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Could the 2012 Drought in Central US Have Been Anticipated?—A Review of NASA Working Group Research

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Abstract: This paper summarizes research related to the 2012 record drought in the central United States conducted by members of the NEWS (NASA (National Aeronautics and Space Administration) Energy and Water cycle Study) Working Group. Past drought patterns were analyzed for signal coherency with latest drought and the contribution of long-term trends in the Great Plains low-level jet, an important regional circulation feature of the spring rainy season in the Great Plains. Long-term changes in the seasonal transition from rainy spring into dry summer were also examined. Potential external forcing from radiative processes, soil-air interactions, and ocean teleconnections were assessed as contributors to the intensity of the drought. The atmospheric Rossby wave activity was found to be a potential source of predictability for the onset of drought. A probabilistic model was introduced and evaluated for its performance in predicting drought recovery in the Great Plains.

Key words: Drought 2012, Great Plains, climate variability and trends, drought prediction.

1. Introduction

The 2012 drought that engulfed most of North America set many records, surpassing by most measures even the severity of the 1988 drought [1]. Numerous press and governmental resources have documented the extent and tremendous impact of the 2012 drought in the United States [2-4]. An assessment report of the NOAA (National Oceanic and Atmospheric Administration) Drought Task Force [5] summarized that the drought—primarily that covering the central Great Plains during May-August of 2012 (Fig. 1a)—resulted mostly from natural atmospheric variations. They concluded: "neither ocean states nor human-induced climate change appeared to play significant roles." and so, the drought could not have been predicted.

Here we ask: If not predictable, could the 2012 drought nonetheless have been "anticipated"? In this group effort as part of the NEWS (NASA (National Aeronautics and Space Administration) Energy and Water cycle Study) Program, we examine how this

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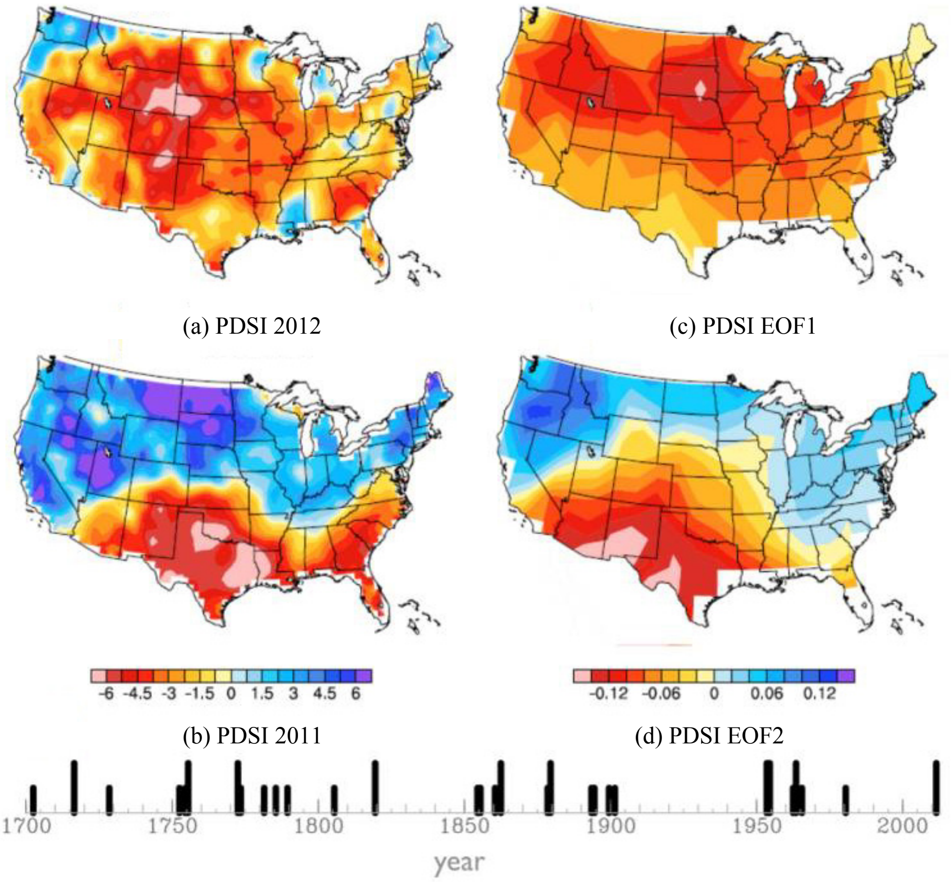


(a) PDSI 2012 (c) PDSI EOF1

(b) PDSI 2011 (d) PDSI EOF2

(e) PDSI PC occurrence histogram

Fig. 1 MJJ (May-July) PDSI during (a) 2012 and (b) 2011, in comparison with (c) EOF1 and (d) EOF2 of the MJJ PDSI from 1900 to 2012. (e) The occurrence of which PC2 is followed by PC1 when both PCs exceed two (one) standard deviation plotted as long (short) sticks, based upon the North American Drought Atlas tree-ring data.

drought developed and whether or not there were signs that could foretell such drought beyond the mere use of forecast models. This paper summarizes relevant and recently published research by members of the NEWS working group on extremes.

The 2012 drought was examined from several aspects: (1) the large-scale pattern and its recurrence over North America; (2) precipitation and synoptic regimes over the Great Plains; (3) the relative roles of ocean surface temperatures, soil moisture, and radiative forcing in drought formation and prolongation; (4) the role and modeling progress of ET (evapotranspiration) fluxes; and (5) potential predictability and model scenarios for drought recovery. These studies, in hindsight, suggest that factors leading to the 2012 drought did reveal signs that could have helped expect its occurrence, and therefore provide the opportunity to recognize and anticipate a possible future recurrence of drought at such scale of the 2012 event.

2. Study Area and Data Sources

The Great Plains of North America extends from central Texas north to southern Canada, covering some 1,300,000 km^2. The climate varies widely by area and time of year, but in general is semi-arid grassland with cold winters, a wet spring, and hot humid summers, and is suitable for rangeland and agriculture. Indeed, much of the region has been developed as pasture and farms, and is a major source of agricultural products for the global food market.

However, the region's climate undergoes significant variability and is prone to extensive drought such as during the mid-1950s, late 1980s, and the infamous 1930s Dust Bowl droughts. Given the economic importance of agricultural activities in the region and the dependence of agriculture on climatic conditions, a better understanding of climate and drought dynamics of the region is critical for planning and management of the region's agricultural activities.

Many data sources were used in the recent research reported on here. Atmospheric data were provided by the NARR (North American Regional Reanalysis) [6], the ECMWF (European Center for Medium-Range Weather Forecasts) Interim Reanalysis (ERA-I) [7], the NCEP/DOE (National Center for Environmental Prediction/Department of Energy) Reanalysis version 2 [8], the CFSR (Climate Forecast System Reanalysis) [9], and the NASA (National Aeronautics and Space Administration) MERRA (Modern Era Reanalysis for Research and Applications) [10]. Precipitation data were provided by NARR, which assimilates rain-gauge data in addition to modeling rainfall, and has been shown to adequately reproduce precipitation and wind patterns over the contiguous US [11], and by the CRU (Climatic Research Unit) monthly precipitation dataset [12]. Drought intensity (PDSI (Palmer drought severity index)) data were obtained from instrumental data [13], derived from the PRISM (Parameter-Elevation Regressions on Independent slopes model) [14, 15] and from tree ring proxies [16]. Remotely sensed surface energy flux measurements were collected by MODIS (moderate resolution imaging spectroradiometer) [17]. Modeled climate data were generated by the NASA GOES-5 (Goddard Earth Observing System Model, version 5) [18]. SST (Sea surface temperatures) were obtained from the NOAA ERSST (extended reconstructed SST) version 3b [19].

3. Results and Discussion

3.1 Drought Pattern and Recurrence

A unique aspect of the 2012 drought is that it evolved from the 2011 drought that devastated the southern Great Plains (Fig. 1b). This precursor drought was associated with a La Niña event [20]. The central Great Plains therefore experienced consecutive drought conditions from 2011 to 2012 (which continued at least through March 2013). On the long-term perspective, the EOF (empirical orthogonal function) analysis of PDSI for the period of 1900-2012 indicated that the first two leading patterns of drought are similar to the recent ones—i.e., EOF1 with a widespread pattern (Fig. 1c) corresponds to the 2012 drought, while EOF2 with the dipole pattern (Fig. 1d) resembles the 2011 drought. The apparent correspondence between the EOFs and the recent droughts suggest that a drought evolution similar to that occurring from 2011 to 2012 may not be unique. To examine further, we plotted the occurrence of when the PC2 (second principal component) leads the PC1—in the sense that the 2011 drought led the 2012 one. The dataset used here is the PDSI derived from tree rings [16]. The result is shown in Fig. 1e with the long (short) bars indicating that both PC1 and PC2 are positive and both exceed two (one) standard deviation. It appears that the evolution of droughts like the 2011-2012 succession did occur sporadically in the past.

3.2 Precipitation and Low-Level Jets

Over the central US, the warm-season precipitation migrates from the southern Great Plains in spring to the upper Midwest in summer, providing crucial growing-season water along its path. Both rainfall and convective storm activity reach their maximum in May and June in the southern Great Plains forming a precipitation center over the Oklahoma-Texas region [21]. Fig. 2 shows the time series of pentad precipitation averaged for Oklahoma-Texas over the period 1979-1995 versus that for 1996-2012, along with the percent difference between the two periods. The late-spring rainfall maximum is depicted by the elevated spring precipitation peaking in May. However, over the past three decades, the amount of spring precipitation has declined: There is a clear reduction in AMJ (April-June) rainfall, particularly the entire month of May, during which deficits of as much as 50% are observed [22]. This rainfall reduction suggests marked decline of a vital water source during the rainy season in the Oklahoma-Texas region, and also makes the region more susceptible to drought during the summer.

A key atmospheric circulation systems closely connected to the region's seasonal precipitation is the GPLLJ (Great Plains low-level jet), a transient pattern of nocturnal strong winds just above the surface. The GPLLJ transports abundant amounts of water vapor from the Gulf of Mexico and provides moisture convergence at its northern edges, facilitating the formation of convective precipitation. Focusing on May, Fig. 3a depicts the climatological precipitation overlaid with 925-mb wind vectors for geographical reference; the white box indicates the sub-region over which averages are calculated in subsequent panels. The trend for all latitudes is calculated using linear least-squares regression for 6-hourly 925-mb v-wind strength of each month (Fig. 3b) and monthly total precipitation (Fig. 3c). There is an apparent increase in the strength of the v-wind between 30°-35° N including the Gulf of Mexico (i.e., upstream of the GPLLJ). North of 40° N the increasing trend becomes very small, to near zero. These v-wind changes accompany a northward migration of the maximum gradient of v-wind speed and the resultant convergence at the exit region of the GPLLJ. Correspondingly, the changes in total precipitation reveal a northward migration, leading to drying in the central and southern Great Plains. These changes are reported in Ref. [22].

3.3 Trends in the Transition to Summer Dry Period

The central US undergoes a seasonal transition between June and July during which precipitation decreases by about 25%. This seasonal precipitation

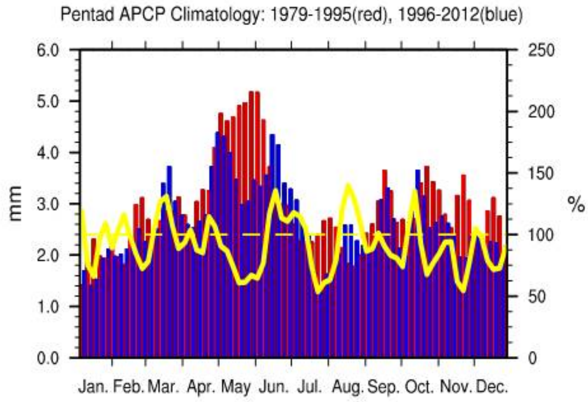
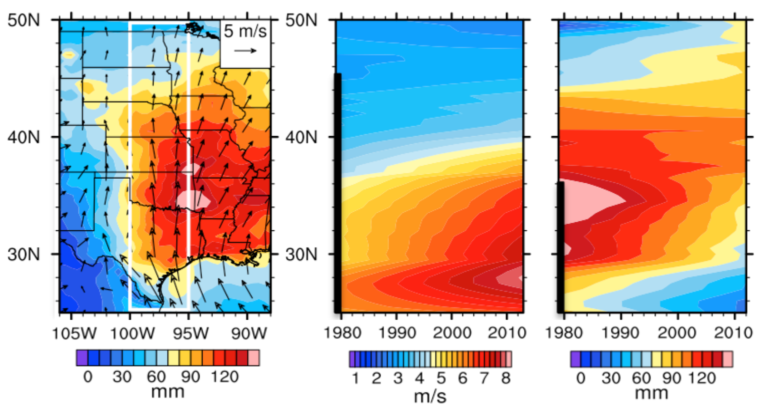


Fig. 25-day mean precipitation over the Oklahoma-Texas region for the period 1979-1995 (red) versus 1996-2012 (blue), and the percent difference between the two periods (yellow line). Note the large decline in May.



(a) 925-mb winds and precipitation (b) v-wind 925-mb (c) precipitation

Fig. 3 (a) Monthly climatology for precipitation (shaded) and 925-mb wind field (vectors); (b) latitude-time Hovmöller trend plots for 925-mb v-wind; (c) total precipitation. Latitudes in which the regression coefficient is significant at 95% confidence are indicated along the y-axis.

Source: Barandiaran et al., 2013 [22].

decrease has been observed as having intensified since 1979 [23]. The concurrence of this intensified dry transition with a spring drought can facilitate the formation of a "flash drought" such as what was seen during the drought of 2012, during which the drought deepened very quickly over a large area from abnormal to exceptional drought conditions.

Wang et al. [28] found that concurrent with the drying trend is an increase in downward shortwave radiation flux (i.e., fewer clouds) and in tropospheric subsidence. There was also an increase in planetary boundary layer height, and an enhanced evaporative fraction associated with this intensified transition from spring to summer over the central Great Plains. Furthermore, these changes are associated with an anomalous ridge over the western US during this transitional season. These changes are weakly associated with SST forcing but rather strongly enhanced by land-atmosphere feedbacks; these suggest a persistent tendency in drought maintenance and expansion during the mid-summer.

3.4 Forcings That Initiate/Enhance Drought

3.4.1 Radiative Forcing

Another unique feature associated with the 2012 drought is its rapid development, coined "flash drought" by the NOAA report [5]. In particular, the drought over the central Great Plains expanded rapidly during June 2012 and quickly formed dry to exceptional drought conditions. As shown in Fig. 4, the rapid development of 2012 drought is associated with enhanced shortwave radiation input, as depicted by MODIS data and also seen in the ERA-I surface shortwave fluxes. The timing of intensive shortwave radiation anomalies coincides with the seasonal maximum of shortwave radiation, and the area is closely associated with the rainfall deficits (not shown).

3.4.2 Land Forcing

Santanello et al. [24] diagnosed the process and impacts of local land—atmosphere coupling during dry and wet extreme conditions in the US southern Great Plains simulated by nine different land-PBL (planetary boundary layer) schemes coupled in a high-resolution regional model. Results show that the sensitivity of land-air coupling is stronger toward the land during dry conditions, while the PBL scheme coupling becomes more important during the wet regime. In other words, soil moisture impacts are felt via land-PBL interactions, where the atmosphere is more sensitive to dry soil anomalies and deep, dry PBL growth can lead to a persistent positive feedback on dry soils. Hubbard et al. [25] found that dry soil moisture conditions could strongly enhance the effects of remote SST forcing. Comparing remote sensing and modeling data, Ozturk et al. [26] found that the ET effect, which is linked to irrigation in the northern Plains, also feedbacks on drought intensity. Fig. 5 demonstrates that, when it is initially dry, irrigation is engaged more in order to grow the crops; then after the drought persists, the crop fails and less irrigation takes place on the dying plants. In other words, early in drought irrigation mitigates drought severity by modulating some of the land-air coupling. But later on in the midst of a large-scale drought, the decrease or lack of irrigation does the opposite and the net land-air feedbacks reverse to exacerbate the drought.

3.4.3 Teleconnection Forcing

As was noted in the NOAA Drought Task Force report [5], the 2012 drought lacked substantial ocean forcing in the tropical Pacific given the ENSO (El Niño/Southern Oscillation) neutral status. Using the NASA GEOS-5 model, Wang et al. [27] found that the winter-spring response over the US to the Pacific SST is remarkably similar for years 2011 and 2012, despite substantial differences in the tropical Pacific SST. The pronounced winter and early spring temperature differences between the two years (warmth confined to the south in 2011 and covering much of the continent in 2012) primarily reflect differences in the contributions from the Atlantic and Indian Oceans, with both acting to cool the east and

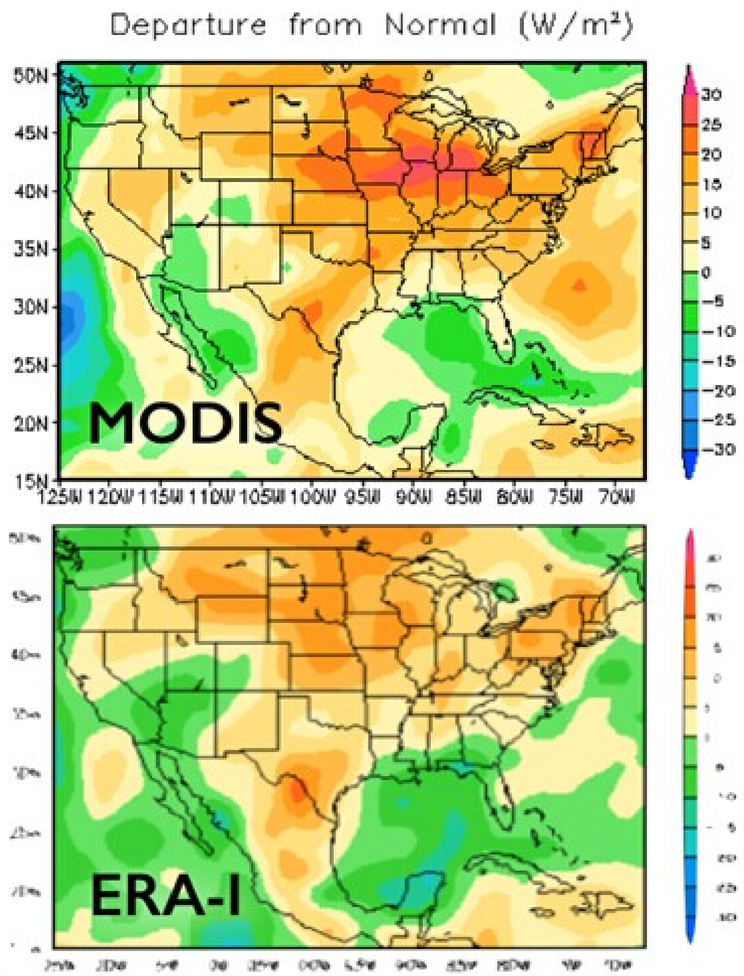


Fig. 4 (top) Shortwave radiation anomaly from MODIS (from 10 year mean); (bottom) shortwave radiation anomaly from ERA-Interim reanalysis.

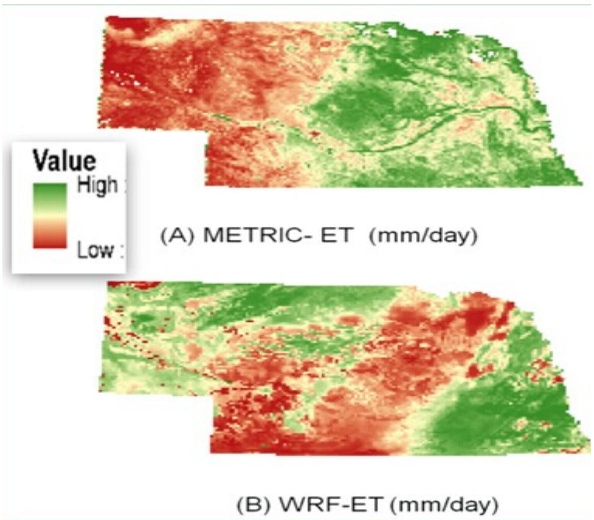


Fig. 5 Surface ET simulated for two days in August 2012 by (a) MODIS-METRIC model that includes irrigation, and (b) WRF-CLM model without irrigation leading to drying in farmed areas.

upper mid-west during 2011; during 2012 the Indian Ocean reinforced the Pacific-driven continental-wide warming and the Atlantic played a less important role. In early summer, the development of a stationary Rossby wave over the North Pacific—an atmospheric process—produced high-amplitude circulation anomalies connected to the record-breaking precipitation deficits and heat in the central Plains in the middle of summer. Wang et al. [28] further indicated that, particularly in July, the seasonal pattern of stationary waves has changed since 1979 in a way that favors/enhances shorter stationary waves that tend to enhance heat and dry conditions over the central Plains.

3.5 Potential Predictability

The GEOS-5 modeling study by Wang et al. [27]

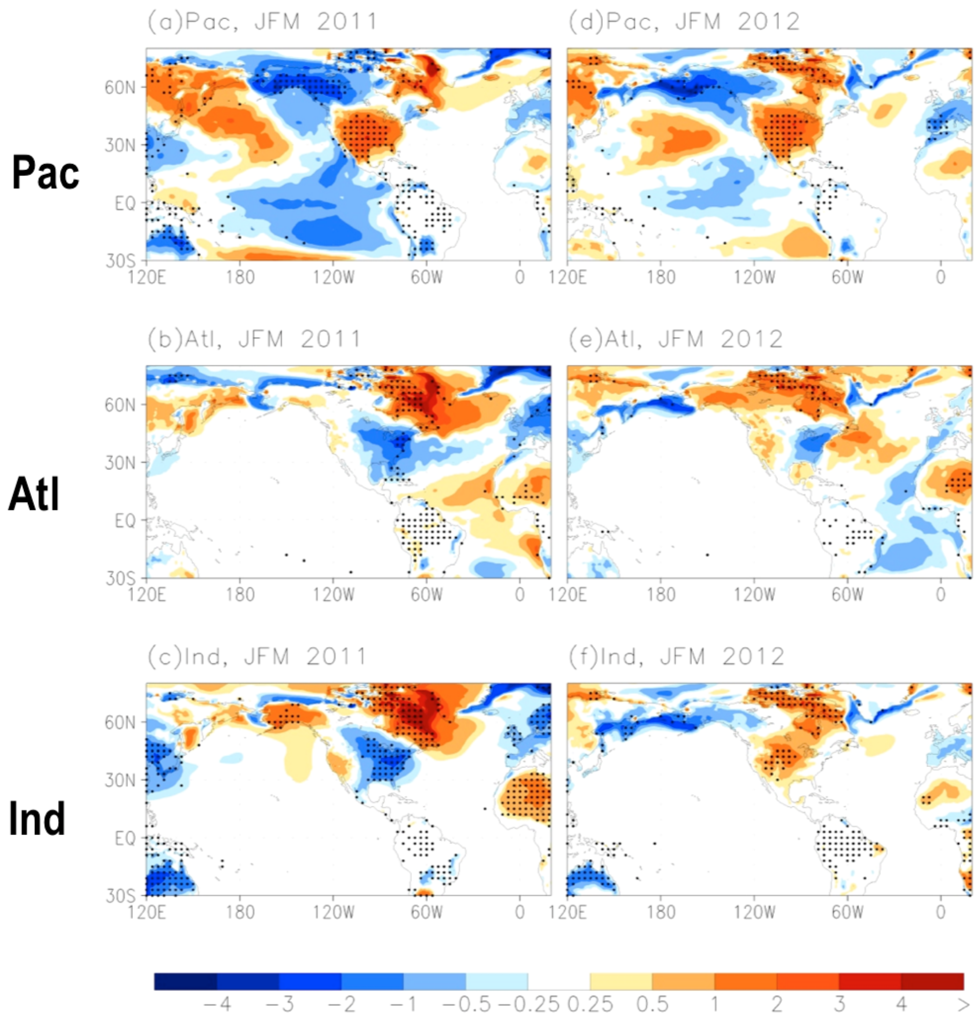


Fig. 6 JFM ensemble mean 2 m air temperature response to SST forcing in individual ocean basins based on GOES-5 ensembles initialized in November of the previous year, for SST in for (a, d) Pacific, (b, e) Atlantic and (c, f) Indian Ocean. Source: H. Wang et al., 2013 [27].

(Fig. 6) suggested that the 2012 drought would not have benefited from long-lead prediction, as the full extent of the event was not forecasted until one month prior. This implies the forcing of stationary Rossby waves reinforcing the drought at intra-seasonal timescales. In other words, short-term climate prediction from 2 weeks to 2 months may be the only remedy for predicting a "flash drought" such as that of 2012.This is because the forcing of short Rossby waves is triggered by submonthly vorticity transients [29] and varies month-by-month [28], and therefore it is difficult topredict them at lead times longer than the seasonal time period. However, once the Rossby waves develop, the perturbation downstream would establish and frequently last for an extensive period of time, about 2-6 weeks [29]. The short-wave regime of Rossby waves also is helpful in identifying the region of impact from extreme climate anomalies. This function of Rossby waves in providing early warning of heat waves in the US was discussed by Wang et al. [27].

3.6 Drought Recovery

An often-overlooked aspect concerns the processes by which drought recovers. Drought management would benefit greatly if more risk-based information

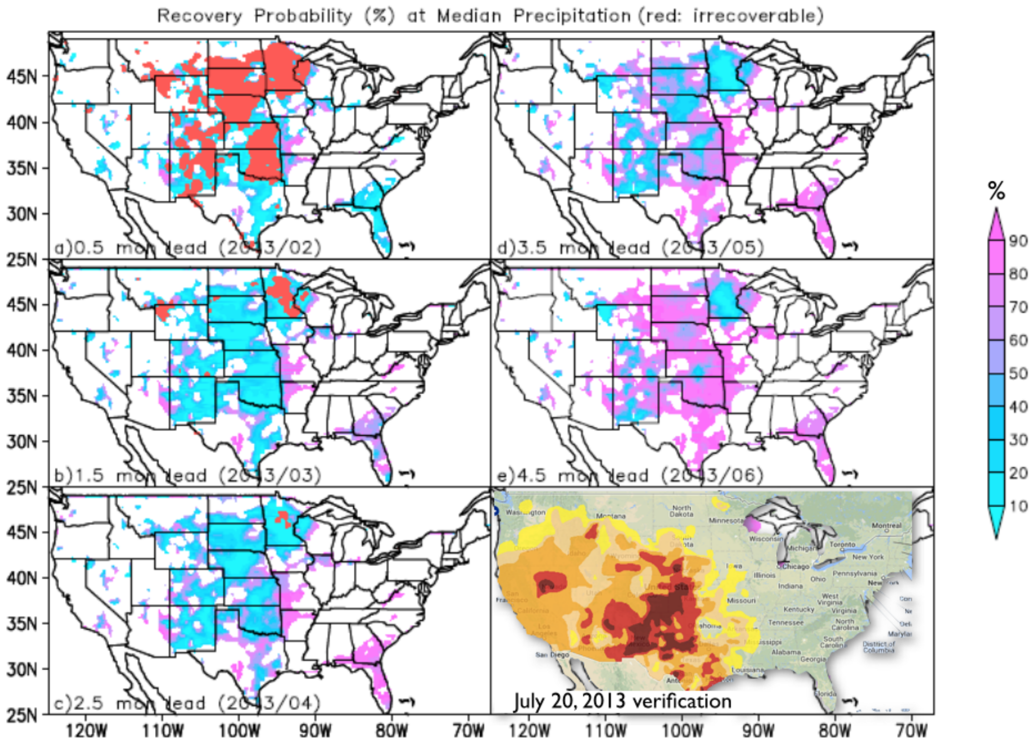


Fig. 7 Maps of the probability of drought recovery under the median (P = 50%) cumulative precipitation scenario. Red-colored areas are those unable to recover from drought under any cumulative precipitation scenario, and uncolored areas are those not in drought ($\theta > \theta_{drought}$) as of February 1, 2013. (a)-(e) The results for lead times of 0.5-4.5 months.
Source: Pan et al., 2013 [30].

is available on how a region in drought may recover, e.g., the likelihood of recovery under different precipitation scenarios and the related uncertainty. As discussed earlier, several factors, such as the initial moisture condition, the amount and timing of precipitation, and the temperature control the recovery process. In view of the aforementioned limit in seasonal forecast skills of the 2012 drought, Pan et al. [30] proposed a probabilistic framework to assess drought recovery that is based on the joint distribution between cumulative precipitation—the main driver for recovery—and a soil moisture—based drought index.

Fig. 7 shows maps of recovery probability under the median cumulative precipitation scenario staring in February, 2013. The smaller the value, the less likely it is to recover and the higher the probability (risk) that the area remains in drought. Fig. 7a shows that large parts of central Plains are irrecoverable at 0.5 month, and the recovery probability is very low. Most areas start to be recoverable from the 1.5 month onward (Fig. 7b), but the recovery probability is low (10%-20%). The recovery probability across the continental United States increases at 2.5 months and 3.5 months until it reaches the 80% level at the 4.5 month lead (very likely to recover if median cumulative precipitation is received for 6 months). As shown in the lower right corner (verification using observed PDSI), by July, 2013, most of the northern Plains has indeed recovered from drought, although the southwestern states remained in drought. The results suggest that a probabilistic analysis for drought recovery still can provide risk information useful to drought managers, even if the onset of drought was not predicted.

4. Conclusions

The 2012 drought was unique in terms of the rapidity with which it developed, the lack of “classic” oceanic forcing patterns, and the concurrence with record heat waves in the central US. Through the collection of studies, we found that the 2012 drought did, however, show signs of precursors, albeit without a long lead time. First, the succession of a meridional "dipole" drought pattern like that in 2011 followed by the widespread drought pattern like that in 2012 is not unprecedented; in fact, it has repeatedly occurred over the past 300 years or more. Model experiments suggested that the tropical Atlantic Ocean status (instead of the tropical Pacific) helped initiate drought conditions in spring 2012. Second, for the past 32 years, the GPLLJ has strengthened making the critical spring (rainy) season over the central and southern part of the Great Plains drier than ever—this echoes the ongoing (2014) drought in Texas. Third, the timing of the drought development in June coincides with the seasonal drying in the central Plains, enhancing shortwave radiation while reducing ET; this further exacerbated the drought as it persists towards the middle of summer. Fourth, the state of the soil moisture can precondition, enhance, and prolong drought conditions. Human activities such as irrigation may partially offset this, but cannot override the effect from large-scale atmospheric circulations. Finally, a standing pattern of stationary Rossby short waves developed in the late spring/early summer season, producing the standing anticyclone that later occupied the central US for the rest of summer.

Although it is difficult to foresee the initiation of a specific stationary Rossby wave pattern, once it develops the standing pattern of short waves did persist for an extensive period of time, thus providing potential sources for short-term/intraseasonal climate prediction—i.e., early warning. In other words, prediction of the 2012-like drought is not without hope, but more emphasis may need to be on intraseasonal scales. Furthermore, predicting the recovery of drought is equally important and this has been shown to be feasible and potentially useful.

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