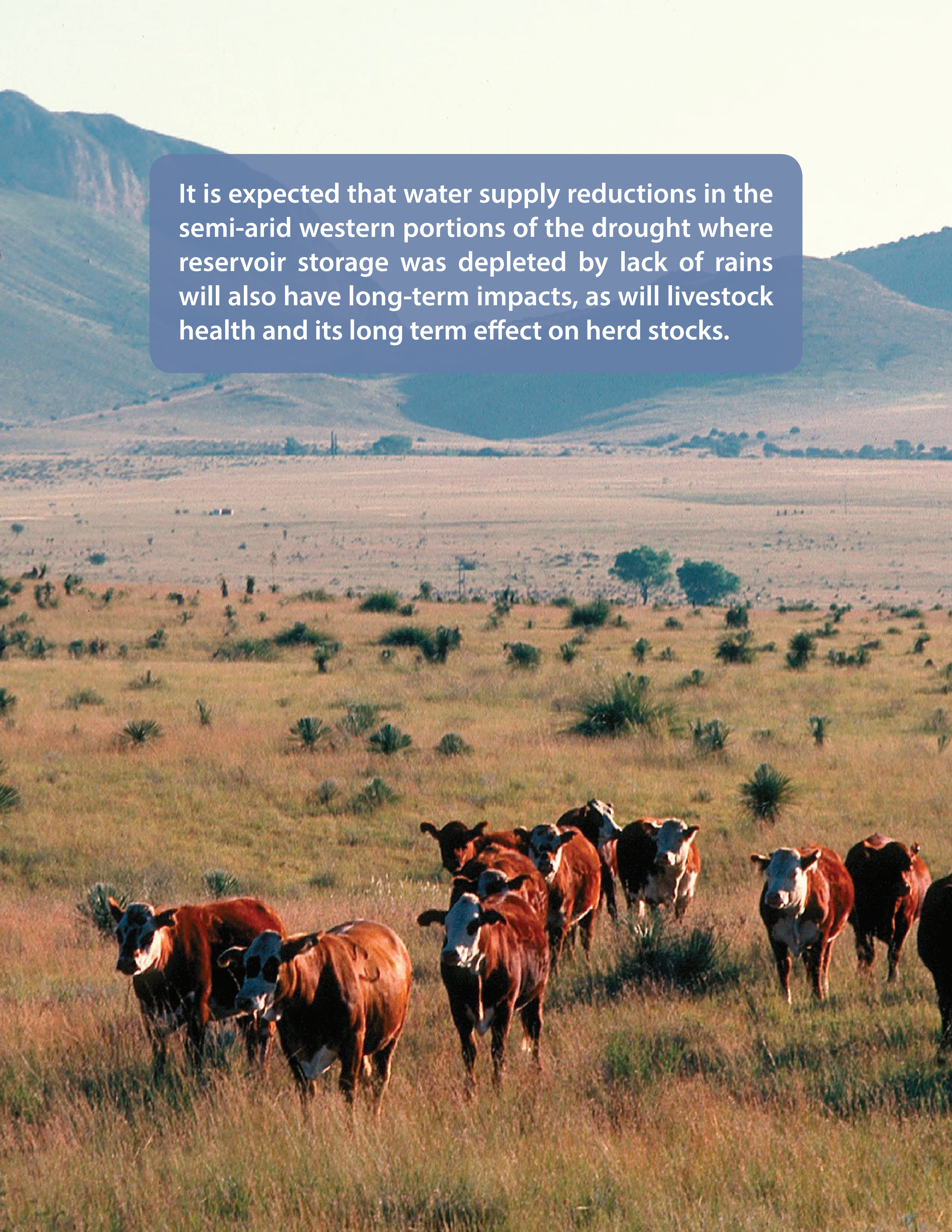


Figure 4. Daily precipitation time series during 2012 for indicated stations. For each station, top panels show the climatological precipitation (smooth curve), the actual 2012 precipitation, and their difference (color shading; brown denotes a deficit, green a surplus). Lower panels show the occurrences of daily precipitation events. Data source is NOAA Climate Prediction Center.



It is expected that water supply reductions in the semi-arid western portions of the drought where reservoir storage was depleted by lack of rains will also have long-term impacts, as will livestock health and its long term effect on herd stocks.

The 2012 Drought's Impact

The suggestion that 2012 was a "flash drought", at least concerning its rapid onset over the central Plains, is supported by the above-mentioned time series of daily rainfall and the sequence of drought monitor maps. Impacts also emerged quite swiftly. Loss estimates by the end of July 2012, before drought severity peaked, were $12B (www.kansascityfed.org/publicat/mse/MSE_0312.pdf). It remains to be seen if the economic effects of the 2012 drought will approach prior events, including the 1988 drought that inflicted $78 billion in losses and the 1980 event that caused $56 billion in losses (adjusted for inflation to 2012 dollars) (www.ncdc.noaa.gov/billions/events.pdf). Broad sectors were affected, and continue to be affected, by the 2012 drought. Notable for the swiftness of impacts was the reduction in crop yields caused by lack of timely rains, as discussed further below. Also, curtailment of commerce on major river systems occurred owing to reduced water flow, a situation that continues many months after the drought. It is expected that water supply reductions in the semi-arid western portions of the drought where reservoir storage was depleted by lack of rains will also have long-term impacts, as will livestock health and its long term effect on herd stocks.

Preliminary USDA estimates of farm and food impacts of the 2012 drought (www.nass.usda.gov) indicate corn yield (per acre of planted crop) was about 123 bushels. This is 26% below the 166 bushel yield expectation that the USDA had at the commencement of the growing season. Likewise, soybean yields were estimated at 39 bushels, 10% below the early season projection of 44 bushels. This was the lowest soybean yield since 2003. Owing to the late onset of drought conditions over the Central Plains, wheat production was not significantly impacted. Drought conditions adversely impacted pasture growth and range land quality, which when combined with elevated corn and soymeal prices, adversely affected livestock and draft capacity, a situation that will unfold over several years (www.fao.org/wairdocs/ILRI/x5446E/x5446e02.htm).

An additional comment regarding corn yields during 2012 helps to illustrate the severity of the drought's impact. The USDA indicated that the 2012 yield of about 123 bushels per acre was the lowest since 1995. But even that confirmation of greatly compromised production fails to convey the severity of crop failure. Fig. 5 shows the time series of U.S. corn yield (per acre) 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*. Figure 6 shows the annual yield departures (computed relative to appropriate trend lines). In terms of absolute loss in bushels of corn production, no single year since 1866 experienced so large a curtailment as occurred during 2012. The 43 bushel/acre productivity loss, though only 26% less than expected by USDA, equates to the total U.S. productivity of 1960. If measured as a % deficit as is shown in Fig. 6, then 2012 was about the second most severe curtailment of corn production on record, eclipsed only by 1901, and comparable to the decline in 1936.

It is from such historical data that the USDA offered its initial expectation, in spring 2012, that annual corn yield would be about 166 bushels per acre. That outlook was based mainly on extrapolating the recent trend in corn yields. This is a reasonable prediction given that year-to-year variations are mostly small relative to the trend "signal" of relentlessly improved yields. Of course, these variations—relative to trend—are mostly the result of interannual climate variability. The question is thus whether this drought could have been anticipated, and if actionable prediction of climate impacts on crop yield might have been rendered.

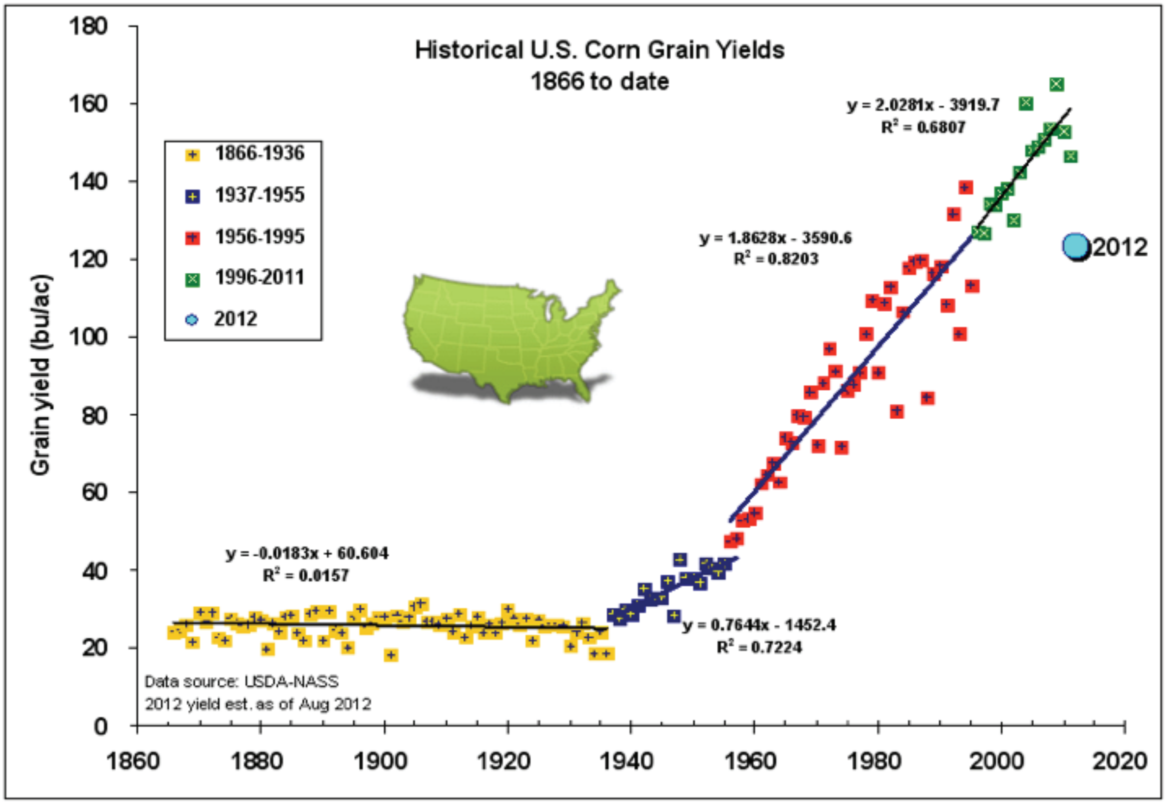


Figure 5. Historical U.S. corn yields from 1866 to 2012 (bushels/acre). Linear fit to different segments of the time series shown in solid lines, including regression formula. The 2012 yield is plotted in the blue circle, based on August estimates. Subsequent data revised the 2012 yield downward to about 123 bushels. Data source is USDA.

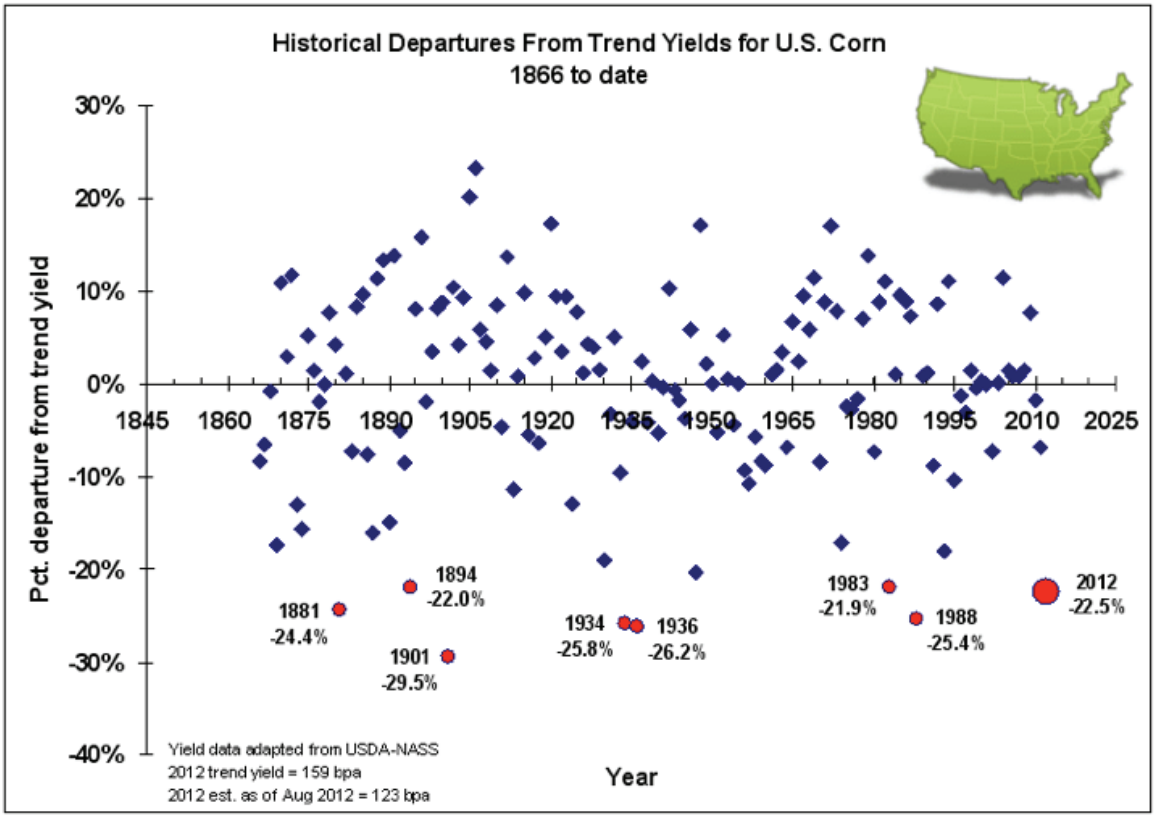
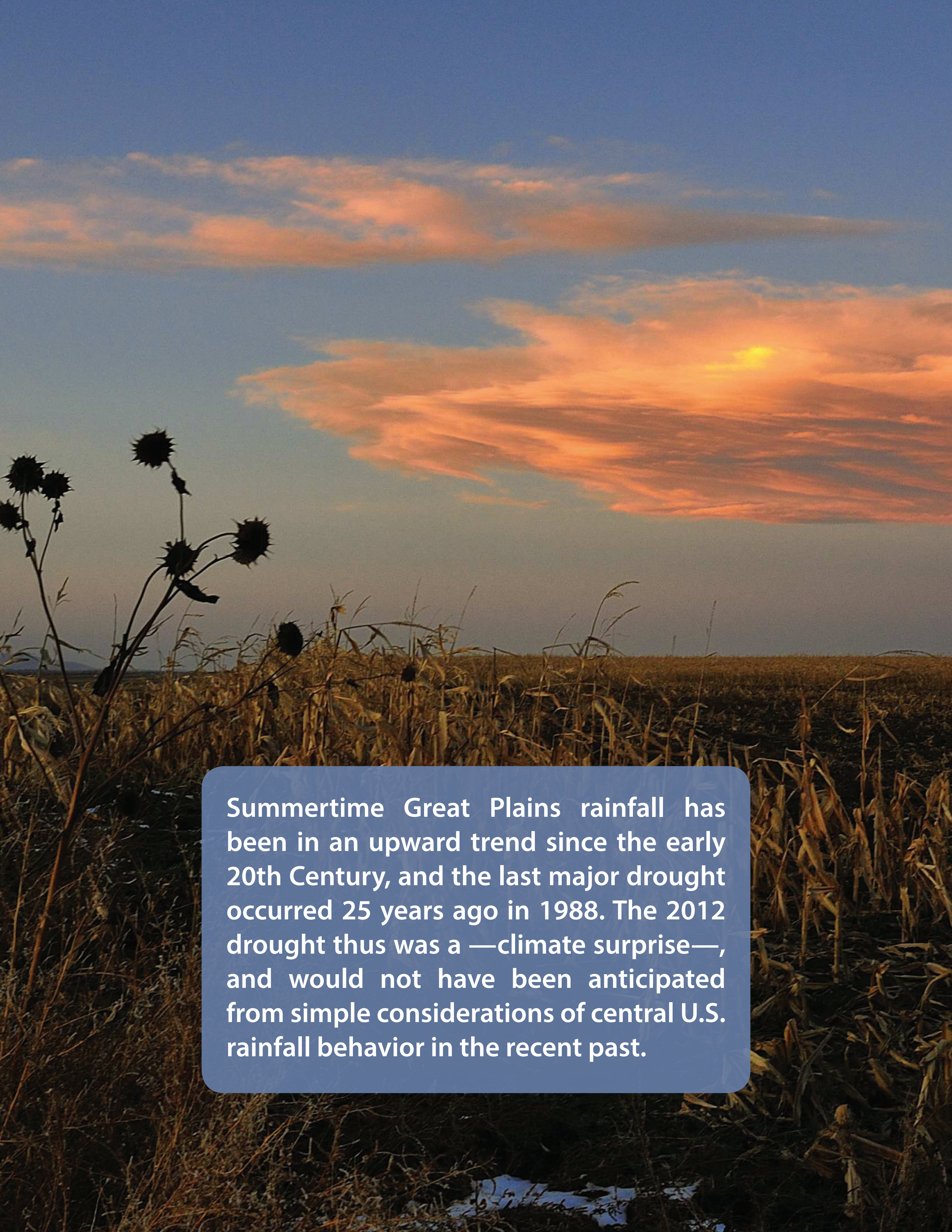


Figure 6. Historical U.S. corn yield deficits from 1866 to 2012 (bushels/acre). Deficits computed relative to the trend lines of Fig. 1. All years having greater than a 20% deficits are highlighted and shown with red circles. The 2012 yield deficit is plotted in the large red circle, based on August estimates (the circle sizes are not proportional to deficit magnitudes). Subsequent data through the end of the growing season revised the 2012 yield deficit downward to about -26%. Data source is USDA.

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.



Summertime Great Plains rainfall has been in an upward trend since the early 20th Century, and the last major drought occurred 25 years ago in 1988. The 2012 drought thus was a —climate surprise—, and would not have been anticipated from simple considerations of central U.S. rainfall behavior in the recent past.

The Historic 2012 Drought and its Antecedent Conditions

By measures of rainfall deficits, the summer of 2012 was an unprecedented year. Fig. 7 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 2.7 standardized deficit.

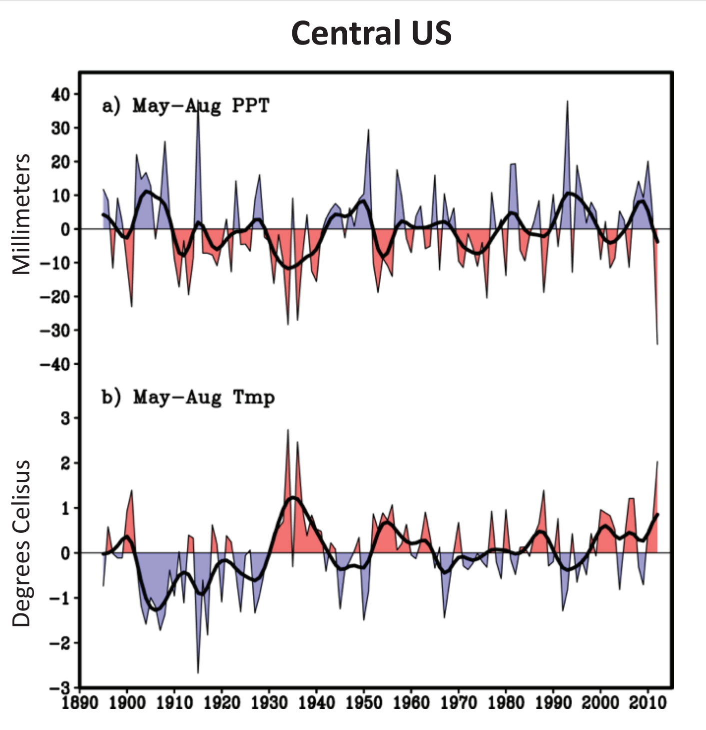


Figure 7. 1895-2012 time series of May-August central Great Plains rainfall departures (mm, top) and surface air temperature departures (°C, bottom). Reference period is 1895-2011. Black curve is a 9-point Gaussian filter. The area is comprised of the 6-State region of WY, CO, NE, KS, MO, and IA. Data source is the NOAA U.S. Climate Divisions.

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, have been suggested to have resulted from unique conditions of that era. 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. Summer rainfall has shown a general upward trend in the recent period, and the last 2 decades were noted more by their abundant summer rainfall, than by severe deficits. The 2012 drought thus appears to be a climate surprise from such empirical considerations alone.

But did early warning signs exist, for instance in the sequence of seasonal events that immediately preceded the 2012 drought? Figure 8 presents estimates of the seasonal soil moisture anomalies, based on the CPC one-layer "bucket" land surface water balance model. The derived soil moisture conditions are estimates for a column of about 1.6 meter depth, and though few representative measurements of actual soil moisture are available over the US, validation against in situ soil moisture data over Illinois has shown realistic variability in the derived product. Depletion of soil moisture associated with the prior southern Plains drought was especially evident over Texas and Oklahoma in Fall 2011. Soil conditions were also estimated to be dry over the northern Plains from Fall 2011 thru early spring 2012. By contrast, antecedent spring soil moisture over the central Plains regions of Missouri, Kansas, and Nebraska were mostly near normal. It is likely that unusually warm early spring temperatures over the Plains and upper Midwest dried soils, especially in the top layers, though this cannot be readily discerned from the column integrated estimates that are derived from the CPC one-layer land surface model. It is evident, however, that the distinguishing characteristic of the model-derived soil moisture for the U.S. was one of overall dryness by early Spring 2012,, whereas the central Great Plains had near normal soil moisture.

Figure 9 illustrates the seasonal precipitation anomalies for the 12-months that preceded May-August 2012. Much of the southern and central Great Plains experienced near normal precipitation during the period October 2011 thru April 2012. This precipitation significantly improved soil moisture conditions over the southern Plains by spring 2012 (see Fig. 8), and was responsible for the amelioration of drought severity over this region as indicated by the Drought Monitor (see Fig. 1). The question of how soil moisture conditions may have affected precipitation is difficult to assess from the empirical data alone, and it is unclear from this analysis alone what if any affect the dry soil conditions may have had upon the summer drought intensification. More will be said about that when various seasonal forecast systems are evaluated in section 6. Suffice it to state here that the region of most severe moisture deficits existing over the southern Plains during fall 2011 into winter 2012 experienced substantially above normal precipitation during the subsequent winter/spring 2012 period. Precipitation was thus mainly driving a recovery in soil moisture through spring 2012, whereas the antecedent deficiencies in soil moisture appeared not to inhibit precipitation processes.

There are additional lines of diagnosis from which one can examine the question of whether antecedent drought over the southern Plains in 2011 may have set in motion a sequence of unavoidable climate events that strongly determined the fate of subsequent central Plains summer rainfall. Here the instrumental record dating to 1895 is examined to probe for historical evidence on how southern Plains droughts typically evolve, and especially if there is any support to a hypothesis that these have a propensity to spread throughout the Great Plains regions as part of a typical life cycle. To address the extent to which droughts of the type that occurred in the central Great Plains during 2012 have exhibited robust precursors and coherent temporal and spatial evolutions, compositing methods are applied. From the historical time series, 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. Perhaps not surprisingly, 5 of these (1901, 2012, 1936, 1934, and 1988) also rank among the top 5 years suffering the most severe corn yield curtailment.

For these 9 historical cases, averages of precipitation for the 12 months preceding and the 12-months following their peak central Great Plains May-August rainfall deficits are calculated. The lead-lag composites of precipitation patterns for these cases (excluding 2012) are shown in Figs. 10 and 11, respectively. There is no appreciable dryness in the prior summer over Texas in this composite (Fig. 10, top left); 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. Likewise, the aftermath of central Great Plains summer drought also reveals a tendency for below average precipitation. These dry signatures are partly related to the fact that several of the individual driest central Plains summers in the composite were immersed within dry epochs than spanned much of the 1930s and also from the late-1940s through the mid-1950s. On average, however, the composite shows no appreciable rainfall anomaly over the central Great Plains in the summer following a severe drought (Fig. 11, lower right panel). In this empirical sense, the composite indicates little basis to expect that central Plains drought would necessarily recur during the subsequent summer.

Estimated 2012 Soil Moisture: MJJ 2011 to May - Aug 2012

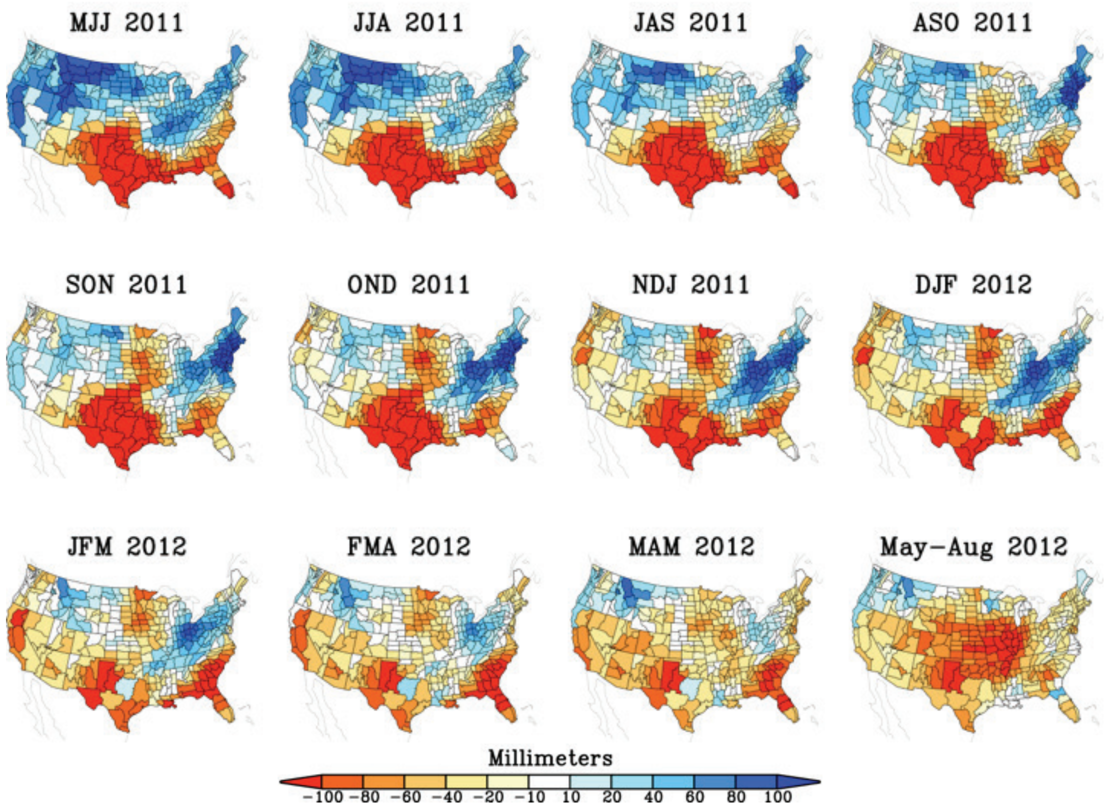


Figure 8. U.S. seasonal soil moisture anomalies (mm) during the 12-month period antecedent to the occurrence of dry May-August conditions over the central Great Plains (lower right panel). Soil moisture has been estimated by driving a one-layer bucket water balance model with observations of monthly temperature and precipitation. The data set spans 1948-present, and the method is described in Huang et al. (1996).

Observed 2012 PPT Departures: MJJ 2011 to May - Aug 2012

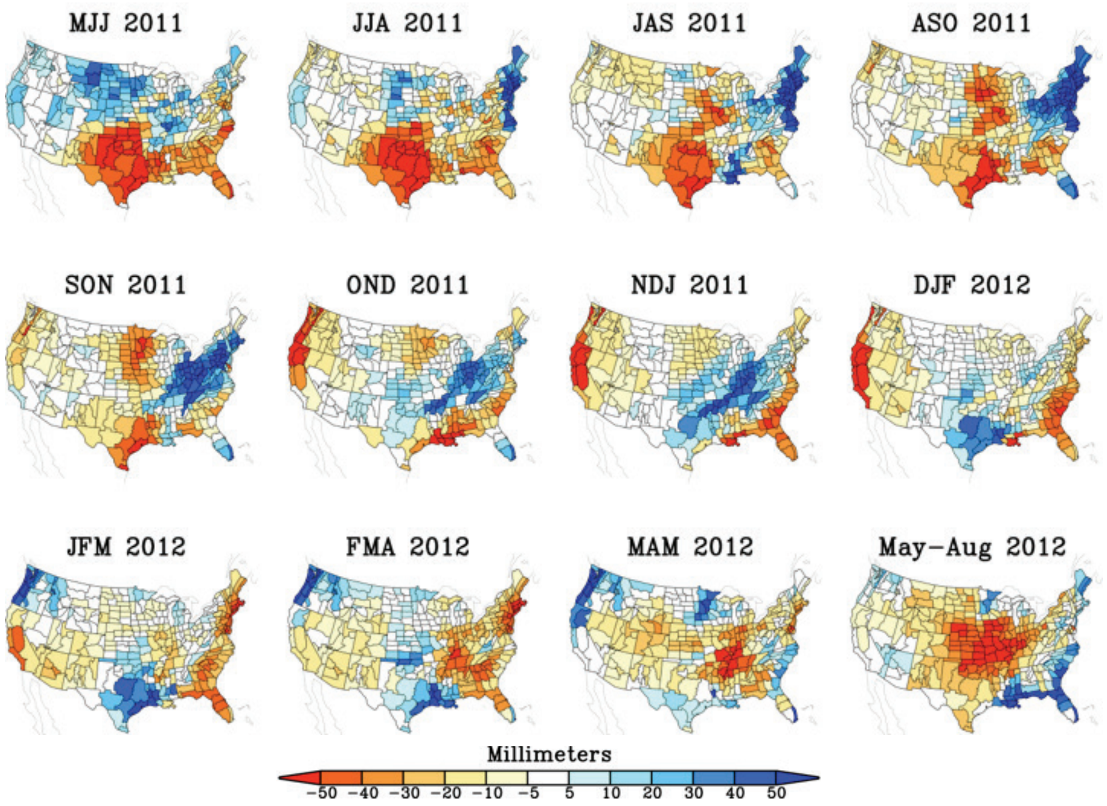


Figure 9. U.S. seasonal precipitation anomalies (mm) during the 12-month period antecedent to the occurrence of dry May-August conditions over the central Great Plains (lower right panel). Note also the prior severe rainfall deficits in summer of 2011 over the southern Great Plains. Data source is the NOAA U.S. Climate Divisions.

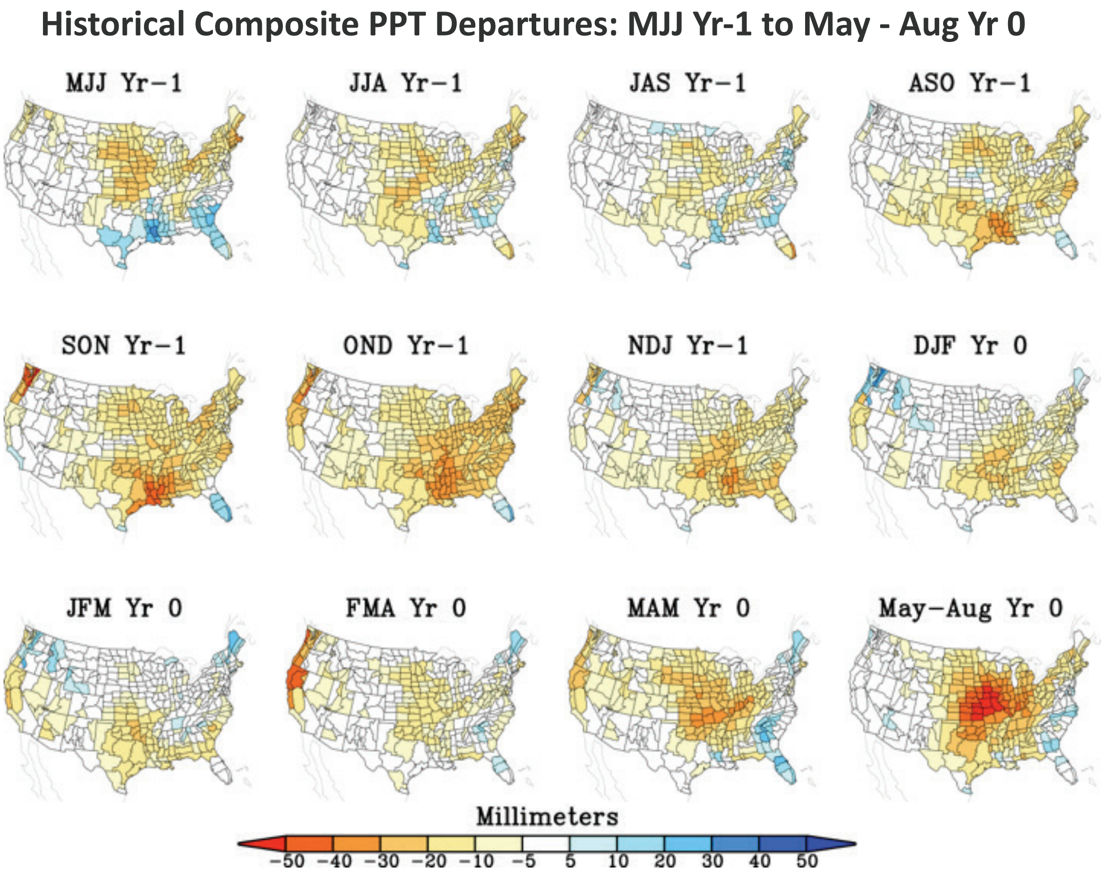


Figure 10. As in Fig. 9, except for the composite U.S. seasonal precipitation anomalies (mm) during the 12-month period antecedent to the occurrence of dry May-August conditions over the central Great Plains. Based on the average of the 9 driest May-August events during 1895-2011, including 1934, 1936, 1901, 1976, 1913, 1988, 1953, 1911, and 1931. Data source is the NOAA U.S. Climate Divisions.

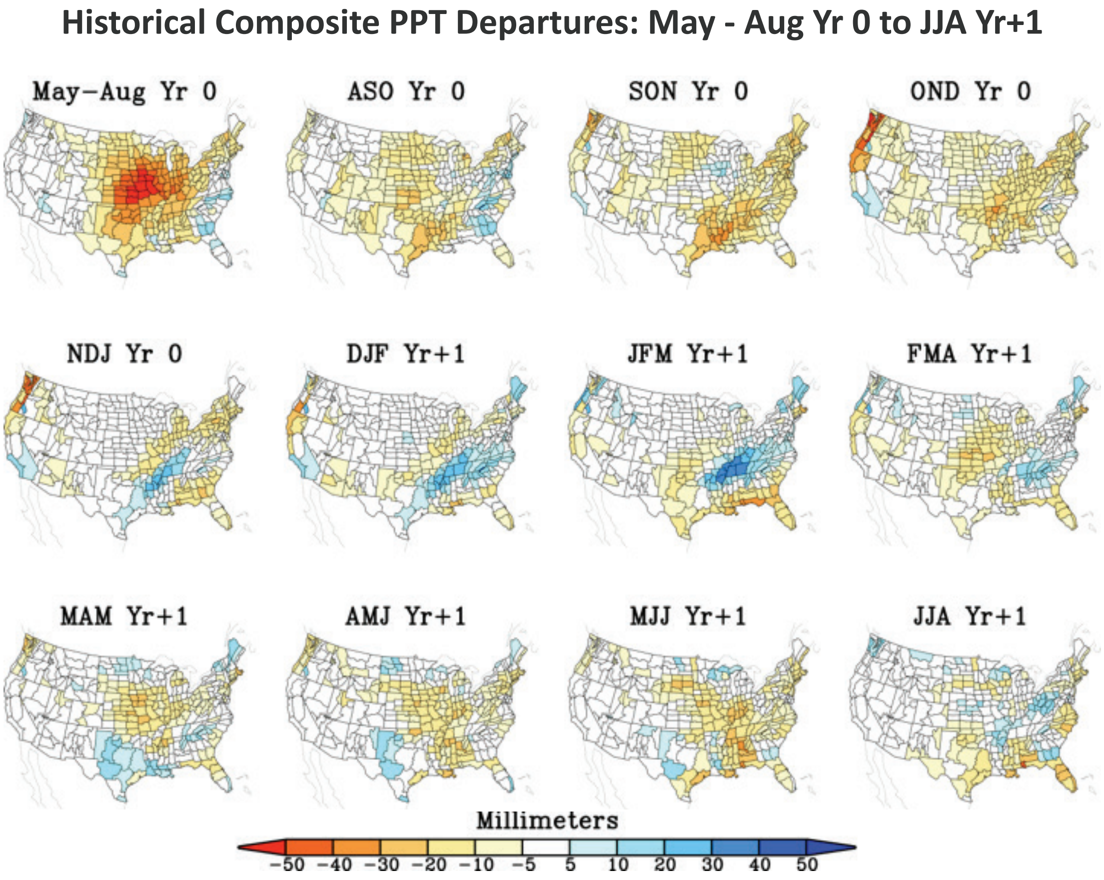
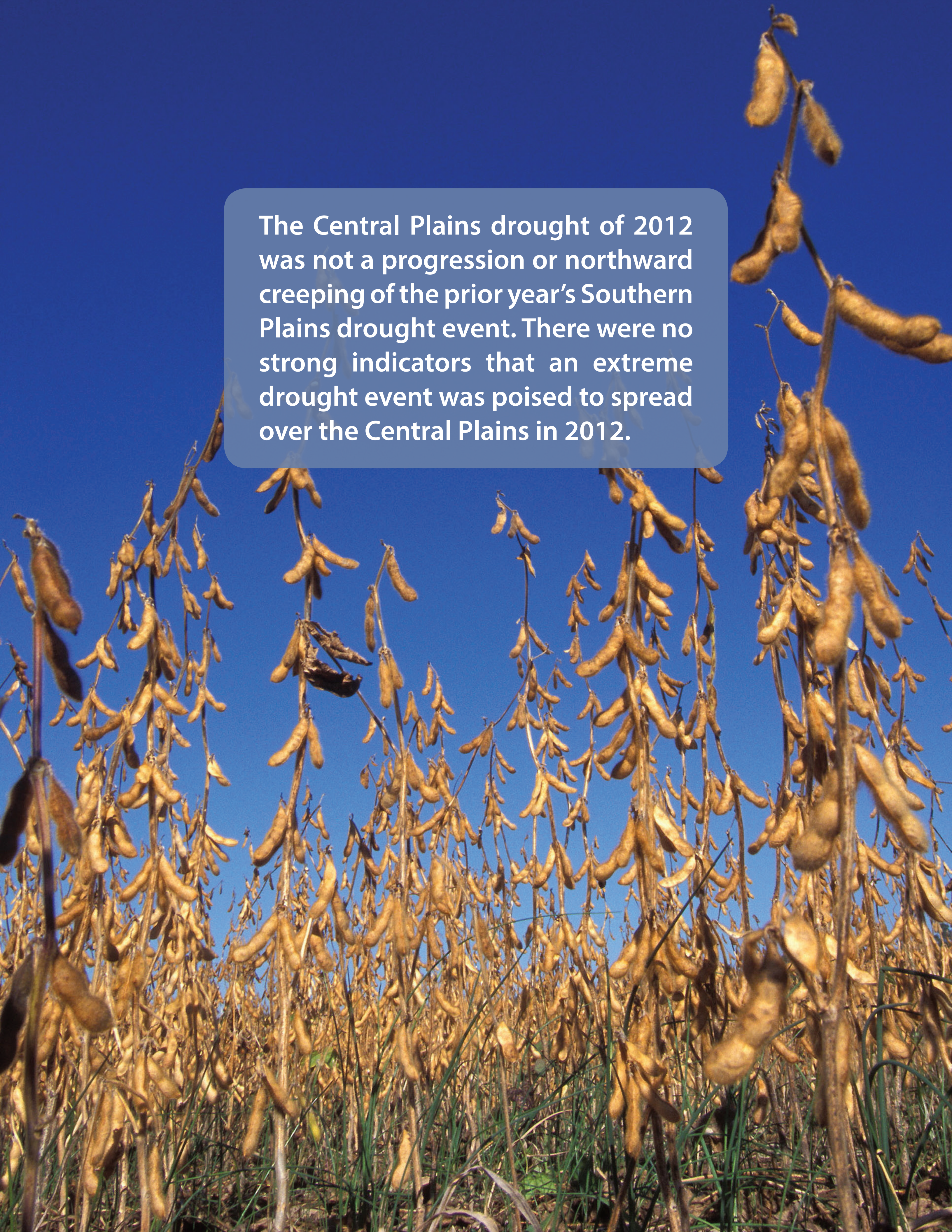


Figure 11. As in Figure 10, except for the composite U.S. seasonal precipitation anomalies (mm) during the 12-month period subsequent to the occurrence of dry May-August conditions over the central Great Plains. Based on the average of the 9 driest May-August events during 1895-2011, including 1934, 1936, 1901, 1976, 1913, 1988, 1953, 1911, and 1931. Data source is the NOAA U.S. Climate Divisions.



The Central Plains drought of 2012 was not a progression or northward creeping of the prior year's Southern Plains drought event. There were no strong indicators that an extreme drought event was poised to spread over the Central Plains in 2012.

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.

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 provide little 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.

A principal source of water vapor in summer over the central U.S. is the Gulf of Mexico region, with vapor-laden air transported inland and northwards to the continent's interior by mean southerly winds. Figure 12 illustrates this latter feature using the long-term mean 700 hPa meridional (north-south component) wind (top right) which shows a peak 2 m/s magnitude immediately on the coast of southwest Texas. This is partly related to mean transport linked to the clockwise air motion around the subtropical high located over the Atlantic Ocean. The influx is also related to the integrated effects of migratory mid-latitude storm systems, especially in the springtime when they exhibit a geographically preferred cyclogenesis in the lee of the southern Rocky Mountains and then track northeastward to the Great Lakes. It is in association with the circulation around such storms that Gulf of Mexico moisture is intermittently, but strongly, drawn northward. These mean and transient features are thus primarily responsible for the influx of moisture that maintains the axis of high 700 hPa specific humidity located in the central and western Great Plains (top left) (though this moisture is also related to the nocturnal low level jet in the western Great Plains).

During late spring/summer 2012 the typical northward 700 hPa meridional wind along the Gulf Coast was much reduced (Fig. 12 bottom right). The seasonal mean anomaly of about -1 m/s (anomalous equatorward flow) was 50% of the magnitude of the typical northward flow. There was thus an appreciable reduction in the typical moisture transport into the continent. Consistent with this, the summertime 700 hPa specific humidity was anomalously low in the Great Plains (bottom left). Departures of about -0.5 g/kg over the Great Plains were on the order of a 10% reduction of climatological water vapor content. Of course, the general absence of migratory low pressure systems across the central Plains would have entailed a similar lack of large scale air mass lifting and precipitation, while simultaneously reducing the influx of Gulf moisture.

Analysis of relative humidity provides another indication of the extent to which dryness prevailed in the lower troposphere during summer 2012 over the Great Plains. The top panels of Fig. 13 show the climatological relative humidity at 850 hPa (left) and 700 hPa (right). Note in particular the 700 hPa axis of high relative humidity that normally characterizes the Great Plains region from northern Texas to Canada (top right). This feature was essentially absent during summer 2012, with departures of -10% running from northern Texas to Montana (lower right). The relative humidity was even further reduced at 850 hPa with widespread deficits of greater than -10% almost exactly matching the scale of the rainfall departures (see Fig. 2). It is worth noting that the relative humidity reductions at 850 hPa were somewhat greater than one would have surmised from just the fractional change in specific humidity. This

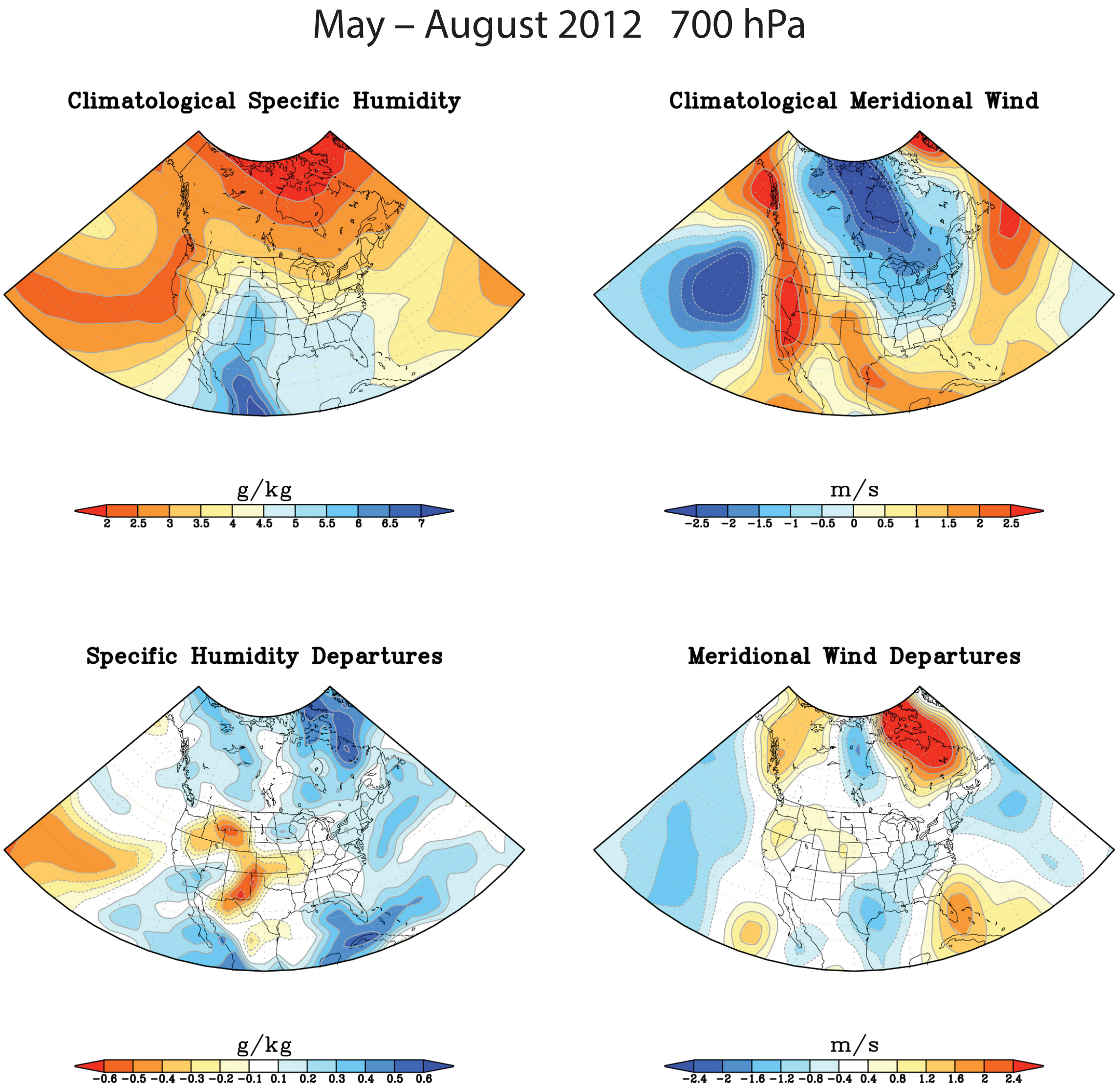


Figure 12. (top) Observed climatological May-August 700 hPa specific humidity (left, g/kg) and 700 hPa meridional wind magnitude (right, m/s) (bottom). Anomalous May-August 2012 700 hPa specific humidity (left. g/kg) and anomalous 700 hPa meridional wind magnitude (right, m/s). Data source is the NCEP/NCAR reanalysis, and graphics from the NOAA/ESRL Physical Sciences Division. Anomalies relative to 1981-2010 reference.

is because the low troposphere temperatures were especially warm, and so the water holding capacity increased even while the actual water vapor content was diminished.

Water vapor deficiencies alone need not guarantee drought, as mechanisms that induce convergence and air mass lift can still operate from time to time to yield precipitation events. But, recall from the station rainfall times series (Fig. 4) that some locations saw rather remarkable sequences of 30-60 days without precipitation, an indication that rain-producing mechanisms and triggers for ascent were scarce in summer 2012. This is further affirmed by the monthly 500 hPa height anomalies for May, June, July and August (Fig. 14). In May and June (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 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, though also drought producing, was yet different again from both June and July. A deep Ohio Valley trough acted to inhibit Gulf of Mexico moisture inflow (as seen in the seasonal map of 700 hPa meridional wind anomalies), while subsidence over the western Great Plains was enhanced on the western edge of this low pressure system. Note that this dry August pattern was also a cool pattern for the central to eastern Plains, which may account for the fact that the May-August 2012 mean temperature anomalies were not greater than would have been surmised given the severity of rainfall deficits.

The upper-level circulation broadly favored large-scale descent during summer and inhibited the normal occurrence of spring storms. When conditions favorable for rainfall were present, the depleted moisture in the low troposphere limited rainfall amount. Together, these conditions conspired to create a 4-month sequence of record rainfall reduction over the central Great Plains. The impression is also rendered of a sequence of unfortunate events. There was considerable monthly variability in the upper level circulation (perhaps belying the impression that such a sustained and

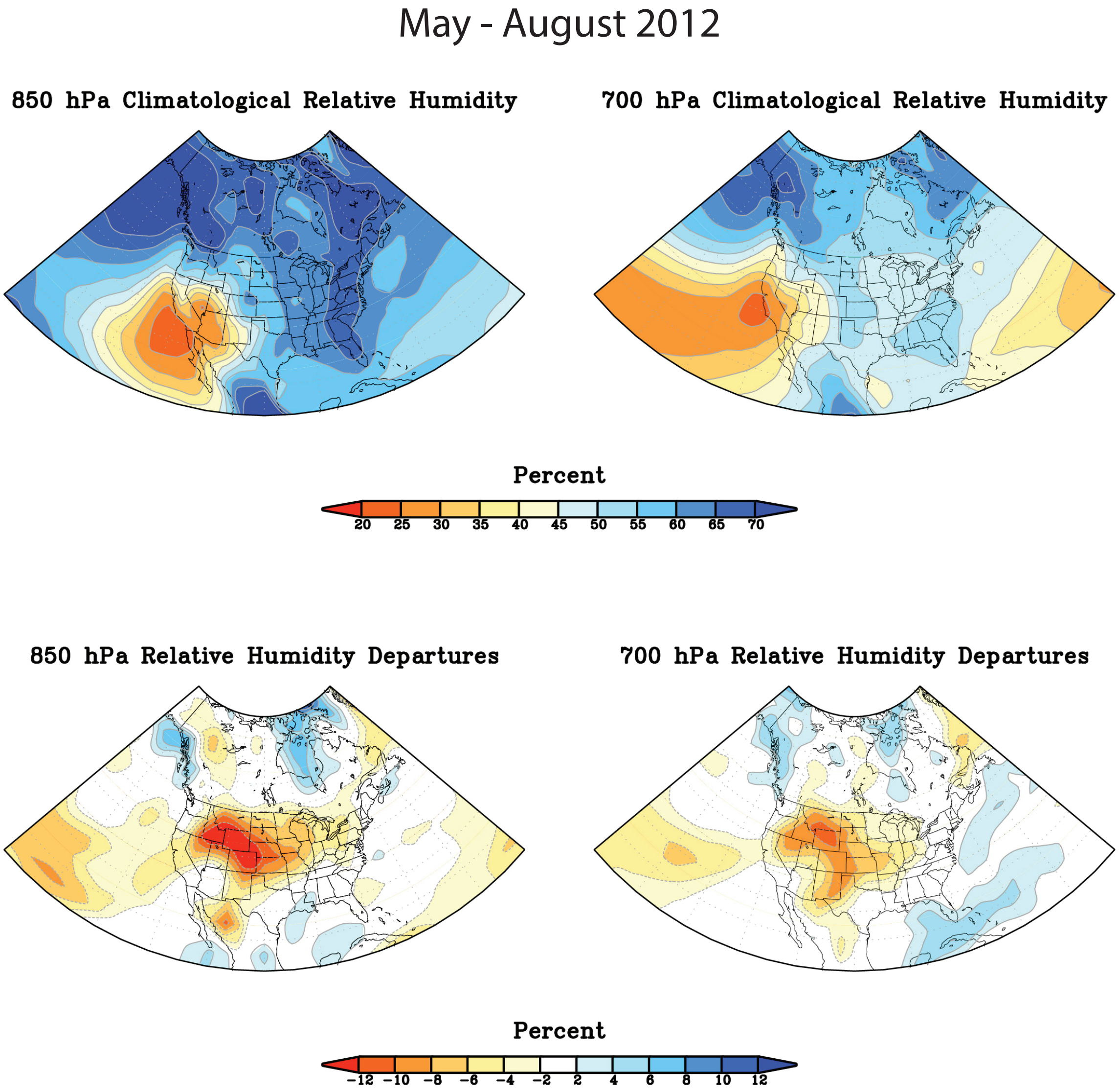


Figure 13. (top) Observed climatological May-August 850 hPa relative humidity (left,%) and 700 hPa relative humidity (right, %) (bottom). Anomalous May-August 2012 850 hPa relative humidity (left. %) and anomalous 700 hPa relative humidity (right, %). Data source is the NCEP/NCAR reanalysis, and graphics from the NOAA/ESRL Physical Sciences Division. Anomalies relative to 1981-2010 reference.

extreme drought must have been the consequence of some strong sustained forcing), yet each of these patterns in their own manner squelched rainfall-inducing processes over the central Plains. And so it began, with drought emerging suddenly in May as late spring storms avoided the region entirely, and intensified through July and August as summertime convection was inhibited. Since the end of summer, the normal dry season emerged, and soil moisture conditions remain depleted. As this report is being written, the 2013 rainy season is anxiously awaited.

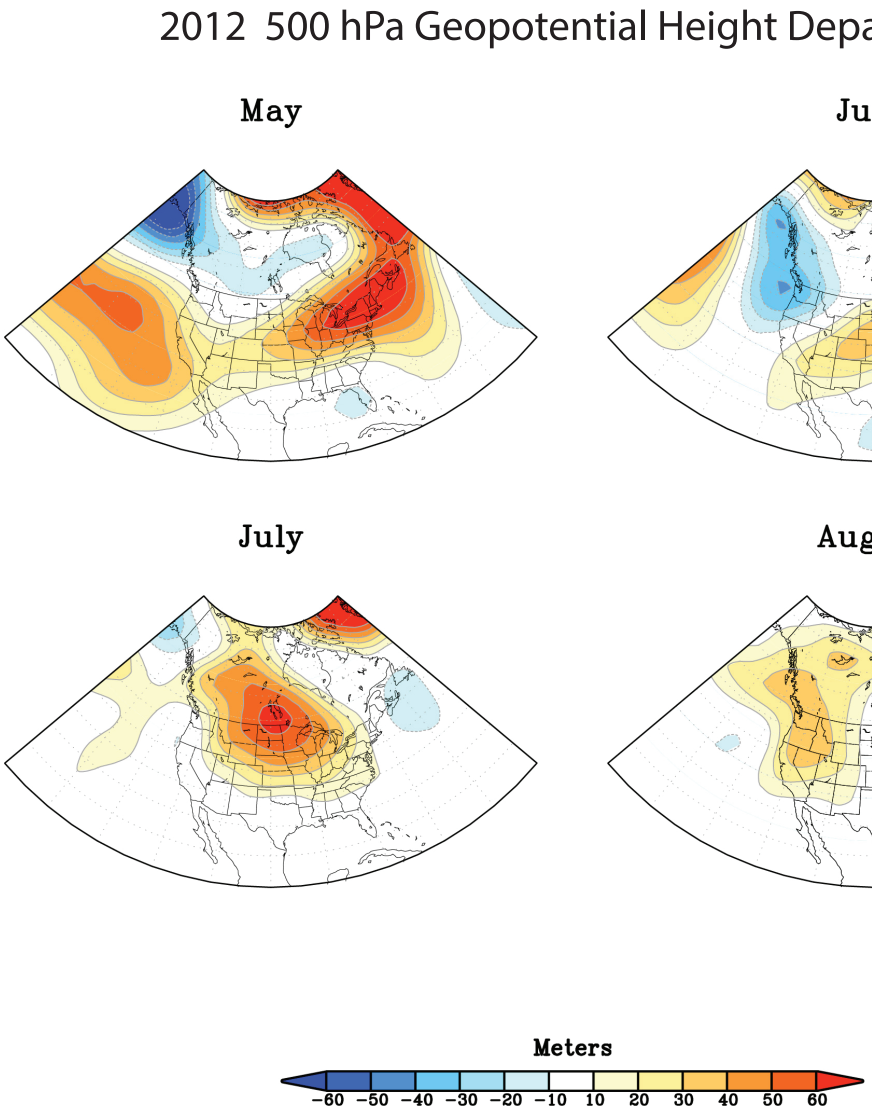
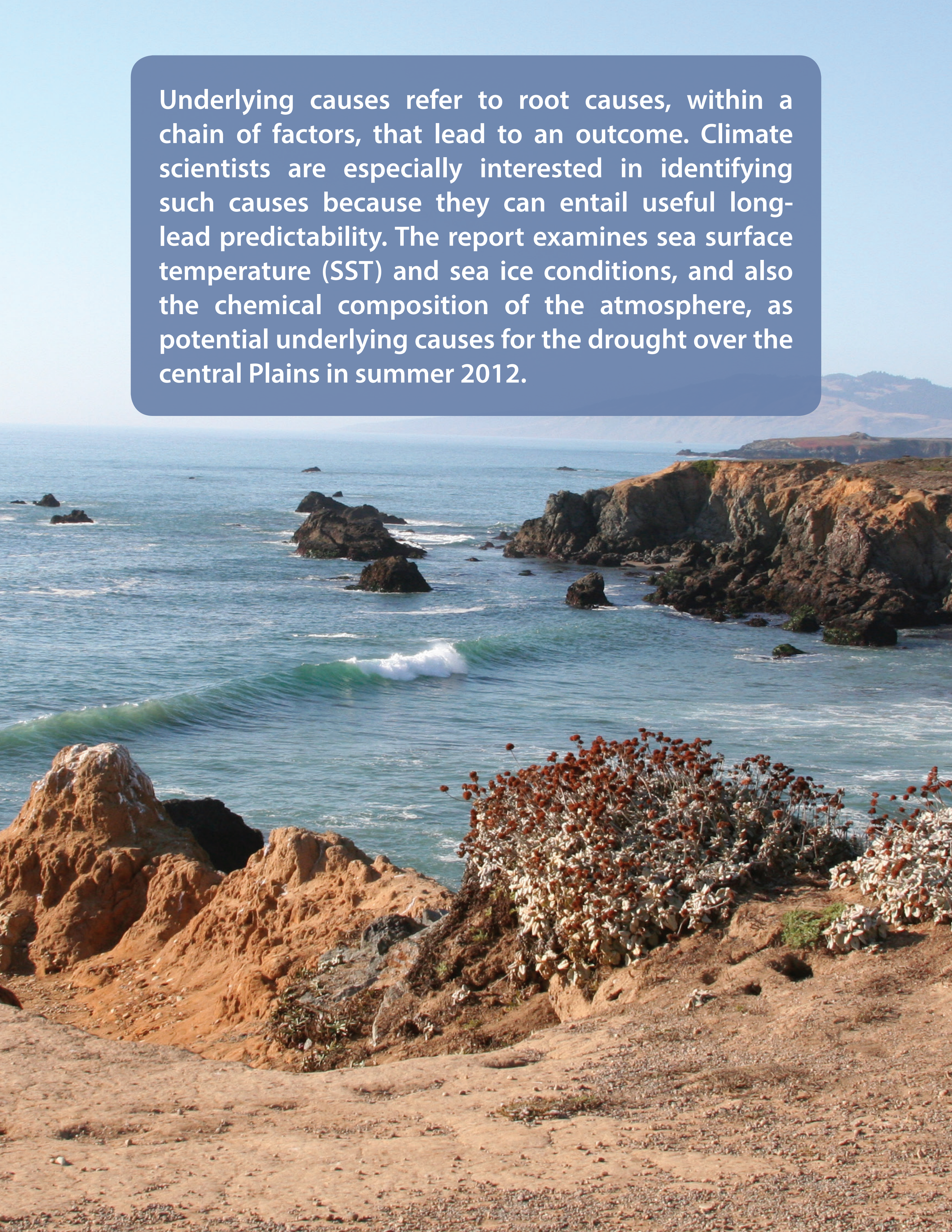


Figure 14. Observed monthly 500 hPa geopotential height anomalies (m) for May, June, July, and August 2012. Data from the NCEP/NCAR reanalysis, and graphics from the NOAA/ESRL Physical Sciences Division.

Underlying causes refer to root causes, within a chain of factors, that lead to an outcome. Climate scientists are especially interested in identifying such causes because they can entail useful long-lead predictability. The report examines sea surface temperature (SST) and sea ice conditions, and also the chemical composition of the atmosphere, as potential underlying causes for the drought over the central Plains in summer 2012.



Climate simulations and empirical analysis suggest that neither ocean surface temperatures nor changes in greenhouse gases induced a substantial reduction in summertime precipitation over the central Great Plains during 2012. Diagnosis of historical data, climate simulation data, and seasonal forecasts paint a picture of an extreme drought that may not have had extreme forcing as its cause and that had limited long lead predictability.

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 multi-year drought life cycle that began over the southern Plains in late 2010 and evolved northward. Here we explore whether particular forcings, including sea surface temperature (SST) and sea ice conditions, and also the chemical 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 examine the state of global oceans that attended prior historical Great Plains droughts. Figure 15 shows the seasonal SST anomaly composite that is based on the same sample of the 9 prior driest summers used to construct the antecedent precipitation maps. Though this composite reveals global SSTs to be cool overall in all seasons, the magnitudes are weak. The composite SST coolness is less indicative of a coherent pattern of interannual forcing, but instead reflects mostly the long-term trend in SSTs (which have been warming in the latter half-century in particular). The effect of this trend on the composite arises because of the inhomogeneous temporal sampling of drought events in the historical record with only two of the nine prior severe droughts occurring after 1953 (to minimize the influence of this trend, the composite SST anomalies in Fig. 15 were calculated relative to a 1901-1990 reference that brackets the years of the 9-case sample).

Nonetheless, several of the prior summer droughts occurred in the immediate aftermath of winters experiencing cold equatorial Pacific SSTs. Examination of a SST index that is used to monitor the occurrences of El Niño (warm) and La Niña (cold) tropical Pacific events reveals that the preceding winters of 3 cases (1910/11; 1933/34; 1975/76) were moderate La Niña events. However, two other severe droughts occurred after wintertime El Niño conditions (1930/31; 1987/88), while the remaining 4 cases were neutral with respect to ENSO's phase.

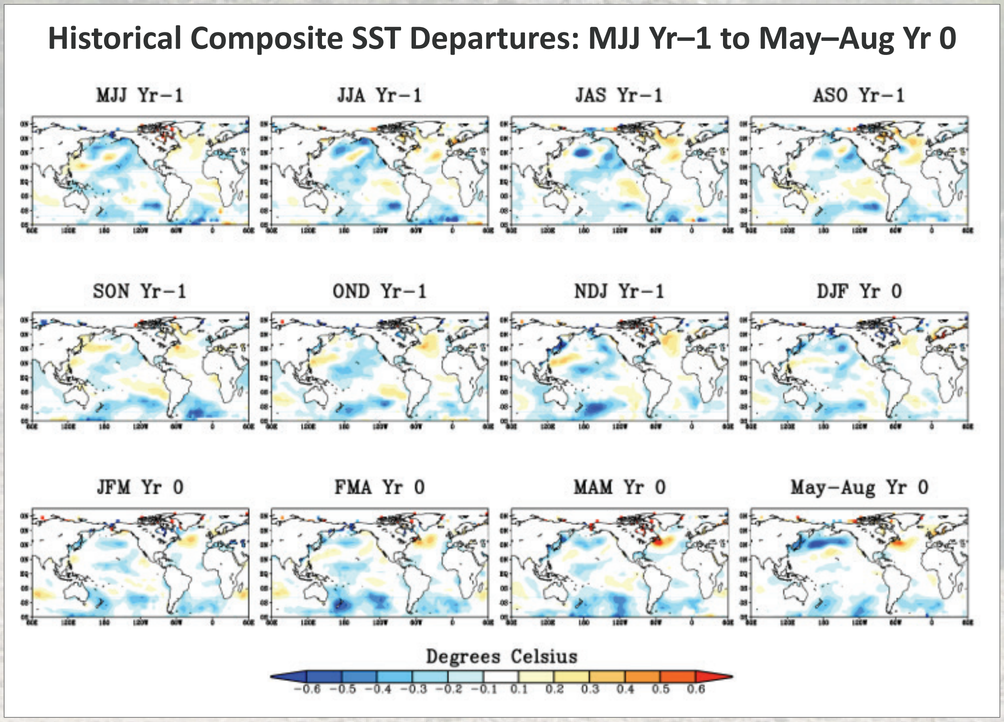


Figure 15. As in Fig. 10, except for the composite seasonal SST anomalies (°C) during the 12-month period antecedent to the occurrence of dry May-August conditions over the central Great Plains. Based on the average of the 9 driest May-August events during 1895-2011, including 1934, 1936, 1901, 1976, 1913, 1988, 1953, 1911, and 1931. Reference period is a shorter 1901-1990 period in order to reduce effects of the long term SST warming trend. Data source is the monthly NOAA Merged Land-Ocean surface temperature analysis (MLOS).

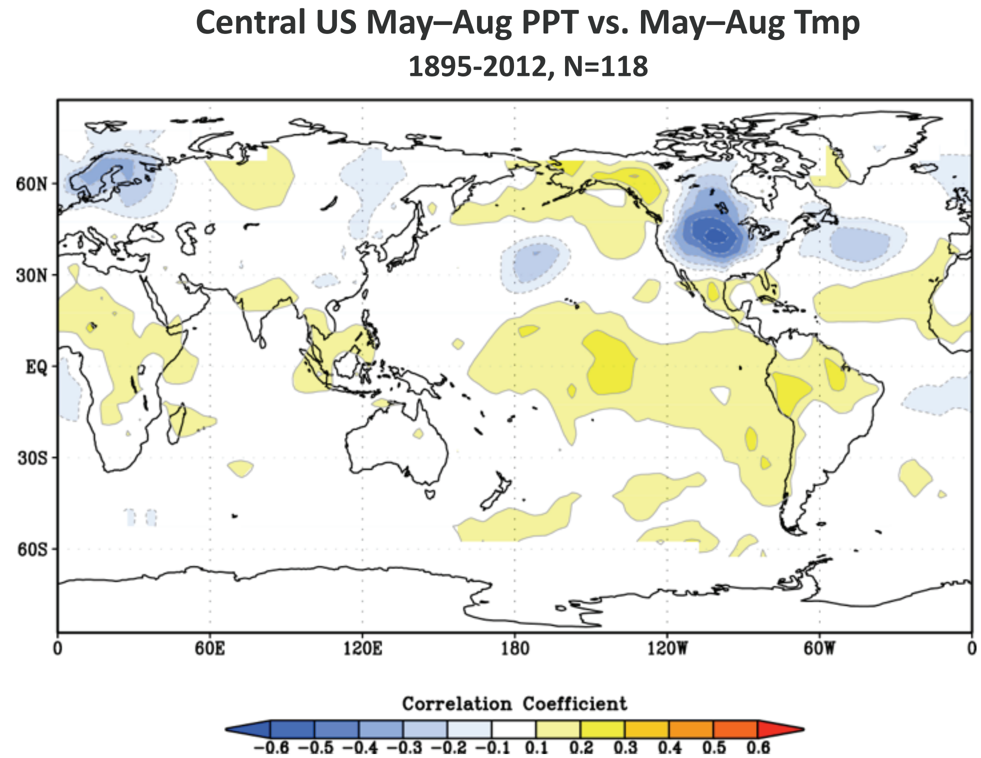


Figure 16. The linear correlation between an index of observed May-August U.S. central Great Plains. summer rainfall (see Fig. 6) and May-August surface temperatures. Period of analysis is 1895-2011. Statistically significant correlations are confined to the central U.S. where there is a strong inverse correlation between summer rainfall and summer land surface temperature. Data source is the monthly NOAA Merged Land-Ocean surface temperature analysis (MLOS).

Consistent with the weak evidence for a coherent precursor SST condition attending summertime central Plains drought, evidence for a strong simultaneous SST effect is not found either. Figure 16 presents the correlation between the index of central Great Plains summer precipitation with summertime ocean surface and land surface temperatures for the entire 1895-2011 period (Fig. 16). The weak positive correlations with ocean surface temperature variability seen over the tropical east Pacific are not statistically significant, nor are most of the correlations in other ocean basins significantly different from zero. The empirical results thus suggest that SST variations, at least those observed during the last century, have likely failed to consistently produce May-August drought occurrences over the central Great Plains. This diagnosis of historical data paints an overall picture in which ocean conditions have not strongly constrained the variations of summertime central Great Plains precipitation. There is thus little compelling evidence that past droughts of this type have had a coherent pattern of sea surface temperature forcing.

However, global SSTs have appreciably changed (principally warmed) since the last major central Plains drought of 1988. Shown in Fig. 17 are the SST anomaly maps during 2012 (using the same 1901-1990 reference), from which the material difference from the SSTs seen in the 9-case historical composite is obvious. One point of similarity with the historical composites is coolness in the equatorial central Pacific in the preceding winter. Otherwise, owing in part to the warming trend and perhaps also due to low frequency decadal ocean variability, the 2012 drought occurred in concert with an appreciably warmer ocean in most basins than was the case for any prior historical drought.

Has this overall ocean warming altered the probabilities for U.S. summertime drought? Recognizing that most of the prior severe Great Plains droughts happened before 1950 when global climate as a whole was appreciably cooler, it becomes important to examine the particular attributes of climate forcings that operated during 2012 and assess if they served to condition 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. Also, the tropical-wide SST pattern of the past year has many of the attributes of the so-called "perfect ocean for drought" pattern. This consists of an increased zonal contrast in SSTs between the eastern equatorial Pacific and the Indo-west Pacific. In a published study, titled the "Perfect Ocean for Drought" (see Additional Reading) an analysis was conducted on how SST conditions during 1998-2002 affected precipitation over the US (especially the southern regions that spanned California to Florida) and other mid-latitude region's of the Northern Hemisphere. Those resembled the conditions seen during 2012, with abnormally warm Indo-West Pacific Ocean conditions and abnormally cold east Pacific conditions. However, the SSTs that were deemed to be effective in drying a widespread portion of mid-latitudes during the turn of the century drought likely did so via tropical-extratropical climate linkages that were endemic to the winter/spring season, and are unlikely as effective during summer. The phrase "perfect ocean" is thus more figurative, and does not connote an elixir explaining the cause for all droughts. In particular, as will be shown subsequently, the issue of central U.S. summertime drought as relates to ocean forcing appears to be rather distinct from the SST forcings conducive for cold season precipitation in the southern portion of the US. What may be "perfect" for understanding some region's drought sensitivity to ocean states, may be flawed and defective for understanding droughts in other seasons and over different regions.

A few more comments on the attribution of droughts to particular forcing patterns is in order. In what has perhaps become jargon, several phrases or phenomena in addition to "perfect ocean for drought" are getting increasingly circulated as "explanatory" for causes of events such as droughts. These include ENSO (the El Nino-Southern Oscillation phenomenon that is associated with interannual warm or cold states of the tropical east Pacific ocean), PDO (the Pacific Decadal Oscillation that is

Observed 2012 SST Departures: MJJ 2011 to May–Aug 2012

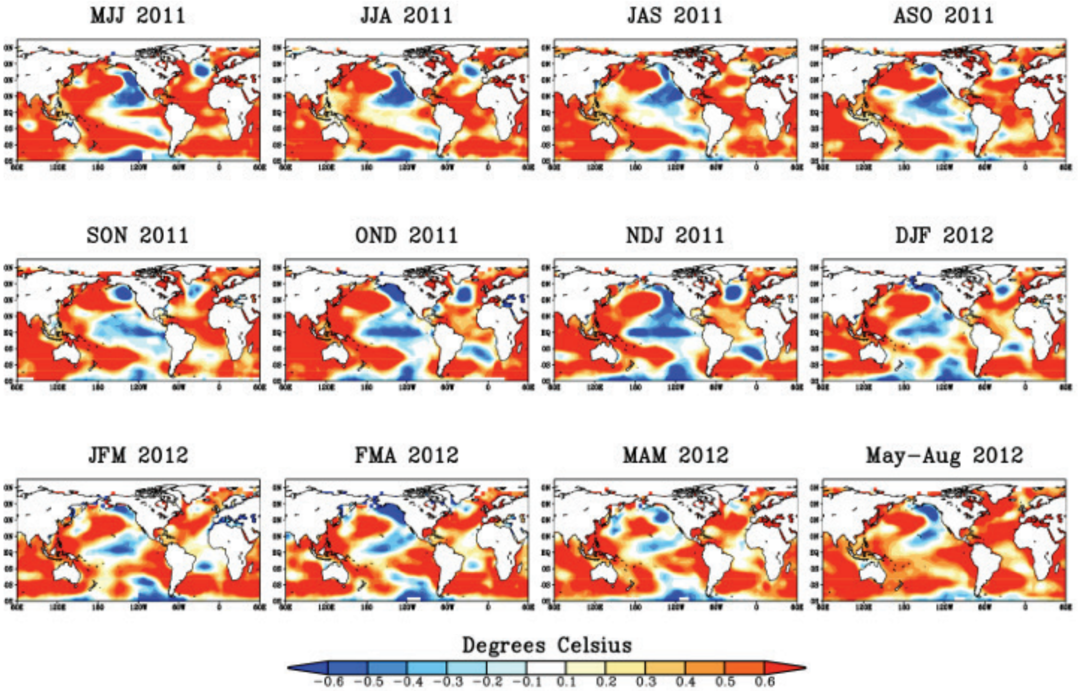


Figure 17. As in Fig. 15, except for the SST anomalies (°C) during the 12-month period antecedent to the occurrence of dry May-August 2012 central Great Plains drought. Reference period is 1901-1990. Data source is the monthly NOAA Merged Land-Ocean surface temperature analysis (MLOS).

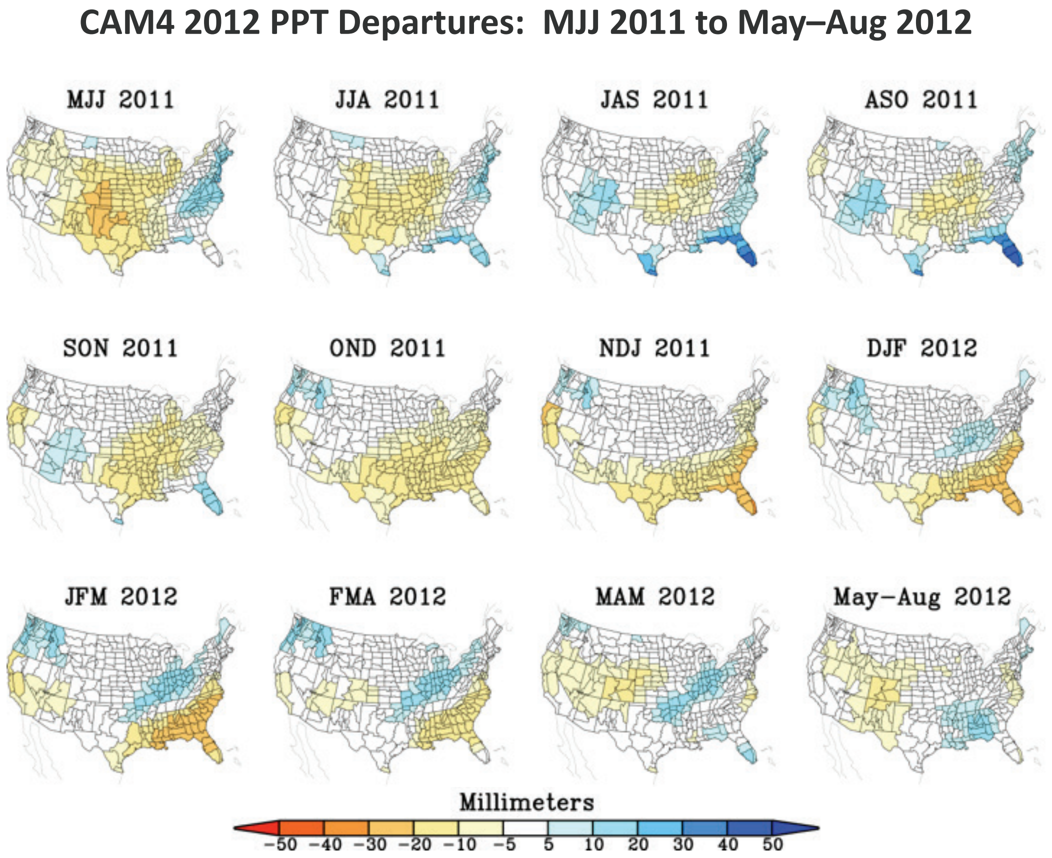
associated with decadal cool or warm states of the Pacific Ocean especially north of 20°N), or global warming (the rise in average surface temperatures over the world land areas and oceans). In the subsequent material of this section, we attempt to rigorously test the connection between ocean conditions and also the state of external radiative forcing that operated during 2012 and the occurrence of drought over the central Plains.

The question of whether the particular SST conditions in 2012 may have exerted a more substantial, and potentially predictable influence on summer U.S. precipitation is addressed using climate simulations. Global atmospheric models that are run over the period 1979-2012 are used herein. These are continuous simulations, begun from atmospheric initial states in January 1979, and conclude in December 2012. The only constraining information representing observed conditions in these simulations is the sea surface temperature, sea ice, and external radiative forcing. These are specified in the atmospheric model as monthly time evolving boundary conditions from January 1979- December 2012. Because the forcings are typically of a time scale that is much longer than the time scale of atmospheric variations, the atmospheric sensitivity to such forcings is judged to be potentially predictable to the extent that such boundary forcings are themselves predictable. The forcing conditions may act to influence the year-to-year variability of the atmosphere and also the probabilities of certain extreme conditions (e.g. severe drought), and the purpose of the experiments is to quantify their influence. 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.

There are two particular aspects of the sensitivity that are of interest. First is the mean response to the specified forcings, a sensitivity that reveals how the most likely (e.g. median) outcome for a particular season changes as a consequence of the forcing. Second is the so-called "tail response", a sensitivity that reveals how the probability of a particular threshold exceedence (e.g., the odds of eclipsing a prior record value) changes as a consequence of the specified forcing.

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 20 times (a 20-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 20 members in order to determine the mean response to specified forcings. Note that the process of averaging eliminates the random internal variability of the atmosphere, and facilitates identifying the coherent signal from the forcing. However, analysis of the statistical distribution of all 20-members is likewise important especially for discerning how the frequency of extreme events is affected by specified forcing. In this assessment, the use of 20-member ensemble simulations may be adequate for estimating the coherent mean signal, however, it is unlikely sufficient for estimating how the statistics of extreme events are affected. This should be kept in mind when judging the reliability of model-based diagnoses. It must also be emphasized that a more thorough assessment would require the use of multiple models in order to minimize the possible influence of a particular climate models' biases, and larger ensemble sizes to better separate forced changes from unforced internal variability.

The model used is the NCAR CAM4 global climate model, with the simulations performed at a 1° (~100 km) resolution. Monthly varying SSTs and sea ice are based on a global monthly 1° analysis, and the specified external radiative forcings consist of greenhouse gases (e.g. CO2, CH4, NO2, O3, CFCs), aerosols, solar, and volcanic aerosols. The latter employ observed estimates through 2005, and then an emission scenario thereafter (RCP6.0, a moderate


CAM4 2012 PPT Departures: MJJ 2011 to May–Aug 2012

MJJ 2011, JJA 2011, JAS 2011, ASO 2011, SON 2011, OND 2011, NDJ 2011, DJF 2012, JFM 2012, FMA 2012, MAM 2012, May–Aug 2012

Figure 18. As in Figure 9, except the simulated U.S. seasonal precipitation anomalies (mm) during the 12-month period antecedent to the occurrence of observed dry May-August conditions over the central Great Plains. The simulated May-August rainfall anomalies are shown in the lower right panel, and simulations for the prior season are shown chronologically in the other panels. Simulations based on NCAR CAM4 forced with observed SST, sea ice, and external radiative forcing. Plots show the 20-member ensemble average, and anomalies are relative to the model's 1981-2010 climatology.

emissions scenario pathway). The model output has been interpolated to U.S. climate divisions to facilitate comparison with observations.

The simulated ensemble mean precipitation anomalies for May-August 2012 are shown in Fig. 18 (lower right), as are the simulated precipitation anomalies for the prior 12 months. Only a weak signal of dryness is simulated during summer 2012 over the central Great Plains, with the area-averaged anomaly over the 6-state index region in the CAM4 ensemble average being an order of magnitude weaker than the observed anomaly. The particular SSTs of 2012 thus appeared not to force the seasonal mean rainfall reduction over the central Plains, and this weak sensitivity implies that the most likely outcome for central Plains precipitation in summer 2012 was close to its climatological normal value. Further analysis to be presented in section 6 will show a similar weak signal in the ensemble rainfall predictions generated at 12 operational forecast centers, indicating that the weak signal in the CAM4 runs is unlikely a symptom of model bias. It is also worth noting that CAM4 simulations exhibit a stronger signal of reduced summer rainfall anomalies in 2011 over the southern Plains (Fig. 18, top left), which though considerably less than the observed dryness in 2011, suggests a stronger SST influence on the prior drought that spanned the southern Plains.

Consistent with a weak signal of reduced seasonal mean rainfall, the overall distribution of the 20-member CAM4 simulations indicates a shift toward drier states. The box-whisker display in Fig. 19 shows, in the far right side, the distribution of the 20 realizations for summer 2012. Note that the extreme driest member, shown by a red asterisk, ranks among the driest model simulations for any year during 1979-2012. Indicated hereby is that the probability of an extreme dry summer over central

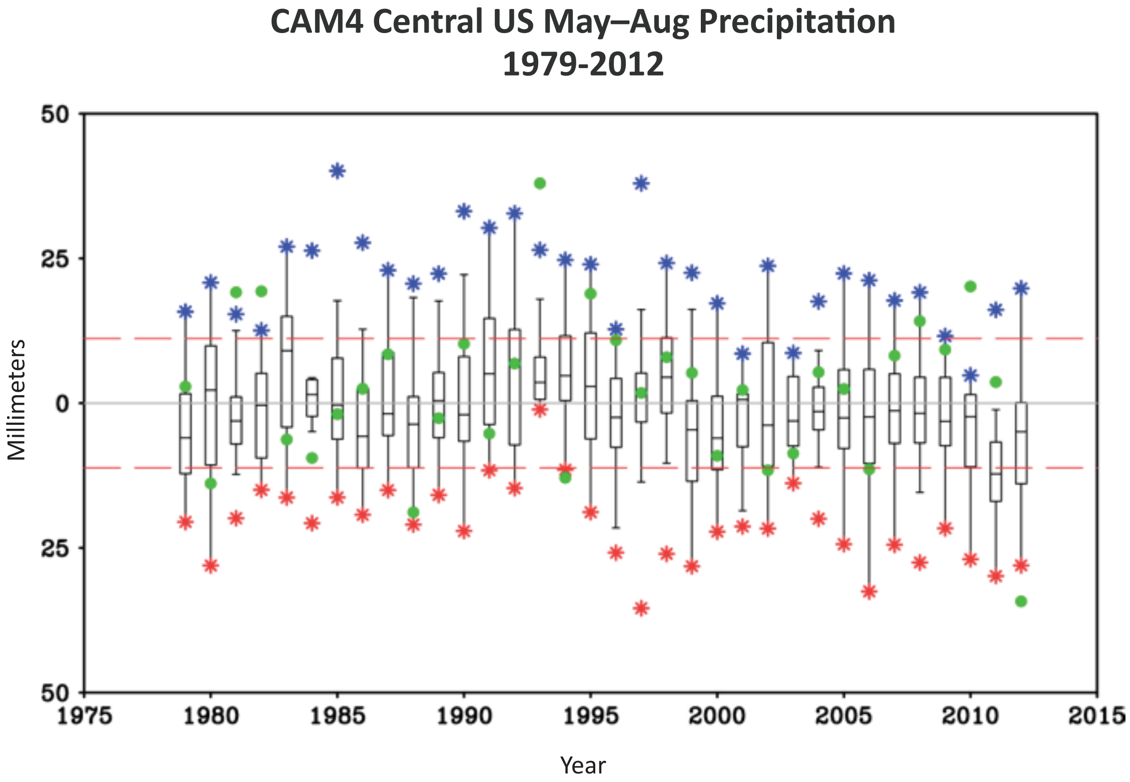


Figure 19. Box-whisker plots of the May-August CAM4 simulated central Great Plains rainfall anomalies for 1979-2012. Extreme wet and dry members are shown with blue and red asterisks, respectively. The horizontal dashed lines are the model's 1-standardized departures of May-August rainfall. Green circles plot the observed rainfall anomalies for each year. The area is comprised of the 6-State region of WY, CO, NE, KS, MO, and IA.

Great Plains may have been elevated during 2012. However, the ensemble size is too small to derive reliable estimates of the change in probability for extreme threshold exceedences during 2012. An additional question, unresolved by the current set of simulations, is whether the tail probabilities in 2012 changed beyond what would be expected from the simple shift in the mean value of the statistical distribution. While these are technical matters laying beyond the scope of this assessment, they do touch on a fundamental science question — how do particular forcings affect not only the mean state of climate but also its modes of variability and the statistics of extreme events?

There is an indication from CAM4 runs that there has been a consistent (albeit weak) dry signal each year during the past decade, and within each year's distribution, the extreme driest member was been considerably lower than in prior decades. Figure 19 also shows the distribution of model rainfall simulations for each year since 1979, and the consistency of a mean dry signal after 1999 is apparent. There is a coherent spatial scale to the simulated summertime rainfall change, shown in Fig. 20 where we have simply divided the simulation period into equal halves and taken the difference between the post and pre-1996 ensemble mean CAM4 rainfall. This pattern bears considerable resemblance to the summer 2012 U.S. pattern of

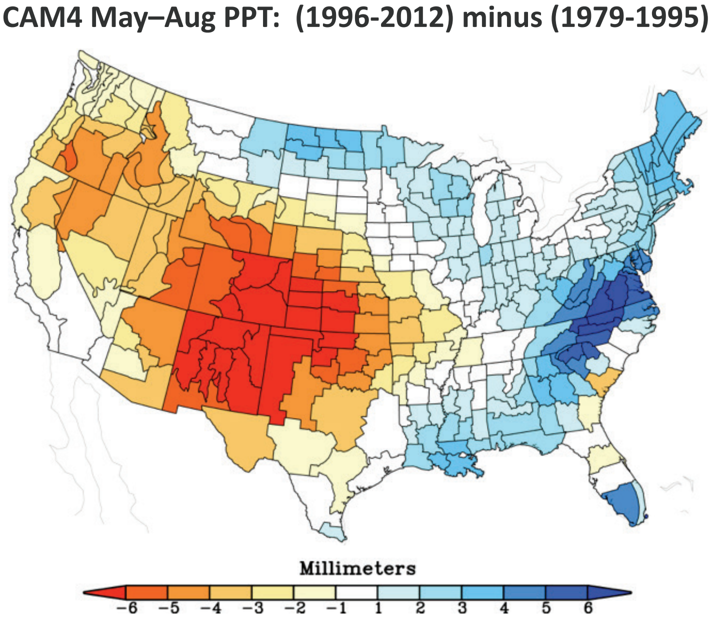


Figure 20. The simulated change in May-August rainfall (mm) for (1996-2012) minus (1979-1995) based on the 20-member ensemble mean CAM4 runs. Note that this change pattern of simulated dryness is quite similar to the pattern of 2012 summer rainfall anomalies (see Fig. 2).

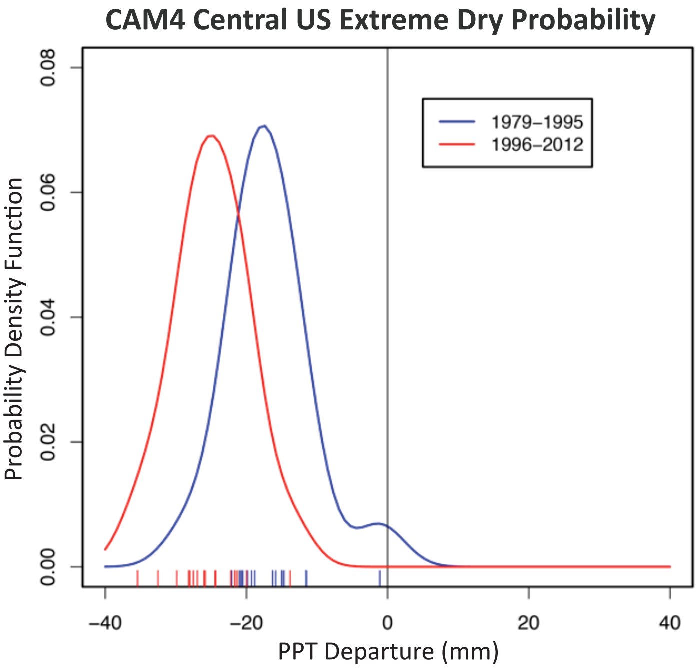


Figure 21. The probability distributions of the rainfall departures (mm) for the driest May-August central Great Plains CAM4 member in each year's simulations during 1996-2012 (red curve) and for 1979-1995 simulations. There is a 20-member ensemble for each year, and the driest member has been extracted. Each PDF is thus based on 17 samples, which are displayed as red asterisks in Fig. 18. The area is comprised of the 6-State region of WY, CO, NE, KS, MO, and IA.

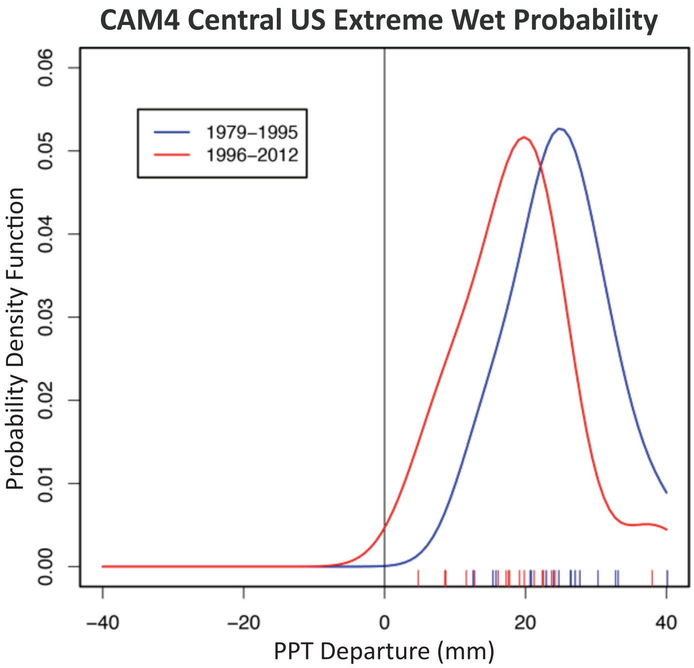


Figure 22. Same as Figure 21, except the probability distributions of the rainfall departures (mm) for the wettest May-August central Great Plains CAM4 member in each year's simulations during 1996-2012 (red curve) and for 1979-1995 simulations. There is a 20-member ensemble for each year, and the wettest member has been extracted. Each PDF is thus based on 17 samples, which are displayed as blue asterisks in Fig. 18. The area is comprised of the 6-State region of WY, CO, NE, KS, MO, and IA.

rainfall anomalies (see Figure 2), though of course of much weaker magnitude. The cause for the model's protracted dryness is not currently known, though it is temporally associated with a shift toward mostly cooler states of the tropical east Pacific that occurred after the large 1997-98 El Niño event.

With this mean rainfall reduction has come an increased risk of severe drought during summer over the central Great Plains in each year of the CAM4 runs after the late 1990s. It is apparent from inspection of the box-whisker plots that the magnitudes of the single most dry ensemble member (shown by the red asterisk) have been consistently lower than in the prior decades of the model simulations. Thus, although a 20-member ensemble for any individual year may not provide reliable information from which to discern the change in extreme event probabilities during any single year, an examination of these extreme event statistics over consecutive years appears to reveal a systematic pattern of change.

It is a speculative yet 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.

To illustrate the change in simulated extreme summer rainfall statistics over the central Plains, the probability distributions (PDFs) of extreme values for the 1996-2012 runs are compared to the extreme values for the 1979-2012. Figures 21 and 22 show the results for the extreme dry and wet PDFs, respectively. Simulated extreme event statistics for the recent period exhibit a distinct increase in severe drought probabilities (and also a distinct decrease in excessively wet probabilities).

It is a speculative yet 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 analysis of CAM4 runs does not explain, however, why the particular extreme drought occurred in 2012 specifically — the model runs indicate that the risks were comparably elevated in all years during the last decade. We know that no such event has occurred in the last decade; one has to return to 1988 to have experienced a drought as severe as occurred in 2012. The fact that an extreme drought did occur in 2012 may thus be largely coincidental, and by the very nature of extreme events, its occurrence was a low probability outcome. And while even those small odds may have been hedged by the particular forcings, the odds remained very small nonetheless. The implication from this analyses is that the 2012 drought may not have been especially predictable even a month or two in advance, an inference that is further supported by results in section 6 wherein the poor performance of operational forecasts for this drought are documented.

Further analysis of other climate models, similarly forced, would be required to build confidence in the realism of the CAM4 results, especially given that such sensitivity is not readily verifiable from the observations themselves. 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 in CAM4 is largely unrelated to the model's sensitivity to gradually increasing anthropogenic forcing. One key 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 CO2) may not 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 (for instance, Pacific and Atlantic Ocean natural decadal SST variability). Note also that the Great Plains surface temperature responses in CAM4 reveal a rather abrupt change in summertime conditions over the central U.S. after 1998, with sustained mean warmth having ensemble averaged magnitudes consistently between +0.5 to +1.0 standardized departures (Fig. 23).

An additional indication that global warming is unlikely a major factor in the 2012 central Plains

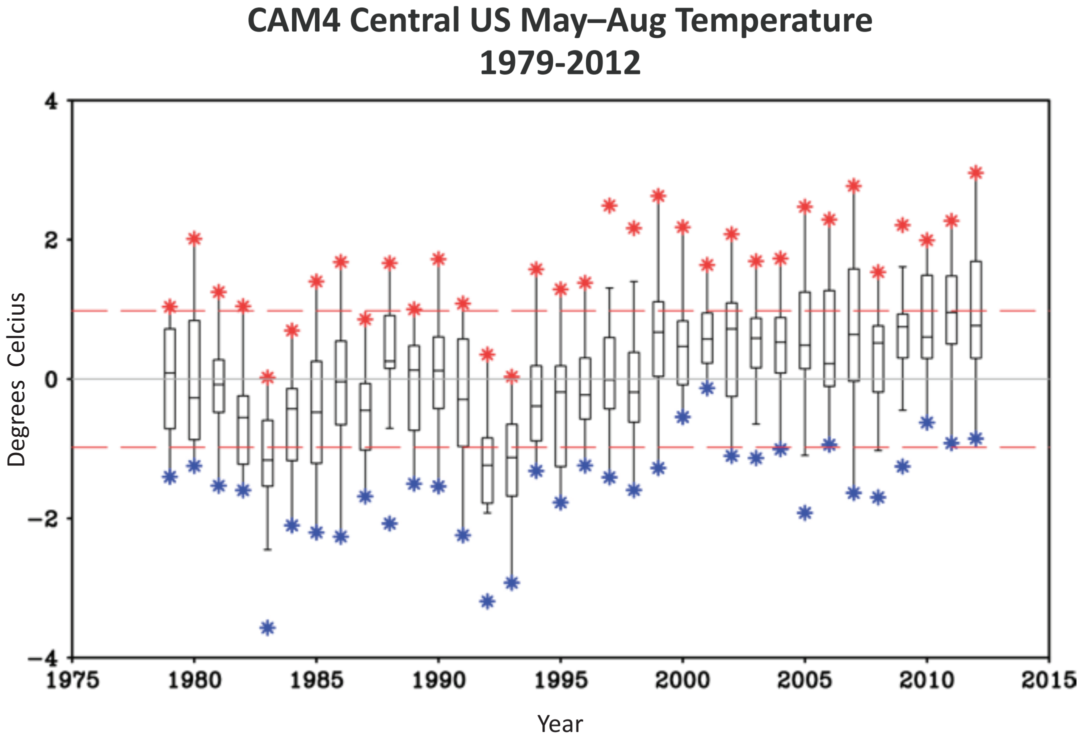


Figure 23. Box-whisker plots of the May-August CAM4 simulated central Great Plains surface temperature anomalies for 1979-2012. Extreme warm and cold members are shown with red and blue asterisks, respectively. The horizontal dashed lines are the model's 1-standardized departures of May-August temperature. The area is comprised of the 6-State region of WY, CO, NE, KS, MO, and IA.

drought is drawn from a further set of climate simulations that have been performed using the NCAR modeling system. Here the coupled ocean-atmosphere version of the model has been used to assess its sensitivity to the change in external radiative forcing since about 1850. This is the same model included among many modeling centers' that are contributing to the upcoming Intergovernmental Panels on Climate Change (IPCC) assessment of climate change. This model is also part of the so-called Climate Model Intercomparison Project – Phase 5 (CMIP5). Two 500-yr long runs of CCSM4 were conducted, one using year-1850 radiative forcing, and a second using year-2000 radiative forcing. In these experiments, which are different from the atmospheric model simulations wherein SSTs were specified, the coupled model's ocean responds to the change in specified radiative forcing. Broadly speaking, the model yields a realistic warming of globally averaged temperatures (~1.5°C) in response to this change in radiative forcing. Nonetheless, the simulations do not show a shift toward mean dryness in summer over the central Plains, or a systematic increase (decrease) in extreme dry (wet) probabilities. Figure 24 plots the PDFs of summer central Great Plains rainfall from two parallel 500-yr CCSM equilibrium runs, one using year-1850 external radiative forcing and the other using year-2000 external radiative forcing. The mean change in summer precipitation is about a 1.5 mm increase over the Great Plains in the warmer climate state. The variability in mean summer rainfall increases in the warmed climate (standard deviation increases about 15%), with both extreme dry and extreme wet summers increasing.

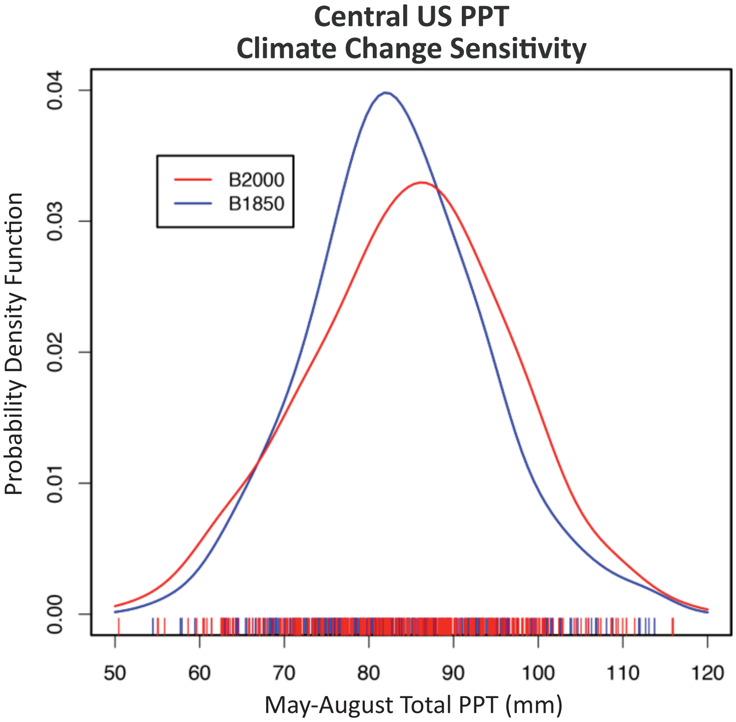
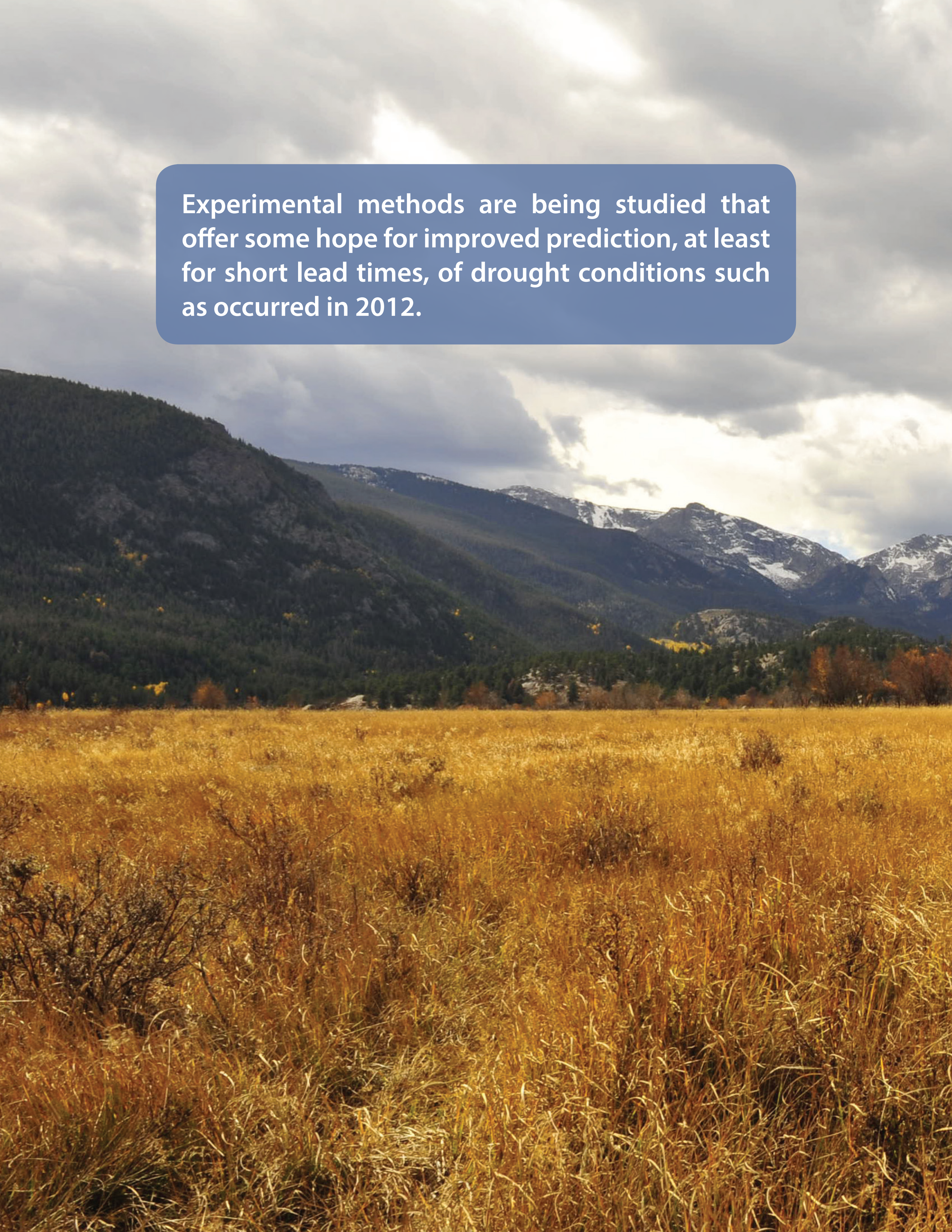


Figure 24. The probability distributions of the May-August total precipitation over the central Great Plains (mm) for CCSM4 equilibrium simulations using Yr1850 external radiative forcing (blue curve) and using Yr2000 external radiative forcing. Each run is 500 yrs long, and plotted are the last 400 years of results. The atmospheric model component in these coupled simulations is the same as used for the 1979-2012 AMIP runs of CAM4. The area is comprised of the 6-State region of WY, CO, NE, KS, MO, and IA.

This is not intended to be a comprehensive assessment of the possible effects of global warming on the 2012 central Plains drought, and hence results here are inconclusive. Further analysis will be required to assess the role of global warming on recent and future precipitation variability over the Great Plains using the full suite of CMIP5 models. A few points are nonetheless worth noting even from the limited analysis presented herein. First, the CAM4 atmospheric model simulations for 1979-2012 using the actual observed SST and specified external radiative forcing did not generate an appreciable dry signal over the central Great Plains in 2012. Second, the CCSM4 coupled model simulations using the change in external radiative forcing between year 1850 and 2000 do not exhibit a systematic change to drier conditions. Perhaps most striking is the wide range of summer central Plains rainfall that occurs within the 500 years of simulations in CCSM4 (shown by the tick marks in Fig. 24) for a particular forcing regime. This range is far greater than any change in that range (and related statistics) associated with the forcing change. The implication is that the signal of climate change may be very small compared to the noise of the intrinsic year-to-year variability. Detectability of a global warming signal in the statistics of summertime Great Plains rainfall may thus be very difficult at this time.



Experimental methods are being studied that offer some hope for improved prediction, at least for short lead times, of drought conditions such as occurred in 2012.

Prediction for the Summer 2012

Operational Precipitation and Temperature Forecast

Global Producing Centers (GPC) of seasonal climate predictions regularly supply their data to the WMO lead center for long-range predictions, which in turn produce various statistics of these predictions. There are currently 12 operational climate prediction centers around the world that participate. Shown in Figures 25 and 26 are simple composites of the 12-centers' seasonal predictions for May-July 2012 and June-August 2012.

The multi-model predictions, based on April initializations, for May-July 2012 reveal a weak dry signal, located over the north central U.S., but a strong signal of warmth that spans the entire contiguous U.S. The May 2012 initialized predictions for the June-August period show no appreciable rainfall signal, but a continued widespread large amplitude warm signal. In many ways, the results of the initialized coupled model predictions are consistent with the retrospective AMIP simulations of CAM4. Namely, both exhibit a weak signal of reduced summertime rainfall over the central U.S., but a comparatively strong signal of surface warmth. In this regard, both simulation and prediction runs imply that there was an appreciable increase in probability that the central Great Plains would experience warmer than normal temperatures during summer 2012. However, this forced warming signal alone fails to explain the heat wave that occurred. The latter almost certainly resulted mainly from rainfall's absence, and the associated feedbacks on temperatures that ensued due to severely depleted soil moisture. Also, the operational predictions suggest that initial conditions in May, which would have begun to reflect the reduced soil moisture states owing to the lack of May rainfall, failed to increase the probabilities of central U.S. drought in June-August. While soil moisture conditions may have affected some aspects of the forecasts during summer 2012 such as temperature,

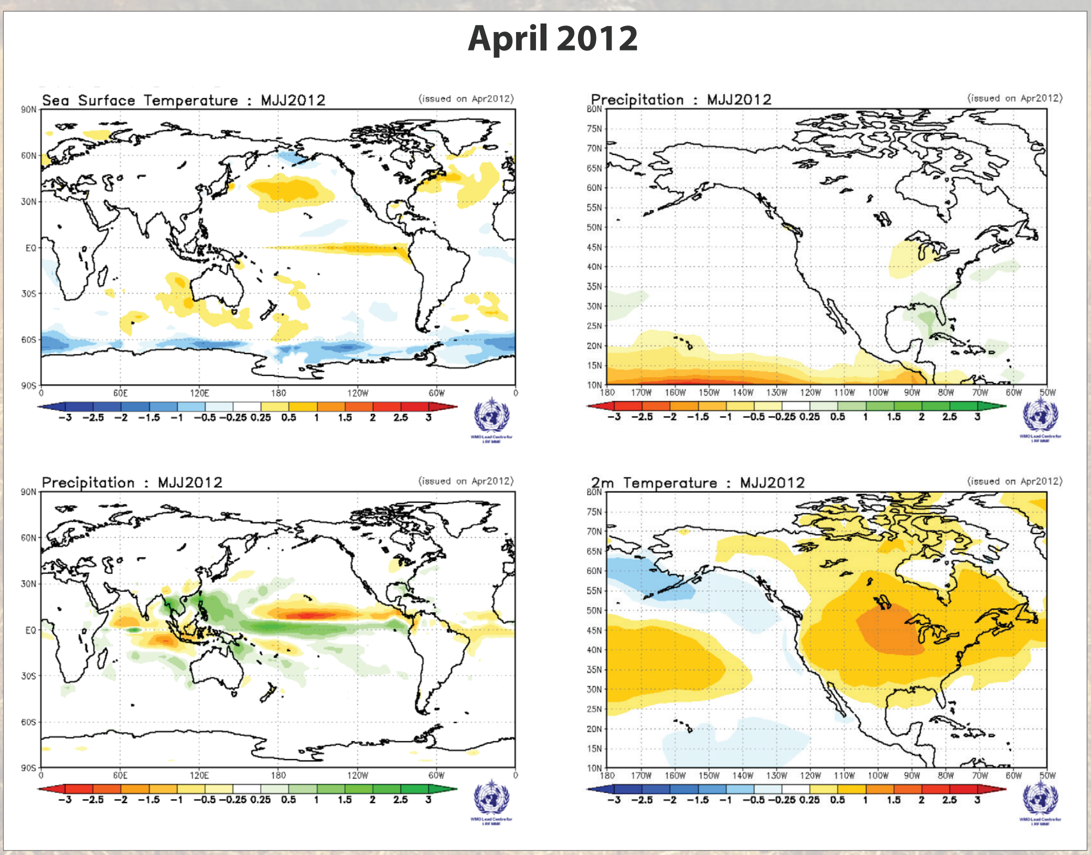


Figure 25. Equal-weighted composites of 12 operational centers' seasonal predictions for May-July 2012 for global sea surface temperature departures (°C, top left), global precipitation departures (mm, bottom left), and for North American sector precipitation departures (mm, top right) and for North American sector surface temperature anomalies (°C, bottom right). Forecasts are based on April 2012 initializations. Data source is the WMO GPC project.

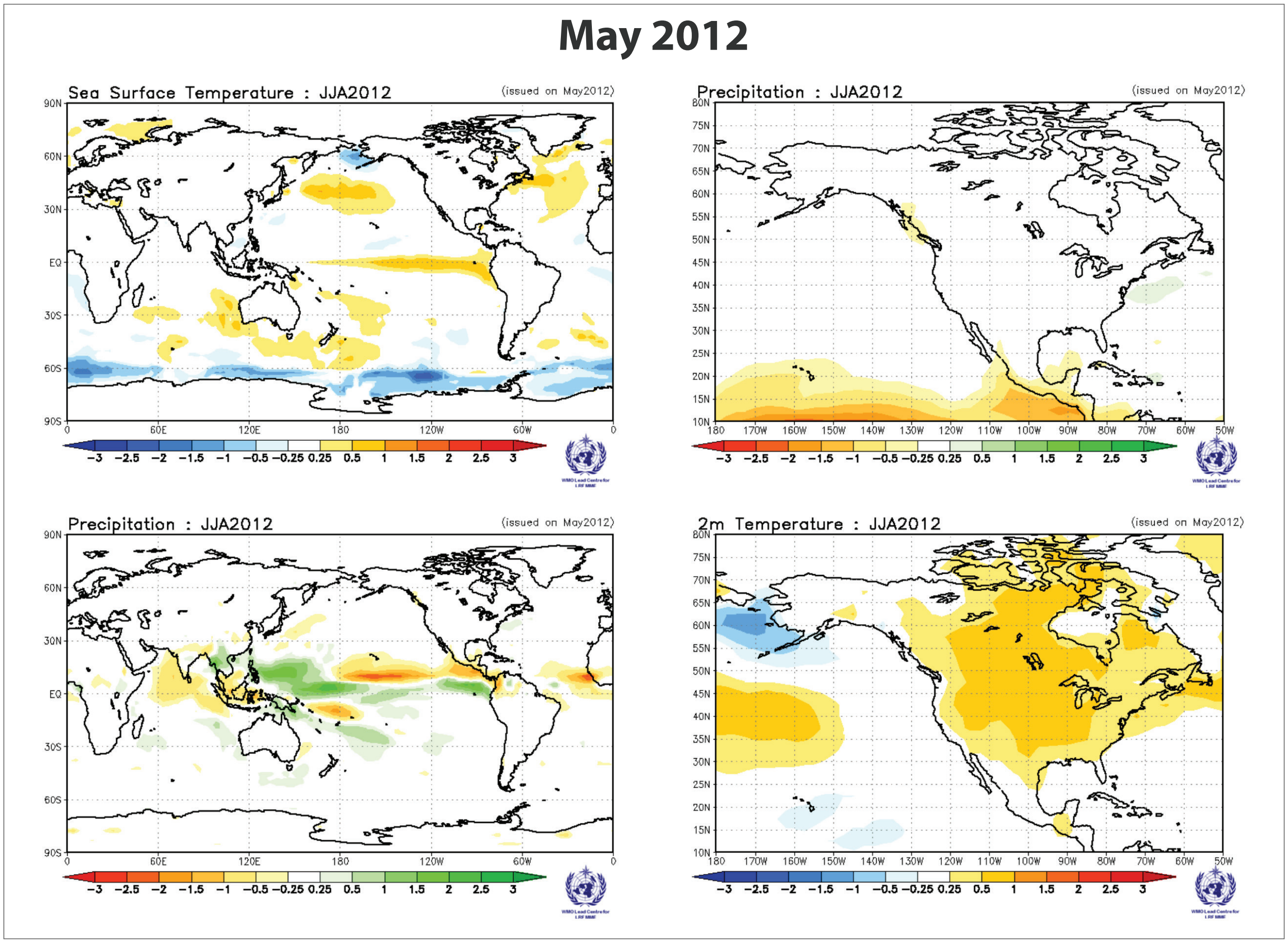


Figure 26. Same as Fig. 25, except for the June-August seasonal predictions based on May 2012 initializations.

their effects on rainfall were either not systematic across the models, or they were weak for the central Great Plains areas of interest.

Simulations of Precipitation and Soil Moisture

Experimental methods are being studied that offer some hope for improved prediction, at least for short lead times, of drought conditions such as occurred in 2012. Shown in Fig. 27 are simulations of summertime Midwest regional mean precipitation differences (2012-2011) driven by ECMWF Interim Reanalysis (ERI) based on the CWRF model. For comparison, also shown are the CFSv2 operational forecasts initialized at May 1, and ECHAM4.5 real-time forecasts initialized at April 1, May 1 and June 1 respectively with initial soil conditions from NCEP Reanalysis 2 (R-2) and NLDAS. As part of ongoing research to test sensitivity, here each case is facilitated with 4~5 CWRF physics configurations. The operational forecast results using the existing configurations of CFSv2 and ECHAM4.5 are also shown as the first blue bar in each grid. The CWRF/ERI simulation consistently captures the low rainfall in summer 2012 (relative to rainfall conditions the prior year), while most other forecasts fail to do so. Whether the gains seen in CWRF/ERI simulation mode translate into improved predictions is matter of current research.

Also shown are the model predicted monthly evolutions of soil moisture at 2m depth (Fig. 28; hereafter denoted as SM_2m). Not surprisingly, initial soil conditions have the dominant impact on subsequent soil moisture conditions for about the first two months, but subsequent soil moisture is dominated by the model itself. In other words, the shorter the forecast lead time, the better the SM_2m prediction. The CWRF/ERI again simulates well the SM_2m drought conditions in 2012 summer, a consequence mostly of its successful rainfall simulation.

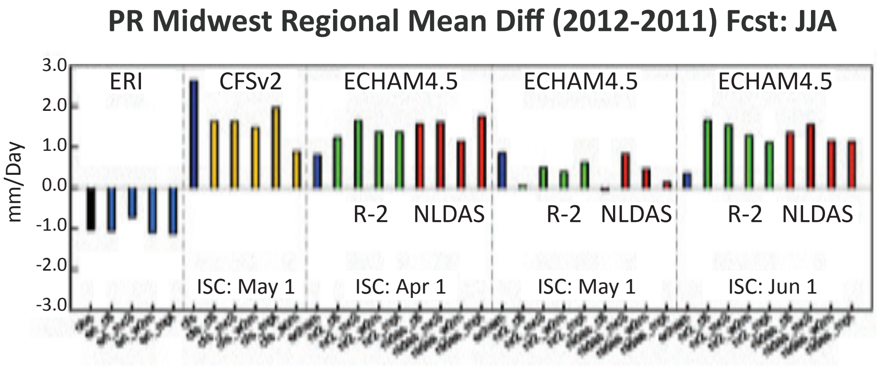


Figure 27. CWRF prediction of summertime midwest regional mean precipitation difference (2012-2011) driven by ECMWF Interim Reanalysis (ERI), CFSv2 real forecast initialized at May 1, and ECHAM4.5 real forecast initialized at April 1, May 1 and June 1 respectively with initial soil conditions from NCEP Reanalysis 2 and NLDAS. Each case is facilitated with 4~5 CWRF physics configurations. Shown also are the real forecast results from CFSv2 and ECHAM4.5 for each realization.

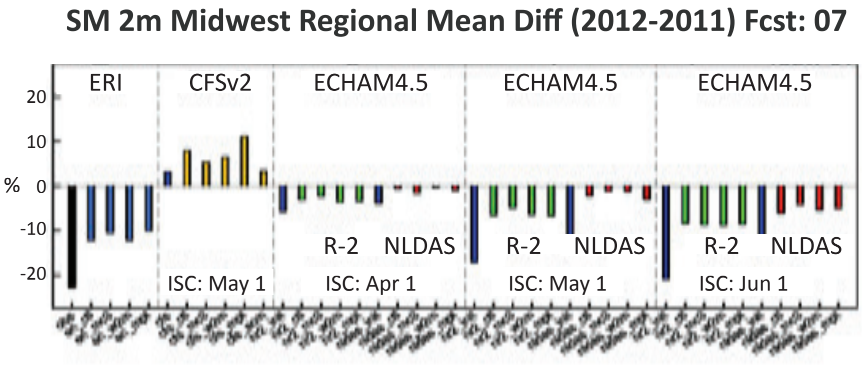
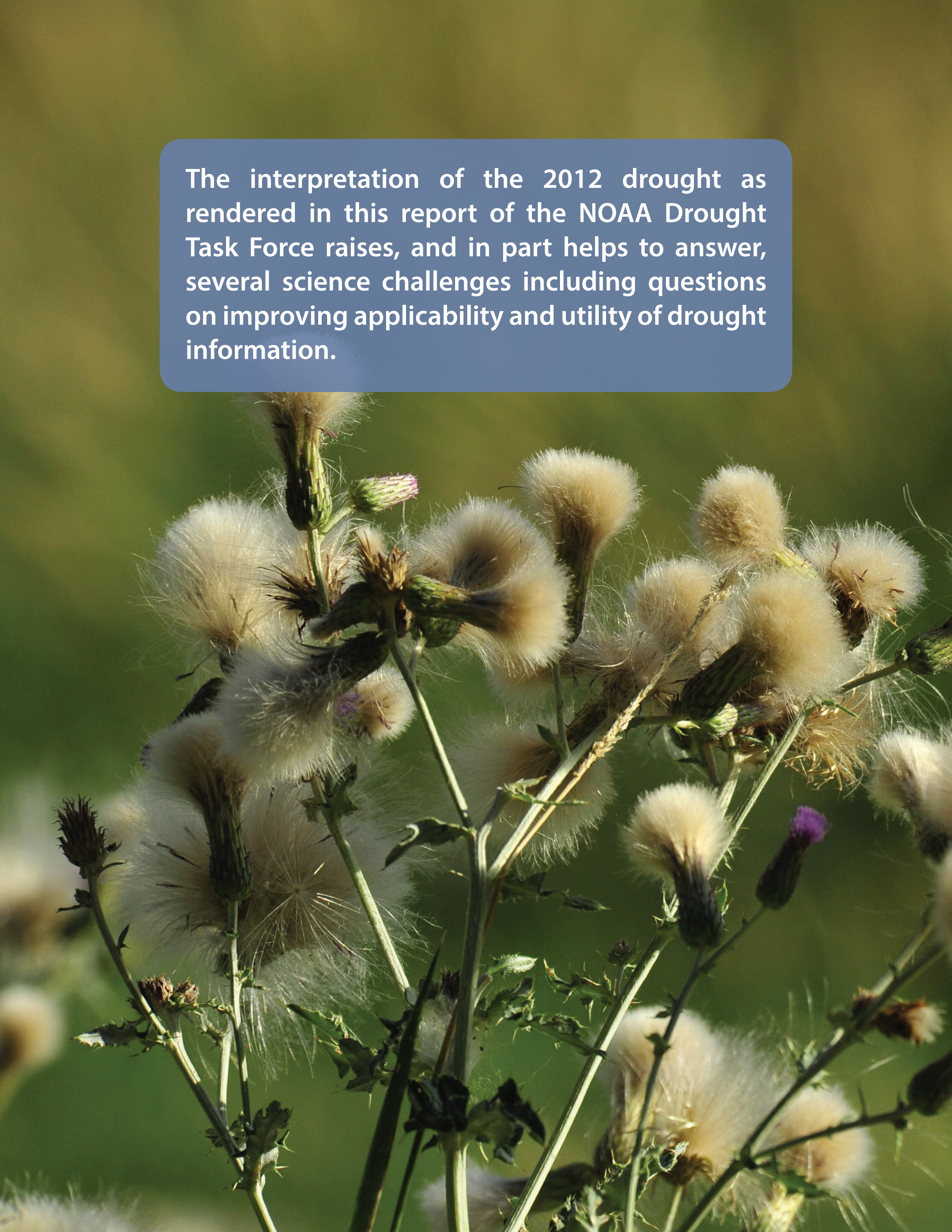


Figure 28. Same as Fig. 27 except for 2m-soil moisture in July. Shown also are the CFSv2 real forecast result and the initial 2m-soil moisture for R-2 and NLDAS respectively.



The interpretation of the 2012 drought as rendered in this report of the NOAA Drought Task Force raises, and in part helps to answer, several science challenges including questions on improving applicability and utility of drought information.

Summary Comments and Additional Questions

Overall Assessment of Origin and Cause

The 2012 drought developed rapidly over the central Great Plains during May and reached peak intensity by August. This being the region's principal rainy season, the failed rains had immediate negative consequences on the region's agricultural production with emergent adverse effects on other sectors including livestock, range land conditions, and river navigation to mention only a few. 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 causes for the drought were 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 assessment of underlying causes for these conditions and the cause for the drought did not reveal substantial effects from boundary forcings. Neither ocean states nor external radiative forcing appeared to play significant roles in determining the location, timing, or intensity of the rainfall deficits in summer 2012. There were, however, indications for boundary forcing of elevated summer temperatures, conditions that may have aggravated impacts of the rainfall deficits on the land surface conditions. There were also indications that an SST-forced change in climate after the late 1990s has subsequently elevated probabilities for drought events over the Great Plains region, though preliminary indications are that the signal is weak compared to the magnitude of individual events.

The overall assessment, while clarifying various *proximate* meteorological factors contributing to the 2012 Great Plains drought, is of an event *that did not have strong underlying causes*. This report's judgment that distinct causes were absent was based on appraising the influence of slowly evolving ocean states, antecedent soil moisture states, and changes in the atmosphere's chemical composition. Neither was found to appreciably constraint summer 2012 rainfall over the Great Plains. Thus, consistent with the poor skill of operational forecasts of the drought event, this report's appraisal is of an extreme event having limited potential for skillful long-lead predictability.

Assessment Limitations

There are several limitations to this assessment that may affect the strength of some of the conclusions on causes for the 2012 central Plains drought. In particular, only a single atmospheric model was used to appraise the sensitivity of climate over the central Great Plains during summer to the estimated boundary and external radiative forcings. Although the simulation results of this single model appeared largely consistent with the prediction results derived from 12 global modeling centers that produced seasonal forecasts for summer 2012, further experimentation with other models is called for. The ensemble size was inadequate to quantify if and how the probability of extreme drought was modified by boundary and external forcings. That is, the 20-member ensemble, though perhaps adequate for assessing the sensitivity of seasonal mean conditions and address the most probable outcome, was far too small to assess how the odds for particular threshold exceedences may have responded to forcings.

The assessment has also not resolved the role of antecedent soil moisture conditions on the summer drought. Indications from experimental tools discussed in section 6 suggest some methods of land data assimilation may lead to more skillful predictions than were operationally generated for 2012, a subject clearly warranting further research. Furthermore, the interaction between soil conditions and the evolving drought during May-August 2012 was not assessed. On this latter point, it remains to be determined how incipient depletion of soil moisture in early summer, as the drought began to unfold, may have affected rainfall chances in late summer. Our comparison of consecutive April and May initialized seasonal forecasts from operational centers implies little if any predictive information associated with such incipient land surface drying. Yet, as mentioned above, the question of land data assimilation methods requires careful further study.

Finally, the question of climate change forcing was not comprehensively studied in this report. The analysis based on a single coupled model needs to be repeated using a suite of CMIP models. In this regard, it is useful to include here the conclusions of other assessment reports, using multiple models and other information than available in this 2012 study, on overall U.S. drought change during the last century and also on projections for the future. These appear in several recent National and International assessment reports. Among the climate issues addressed in 21 Synthesis and Assessment Products (SAPs), the U.S. Climate Change Science Program inquired into current understanding of the causes for high-impact drought events over North America. The 2008 SAP 1.3 report concluded 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. It is likely, according to that report, that anthropogenic warming has increased drought impacts over North America through increased water stresses associated with warming, though the magnitude of the effect was judged to be uncertain. 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. For the 2046-2065 period, little agreement between projections of drought among 17 climate models studied in that report was found to exist over the U.S. heartland. How Great Plains drought will respond under global warming therefore continues to be a key unresolved question and a matter of future research.

Science Challenges Regarding Great Plains Drought

The interpretation of the 2012 drought as rendered in this report of the NOAA Drought Task Force raises, and in part helps to answer, several science challenges including questions on improving applicability and utility of drought information.

What are the current gaps in drought monitoring that, if addressed, would enhance assessments of the agricultural and hydrological consequences of meteorological drought?

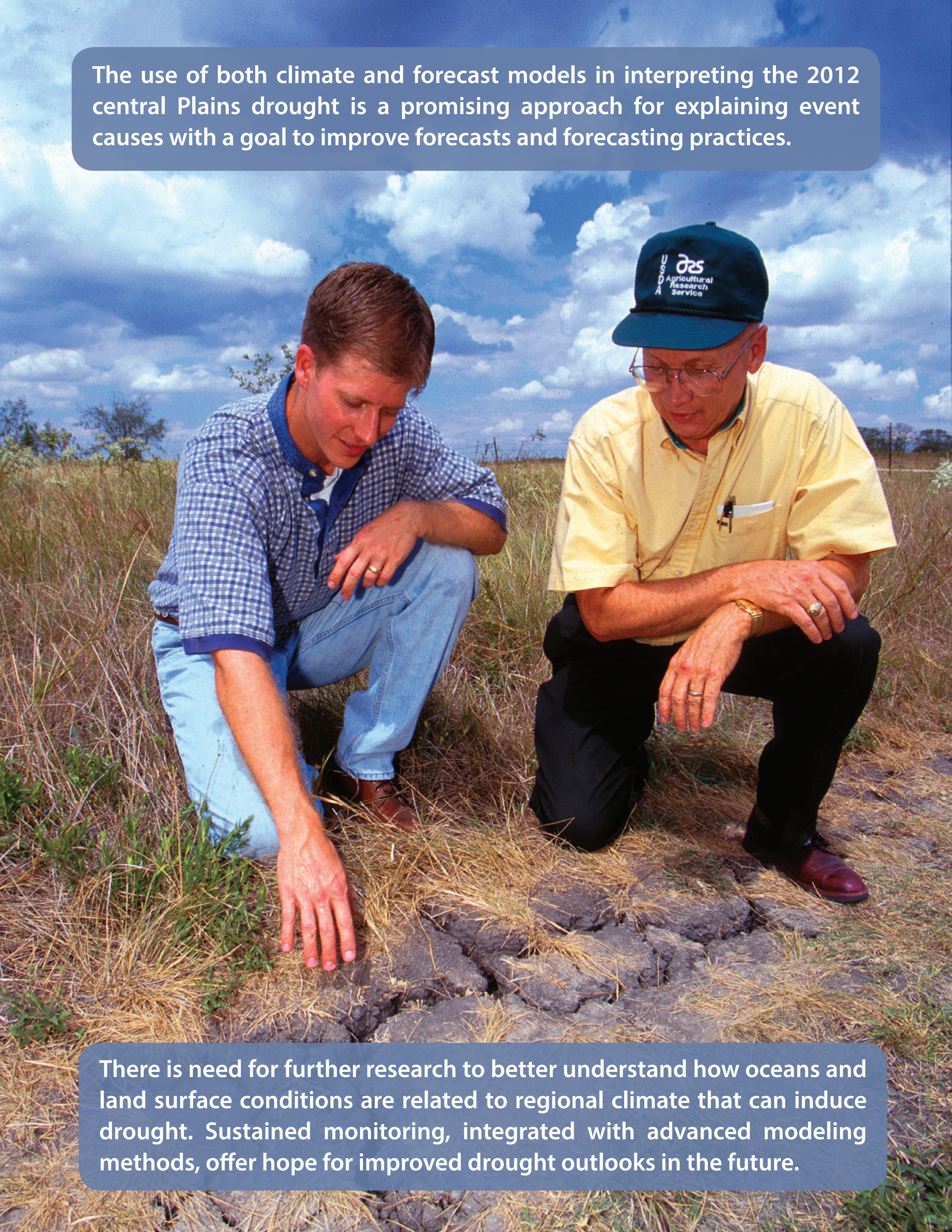
- What factors are currently limiting predictability of “flash droughts” over the central Great Plains during summer?
- What new products, both from monitoring and from prediction, could make drought information more actionable?
- What are the investments required, and what would be the probable payoffs,in enhancing and improving drought forecasts?

- What is the state of knowledge on the predictability of North American drought during different seasons, over different regions, and on different time scales?
- How does the science reconcile occurrences of extreme drought events with random (and largely unpredictable) atmospheric variability on the one hand, and the potentially predictable impacts by forcings such as ENSO, other SSTs, and also anthropogenic greenhouse gases?
- What are the lessons learned from the assessment of the causes for the 2012 central Great Plains drought (and also from recent assessments of the 2010-11 southern Plains drought, and the western U.S. drought of 1998-2004) that can be incorporated into advancing new prototype drought monitoring and prediction systems?
- What are the roles of natural variability of sea surface temperatures over the global oceans and the role of radiative forcing in altering probability of drought events like the 1998-2004 western U.S. drying, the 2010-11 Texas drought, and the 2012 central Great Plains drought?

The use of both climate and forecast models in interpreting the 2012 central Plains drought appears to be a promising approach for explaining event causes and understanding event predictability. There is need for further modeling and analysis efforts that would focus on improved understanding of how sea surface temperatures and land surface conditions are related to regional precipitation and temperature anomalies associated with drought conditions in general. Also, a further integration of monitoring with modeling is needed to improve the depiction of the physical processes, antecedent conditions, and ameliorating events affecting regional variability of drought including initiation and termination.

There thus remain key science challenges that must be met toward achieving a vision of developing new probabilistic prediction systems based on the optimal combination of dynamical models and statistical methods. Importantly, such systems must seek to improve the reliability and skill of drought forecasts, and be able to better depict associated uncertainties, so as to yield more actionable drought information.

The use of both climate and forecast models in interpreting the 2012 central Plains drought is a promising approach for explaining event causes with a goal to improve forecasts and forecasting practices.



There is need for further research to better understand how oceans and land surface conditions are related to regional climate that can induce drought. Sustained monitoring, integrated with advanced modeling methods, offer hope for improved drought outlooks in the future.

Acknowledgments

The authors acknowledge resources and organizational support for the Drought Task Force from the Modeling, Analysis, Predictions and Projections Program (MAPP) of NOAA's Climate Program Office (CPO); activities are supported by MAPP in partnership with the National Integrated Drought Information System (NIDIS) Program. The authors also gratefully acknowledge support from their home institutions and various funding agencies who help sustain their work.

Authors and MAPP Program management wish to thank all who helped finalize and publish this report: input from Drought Task Force participants on an early version of this report ; reviewers from the Drought Task Force and the external scientific community; staff at NOAA/CPO, the NIDIS Program Office and the NOAA Earth System Research Laboratory's Physical Sciences Division (ESRL/PSD). The authors also wish to thank Jon Eischeid of the University of Colorado-CIRES for his assistance with graphical analyses, and Barb DeLuisi of NOAA/ESRL/PSD for graphic design/layout of the report. The CAM4 and CCSM4 models used in this report were developed by NCAR, and have been kindly provided as a resource to the broader scientific community.

Contributing Authors

Amir AghaKouchak, University of California, Irvine
Hugo Berbery, University of Maryland, Earth System Science Interdisciplinary Center
Jiarui Dong, NOAA/NCEP/Environmental Modeling Center
Martin Hoerling, NOAA/ESRL/Physical Sciences Division
Arun Kumar, NOAA/NCEP/Climate Prediction Center
Venkhat Lakshmi, University of South Carolina
Ruby Leung, DOE Pacific Northwest National Laboratory
Xing-Zhong Liang, University of Maryland, Earth System Science Interdisciplinary Center
Lifeng Luo, Michigan State University
Brad Lyon, International Research Institute for Climate and Society
David Miskus, NOAA/NCEP/Climate Prediction Center
Kingtse Mo, NOAA/NCEP/Climate Prediction Center
Xiao-Wei Quan, NOAA/ESRL/Physical Sciences Division and University of Colorado-CIRES
Siegfried Schubert, NASA Goddard Space Flight Center/GMAO
Richard Seager, Lamont-Doherty Earth Observatory, Columbia University
Soroosh Sorooshian, University of California, Irvine
Hailan Wang, NASA Goddard Space Flight Center/GMAO
Yulong Xia, NOAA/NCEP/Environmental Modeling Center
Ning Zeng, University of Maryland, Earth System Science Interdisciplinary Center

Drought Task Force Organizational Contact: Annarita Mariotti, NOAA/OAR/Climate Program Office

For more information on the Drought Task Force, visit: http://cpo.noaa.gov/ClimatePrograms/ModelingAnalysisPredictionsandProjections/MAPPTaskForces/DroughtTaskForce.aspx

For more information on NIDIS, visit: http://www.drought.gov

Additional Reading

Brubaker K. L., P. A. Dirmeyer, A. Sudradjat, B. S. Levy, and F. Bernal, 2001: A 36-yr climatological description of the evaporative sources of warm-season precipitation in the Mississippi River basin. *J. Hydrometeor.*, **2**, 537–557, doi:10.1175/1525-7541(2001)002<0537:AYCDOT>2.0.CO;2.

CCSP SAP 1.3, 2008: Reanalysis of Historical Climate Data for Key Atmospheric Features Implications for Attribution of Causes of Observed Change. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Randall Dole, Martin Hoerling, and Siegfried Schubert (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, 156 pp.

Cook, B.I., R. L. Miller and R. Seager, 2009: Amplification of the North American Dust Bowl drought through human-induced land degradation. *Proceedings of the National Academy of Sciences of the United States of America.* **106**(13), 4997-5001.

Hoerling, M. P., and A. Kumar, 2003: The perfect ocean for drought. *Science*, **299**, 691-694, doi:10.1126/science.1079053.

Hoerling, M., X. Quan, and J. Eischeid (2009), Distinct causes for two principal U.S. droughts of the 20th century, *Geophys. Res. Lett.,* **36**, L19708, doi:10.1029/2009GL039860.

Hoerling, M., J. Eischeid, X. Quan, H. Diaz, R. Webb, R. Dole, and D. Easterling, 2012: Is a Transition to semi-permanent drought conditions imminent in the U.S. Great Plains? *J. Climate*, **25**, 8380-8386, doi:10.1175/JCLI-D-12-00449.1.

Hoerling, M., and Co-Authors 2013: Anatomy of an extreme event. *J. Climate*, **26**, in press, doi:http://dx.doi.org/10.1175/JCLI-D-12-00270.1.

Huang, J., H. van den Dool, and K. Georgokakis, 1996: Analysis of model-calculated soil moisture over the U.S. (1931-1993) and applications to long range temperature forecasts. *J. Climate*, **9**, 1350-1362, doi: 10.1175/1520-0442(1996)009<1350:AOMCSM>2.0.CO;2.

IPCC, 2012: Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). Report available at: http://ipcc-wg2.gov/SREX/report/

Kushnir Y, R. Seager , M. Ting, N. Naik , and J. Nakamura, 2010: Mechanisms of tropical Atlantic influence on North American hydroclimate variability. *J Climate*, **23**, doi:10.1175/2010JCLI3172.1.

Quan, X.W., MP Hoerling, B Lyon, A Kumar, MA Bell, MK Tippett and H Wang, 2012: Prospects for Dynamical Prediction of Meteorological Drought. *J. Appl. Meteorol. Climatol.* , **51**(7) 1238-1252, doi:10.1175/JAMC-D-11-0194.1.

Schubert, S. D., M. J. Suarez, P. J. Pegion, R. D. Koster, J. T. Bacmeister, 2004. Causes of Long-Term Drought in the United States Great Plains. *J. Climate*, **17**, 485-503. doi:10.1175/1520-0442(2004)017<0485:COLDIT>2.0.CO;2.

Schubert, S.D., M. J. Suarez, P. J. Pegion, R. D. Koster, J. T. Bacmeister, 2004: On the Cause of the 1930s Dust Bowl. *Science*, **33**, 1855-1859, doi:10.1126/science.1095048.

Schubert, S. D., M. J. Suarez, P. J. Pegion, R. D. Koster, and J. T. Bacmeister, 2008. Potential Predictability of Long-Term Drought and Pluvial Conditions in the United States Great Plains. *J. Climate*, **21**, 802-816, doi:10.1175/2007JCLI1741.1.

Schubert, Siegfried, and Coauthors, 2009: A U.S. CLIVAR Project to Assess and Compare the Responses of Global Climate Models to Drought-Related SST Forcing Patterns: Overview and Results. *J. Climate*, **22**, 5251-5272, doi:10.1175/2009JCLI3060.1.

Seager, R., Y. Kushnir, C. Herweijer, N. Naik and J. Velez, 2005: Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856-2000. *Journal of Climate*, **18**(19), 4068-4091, doi:10.1175/JCLI3522.1.

Seager, R., Y. Kushnir, M.F. Ting, M. Cane, N. Naik and J. Velez, 2008. Would advance knowledge of 1930s SSTs have allowed prediction of the Dust Bowl drought? *Journal of Climate*, **21**, 3261-3281. doi:10.1175/2007JCLI2134.1.

Seager, R., and G. Vecchi, 2010: Greenhouse warming and the 21st century hydroclimate of southwestern North America. *Proc. Nat. Acad. Sci*., **107**(50), 21277–21282.