# An enhanced seasonal transition that intensified summer drought in the central U.S.

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## Abstract

Precipitation in the central U.S. decreases by about 25% during the seasonal transition from June to July, and this precipitation decrease has been observed to have intensified since 1979. Such an intensification could enhance future spring drought occurrences such as was the case in the 2012 “flash drought” in the Midwestern U.S., where conditions evolved quickly from being abnormally dry to exceptionally dry within a mere month from June to July. In this study, various atmospheric and land reanalysis datasets were analyzed to examine the trend calculated from 1979 to 2012 in the June-to-July seasonal transition. It was found that the change in precipitation deficit was accompanied by increased downward shortwave radiation flux and tropospheric subsidence, enhanced evaporative fraction, as well as an elevated planetary boundary layer height. The change in the tropospheric circulation encompassed an anomalous ridge over the western U.S. and a trough on either side; this wave-form circulation pattern is known to induce dry conditions in the central U.S. Possibly, the trends in the June-to-July seasonal shifts in precipitation, drought severity and tropospheric circulation intensified the 2012 “flash drought” in timing and extent. The knowledge of the trends allows one to anticipate the evolution of spring onset of drought into the summer.

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## 1. Introduction

In the summer of 2012, the central United States experienced severe and widespread drought conditions. Precipitation during May-August 2012 was the lowest since instrumental records began, and summer heat waves made conditions worse [*Hoerling et al.*, 2013a; *Hoerling et al.*, 2013b]. The severity of the 2012 drought caused significant losses in crops and had an even larger economic impact on the livestock industry; this triggered federal agencies such as the U.S. Department of Agriculture and a number of states to declare disaster areas [*USDA*, 2012]. In hindsight, one unique feature of the 2012 drought was its rapid intensification during the early summer, coined a "flash drought" by a NOAA Assessment Report [*Hoerling et al.*, 2013a]. A figure from the NOAA report [*Hoerling et al.*, 2013a], shown here in Fig. 1a, depicts the rapid expansion of drought conditions in Wyoming, Colorado, Kansas, Nebraska and South/North Dakota, evolving over a mere month from moderate to severe status (categorized as per the U.S. Drought Monitor).

The timing of the Central Plains's drought intensification coincided with a common feature of seasonal drying: Climatologically, precipitation in the central U.S. generally is reduced by about 25% from June to July (as shown in Fig. 1b by the long-term monthly rainfall averaged over the central U.S.). Such a rainfall reduction occurs in association with the development of the North American Monsoon (NAM) and the concurrent formation of the upper-level anticyclone over the western U.S., nudging the jet stream northward [*Barlow et al.*, 1998; *Higgins et al.*, 1997; *S-Y Wang and Chen*, 2009]. The precipitation difference of July minus June (Fig. 1c), **denoted hereafter as "July-June"**, depicts a distinct zone of rainfall reduction to the north and east of the NAM region, covering the Central Plains and the Great Plains. While this seasonal rainfall reduction is a well-known phenomenon, the extent to which a progression of drying may have amplified has not been examined.

The extremity and extensive impacts of the 2012 drought have prompted a number of studies, including those dealing with the meteorological processes and drought prediction [*Hoerling et al.*, 2013a; *Hoerling et al.*, 2013b; *Kumar et al.*, 2013], drought depiction using various monitoring tools [*Mallya et al.*, 2013], drought recovery forecasts [*Pan et al.*, 2013], the connection with low-frequency climate variability and trends [*Barandiaran et al.*, 2013; *S-Y Wang et al.*, 2013b], the impacts on agriculture and economy [*Al-Kaisi et al.*, 2013] and global food security [*Boyer et al.*, 2013]. However, the lack of prominent large-scale forcing factors in the tropics, such as that of ENSO, is a probable reason that has impeded climate forecast models' prediction of the 2012 drought [*Hoerling et al.*, 2013b; *H Wang et al.*, 2014]. Therefore, the focus of this study was to examine possible forcing factors other than ENSO, as well as regional drivers and mechanisms that may be related to the 2012 flash drought, including the role of land-atmosphere interactions, circulation patterns, their interaction and, subsequently, how some or all of these may have changed.

To accomplish our analysis, we utilized an array of surface observations and global reanalysis datasets; these are outlined in Section 2. Surface conditions associated with the change in the June-to-July circulation transition are presented in Section 3, followed by an analysis of the atmospheric and oceanic conditions in Section 4. A climate attribution analysis is presented in Section 5. Concluding remarks are provided in Section 6.

## 2. Data and models

*a. Data sources*

Global reanalysis products are an ideal set of data to support this study. However, any exploration of long-term changes using a single reanalysis is of concern due to changing observation systems that may result in spurious trends [*Paltridge et al.*, 2009]. Thus, to obtain an optimal estimate of long-term trends in the atmosphere, we utilized an array of global reanalyses and sought consensus. We used four post-1979 datasets that cover the satellite era – the acronyms, full names, and description of each dataset are provided in Table 1. The data group consists of MERRA [*Rienecker et al.*, 2011], CFSR [*Saha et al.*, 2010], ERA-Interim [*Dee et al.*, 2011] and the NCEP/DOE "R-2" reanalyses [*Kanamitsu et al.*, 2002]. In the following analyses, the atmospheric variables are derived from an ensemble of these four reanalysis datasets using equal-weight averaging. In addition, the NARR regional reanalysis data [*Mesinger et al.*, 2006] was used for the analysis of boundary layer heights. Other observational datasets included the monthly Climatic Research Unit (CRU) precipitation and surface air temperature data (http://www.cru.uea.ac.uk/data/) and the Palmer Drought Severity Index (PDSI) at 1/8° – derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (http://www.wrcc.dri.edu/wwdt/ batchdownload.php). We also analyzed the NOAA Extended Reconstructed SST (ERSST) Version 3b data [*Smith et al.*, 2008] for the depiction of ocean states.

Land surface analyses were obtained from the Mosaic [*Koster and Suarez*, 1994] and Noah [*Ek et al.*, 2003] land surface models as part of the recently released North American Land Data Assimilation System project Phase 2 (NLDAS-2) [*Xia et al.*, 2012]. All land surface models were run offline at 1/8° horizontal resolution using gauge and bias-corrected atmospheric

(NLDAS-2) forcing data. Monthly means were calculated across the period of record (1979-2012) while linear trends were calculated up to 2011 (to leave 2012 out for validation).

*b. Model simulations*

To investigate the possible sources of change in the June-to-July transition, we also examined a set of idealized model simulations using the NASA Goddard Earth Observing System Model, Version 5 (GEOS-5) Atmospheric General Circulation Model (AGCM). The AGCM simulations consist of a control run forced with a seasonally varying SST climatology (1901-2004), and three anomaly runs forced with a warm trend pattern, a cold Pacific pattern, and a warm Atlantic pattern (superimposed onto the seasonally varying SST climatology). Following *Schubert et al.* [2009], the warming trend, Pacific pattern and Atlantic pattern were obtained as the three leading rotated empirical orthogonal functions (REOFs) of annual mean SST over the period 1901-2004. The amplitudes for the imposed Pacific and Atlantic SST patterns corresponded to two standard deviations of their principal components (PCs), with the assumption of linear model response. Global warming trend was imposed on the model in separate runs to simulate the impact of warming during the latter half of the 20$^{th}$ century. The model response to a leading SST pattern was obtained as the mean difference between the control run and the anomaly run. For these experiments, the GEOS-5 AGCM was run with 72 hybrid-sigma vertical levels extending to 0.01hPa, and 1° horizontal resolution on a latitude/longitude grid. *Schubert et al.* [2009] provides more details of the leading SST patterns and the AGCM experiment design. The GEOS-5 AGCM is described in *Rienecker et al.* [2008] and *Molod et al.* [2012], with the latter providing a comprehensive assessment of model fidelity. All the AGCM simulations were 50 years long.

## 3. Surface and PBL conditions

The linear trend of the post-1979 change in the July-June (i.e. July minus June) precipitation difference is shown in Fig. 2a. In comparison with Fig. 1c, the precipitation deficit from June to July is noticeably intensified in the northern part of the U.S., covering both the Central Plains and the northern Rockies. Around Iowa, Nebraska and part of Illinois, the precipitation reduction has diminished twofold when compared to that of the 1980s. Likewise, the linear trend of the July-June PDSI difference (Fig. 2b) indicates that drought conditions have tended to intensify over the Central Plains and the northern Rockies during the June-to-July transition. A trend analysis conducted on the difference between the averages of May and June (MJ) and July and August (JA) also yielded a similar result in both precipitation and PDSI (not shown).

Another factor worth noting is the trend in the July-June net downward radiation flux at the surface (Fig. 2c) – derived from NLDAS-2 data. The increased (positive) trend in the July-June net downward radiation flux reveals a pattern very similar to the decreased (negative) trend in precipitation, i.e. meridionally elongated pattern with a particularly strong increase in the northern Rockies and the northern Great Plains. The pattern of net downward radiation flux results primarily from the change in downward shortwave radiation (DSWR) flux (Fig. 2d) caused by change in cloud cover or cloud thickness. In comparison, the trend in the July-June downward longwave radiation (DLWR; Fig. 2e) depicts an east-west dipole pattern with increased radiation in the southwest and decreased radiation in the northeast. The net result indicates that the central U.S. received either increased shortwave radiation in July or decreased radiation in June, or a combination of both (this will be discussed further with Fig. 4).

The impact of the downward radiation shift on the near-surface meteorology was examined by computing the trend in the 2-m air temperature (T2m) for (a) June, (b) July and (c) July-June; this is shown in Fig. 3. In June, warming was observed over the Southwest U.S. and south of the U.S.-Mexico border. There was a slight cooling in the northwest. In July, a distinct warming trend is observed to cover the entire Interior West. Therefore, the July-June change in T2m depicts a marked warming centered around Idaho, Montana and surrounding states (Fig. 3c); this suggests an enhancement in the seasonal warming from June to July. The observed warming is consistent with the increase in net radiation and enhanced drying over the northern Rockies (Fig. 2). Consequently, the atmospheric thickness between 200 and 700 hPa has increased: the line graph in Fig. 3d shows the seasonal evolution of thickness during the recent era (1996-2012) and the earlier era (1979-1995), and their difference is highlighted in yellow. The air mass in July has evidently expanded, hence the increasing rate of change in the thickness from June to July (bar graph). These results suggest that the regional warming is accompanied by an upper-air ridge formation. A stationary ridge in this vicinity is known to induce dry conditions over the Central Plains; this will be discussed further.

Next, we examined the changes in near-surface variables and the land-atmosphere coupling by computing (a) the evaporative fraction (EF), (b) soil moisture in the near-surface (top 40 cm.) soil layer, and (c) the planetary boundary layer (PBL) height; these are shown in Fig. 4 and were derived from the Mosaic model. Here, EF is the ratio of evaporation flux to available energy calculated as the difference between net radiation and soil heat flux. The trends were also computed using the Noah model where the outputs were very similar in sign and spatial pattern, and therefore are not shown here. Both the Mosaic and Noah models calculated EF using the Penman-Monteith formulations containing soil moisture-based surface conductance algorithms.

The EF estimates are therefore dependent of precipitation inputs and assumed soil properties and generally do not reflect the influence of irrigation, which can substantially increase ET rates across a region (Ozturk et al. 2013). The linear trends of EF, soil moisture and PBL variables were computed for June, July and the July-June difference for the period 1979-2011, and compared with the 2012 anomalies of the July-June difference. The decreasing trend in EF (Fig. 4a) in the Central/Northern Great Plains indicates that there is a larger transition in the rain-fed surface energy balance from June to July. Further, it appears that the soil moisture has increased in June but subsequently decreased rather quickly during July (Fig. 4b), in which June has become significantly wetter in the Northern Plains while July has become slightly drier [*Barandiaran et al.*, 2013]. A trend such as this increased the difference in EF between the two months. In the southern Great Plains (e.g. Oklahoma and especially southern Texas), the situation is reversed owing to an overall drying in the month of June and increased wetness in July.

The patterns of the 2012 July-June change in the EF, soil moisture, and the PBL height (bottom row of Fig. 4) are consistent with those of the long-term trend. Surface drying and PBL growth from June to July 2012 are particularly pronounced over the Central Plains (Kansas, Missouri, Illinoi and Indiana). Analyses of satellite-derived greenness vegetation fraction from MODIS (not shown) support the fact that negative anomalies in vegetation amount and health were already present in summer 2012. Likewise, as was shown in Santanello et al. (manuscript submitted to Journal of Climate), the Atmospheric Radiation Measurement-Southern Great Plains Facility at Lamont, OK observed a record increase in the PBL height in July during the entire period of record. Apparently, the land-PBL feedbacks have tended to take hold more suddenly in recent years, leading to a rapid drying of the lower atmosphere, an increase in the

PBL height and, inferring from Fig. 4c, an increased entrainment in July. *Cattiaux and Yiou* [2013] also indicated that, during the 2012 "flash drought", the record high temperature and lack of rains in May played an important role in the later development of the drought through land surface processes. These processes can establish a deep residual boundary layer that promotes further desiccation of the soil [*Santanello et al. 2007, 2011*]. A positive feedback such as this is manifest in the greater July-June change in EF and the PBL during the 2012 flash drought.

## 4. Circulation and SST

As previously noted, the development of the NAM is associated with a noticeable transition in upper-level circulations from the cold season regime (trough) to mid-summer regime (ridge); this is illustrated in Fig. 5. In June, the upper-level circulation is characterized by a stationary trough near the West Coast with the jet exit located over the Central Plains (Fig. 5a). In July, the monsoonal anticyclone develops, pushing the jet stream northward to about 50°N (Fig. 5b); consequently the circulation change from June to July forms an anticyclonic anomaly over the western U.S. (Fig. 5c) and creates subsidence over the Central Plains [*Barlow et al.*, 1998; *Higgins et al.*, 1997]. The linear trends in these circulations (Figs. 5d-f) reveal an intensification manifest as a deepened western trough in June and enhanced western ridge in July. As a result, the July-June shift in the circulation (Fig. 5f) depicts an amplified ridge in the northwestern U.S. and a deepened trough in the northeastern U.S. The ridge corresponds well with increased surface warming and tropospheric thickening (*ref.*, Fig. 3). Such a change in the circulation is apparent as a distinct short-wave pattern with a zonal wave-5 structure, a feature of which has been found to suppress summer moisture in the central U.S. [*Barlow et al.*, 2001; *Lau and Weng*, 2002; *S-Y Wang and Chen*, 2009; *Weaver and Nigam*, 2008].

Subsidence over the central U.S. also has strengthened. The trend in the July-June velocity potential at 200 hPa (Fig. 6a) shows an increase in the upper-level convergence over the central U.S. Increased subsidence is illustrated by the trend in 500-hPa vertical velocity (Fig. 6b) and suggests a tendency for any spring drought to quickly intensify during the June-to-July transition. These changes in the tropospheric circulation also support the observed trend in EF, since they provide the subsidence, clear sky conditions and surface warming that allow the soil to dry. For instance, the largely negative trend in EF (Fig. 4a) appears to be linked to enhanced surface drying in July and this is consistent with positive feedbacks enhancing drought conditions, as was the case in 2012 [*Cattiaux and Yiou*, 2013].

For further comparison, the circulation anomalies associated with the 2012 drought are shown in Fig. 7 for a) June, b) July and c) July-June. The persistent anticyclonic anomalies throughout the summer of 2012 are evident. In June, the anticyclonic anomaly over the central U.S. is known to suppress precipitation [*Bates et al.*, 2001; *Chen and Newman*, 1998] while in July, the anticyclonic anomaly anchored over the U.S./Canada border (Fig. 7b) is conducive to heat waves [*Chang and Wallace*, 1987]. In terms of long-term change, the July circulation over North America has become increasingly anticyclonic over the western U.S. [*S-Y Wang et al.*, 2013a]. Combined, the July-June circulation anomalies in 2012 (Fig. 7c) formed a short-wave structure broadly similar to that of the trend in the July-June circulation (*ref.*, Fig. 5f). Such a similarity suggests a link between the intensified ridge in July 2012 and the enhanced suppression of July rainfall in the Central Plains.

Summer anticyclonic anomalies in western North America are frequently connected to remote forcing in the North Pacific and Asia [*Newman and Sardeshmukh*, 1998; *Teng et al.*, 2013].

Thus, to explore the climatic forcing of the circulation patterns, we expanded the analysis domain to show the large-scale SST and 200-hPa streamfunction anomalies associated with the July-June change in 2012 (Fig. 8a). Despite the large SST anomalies in the midlatitude North Pacific, the tropical SST anomalies are generally weak; this feature is consistent with earlier studies indicating the lack of prominent tropical forcing in 2012 [*Hoerling et al.*, 2013b; *Kumar et al.*, 2013; *H Wang et al.*, 2014]. Fig. 8b displays the trends in the July-June SST and 200-hP streamfunction and reveals a marked similarity with the 2012 situation, suggesting a contribution of the post-1979 trend. The distinct short-wave train across the midlatitudes implies a link with remote forcing that triggers a circumglobal teleconnection, from which wave energy propagates zonally along the jet stream and affects North America [*Schubert et al.*, 2011; *Teng et al.*, 2013; *H Wang et al.*, 2014; *S-Y Wang et al.*, 2013a]. By comparison, trends in the June and July circulation and SST (Figs. 8c and 8d) reveal a La Niña type of SST change in both months, consistent with previous studies of the global SST trends (e.g., *Xie et al.* [2010]). However, July is accompanied by a stronger warming over the central North Pacific in comparison to June, while the circulation anomalies between the two months are quite different. June circulation exhibits a teleconnection emanating from the central tropical Pacific through the "PNA route", yet such a teleconnection is lacking in July.

The implication from Fig. 8 is that the July-June circulation is not directly related to the July-June SST anomalies, but rather is related to the monthly evolution of climatological SST (which determines atmospheric circulation forcing such as diabatic heating) and the tropospheric background flow (which in large measure determines atmospheric teleconnections). For example, given a diabatic heating anomaly in the tropics, the mean flow in June could still facilitate some Rossby wave propagation from the tropics to the U.S. [*Newman and*

*Sardeshmukh*, 1998], as is suggested in Figs. 8c and 8d. However, the mean flow in July would prohibit such meridional propagation of Rossby waves but would instead facilitate zonally propagating short waves under the guidance of summer jets, as was proposed in previous research [*Ding and Wang*, 2007; *Schubert et al.*, 2011; *S-Y Wang et al.*, 2010]. Likewise, an increase in regional warming over the Rocky Mountains (*ref.*, Fig. 3b), which acts to thicken the middle to upper troposphere, also can facilitate the rapid drying in the central U.S.

## 5. Climate attribution

Pervious studies have suggested that the trends in T2m and precipitation over the U.S. are attributable to a combined contribution from phase changes of natural decadal-to-multidecadal oscillations, such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO), in addition to global warming [*Robinson et al.*, 2002; *H Wang et al.*, 2009; *Weaver et al.*, 2009]. During the analysis period (1979-2012), the PDO in the late 1990s had shifted from the positive to negative phase; likewise the AMO had shifted from negative to positive phase, and the prominence of global warming has become increasingly so. Thus, to understand the extent to which the phase changes of PDO, AMO and global warming might have contributed to the observed trend in the July-June difference, we undertook a set of idealized GEOS-5 AGCM experiments forced with three leading SST patterns: the cold Pacific pattern (i.e. warmer SST in the central North Pacific), the warm Atlantic pattern and the warm trend pattern (*ref.*, Section 2b). These SST patterns respectively reflect the phase changes of the PDO and AMO during 1979-2012, and global warming [*Schubert et al.*, 2009]. While the cold Pacific pattern contains both PDO and ENSO signals and thus may exaggerate the effect of the PDO, it echoes the substantial SST warming across 40°N as that shown in Fig. 8d. The responses of GEOS-5

AGCM to these SST patterns and global warming can be used to suggest their relative contribution to the overall observed trends.

Fig. 9 displays the AGCM responses of the July-June shifts in (a) precipitation, (b) T2m and (c) 200-hPa geopotential height (with the magnitudes scaled to one standard deviation corresponding to the SST forcing). In terms of precipitation anomalies (Fig. 9a), the warming trend SST forcing produced a substantial drying that covers the Midwest and this might exacerbate the weak drying in response to both the cold Pacific and warm Atlantic forcings. However, the cold Pacific pattern forced a surface warming and an anticyclonic anomaly over the northwest U.S. (Fig. 9b, c), alone with a cooling and a cyclonic anomaly over the northeastern U.S., resembling the observed trends. Neither the warm Atlantic nor the warming trend produced a T2m or circulation pattern that corresponds with the observation. The implication from these modeling experiments is that both the Pacific decadal variability (i.e. cold Pacific) and the warming trend (similar to a La Nina response) were contributing to the intensified drying over the central U.S. in the June-to-July seasonal transition.

In order to provide a quantitative assessment for the contribution of the post-1979 trends in the aforementioned climate anomalies to the 2012 flash drought, we calculated the ratio of the July-June PDSI (percent) between those of the 1979-2011 trend and the 2012 drought. For the central U.S., an estimated 30% of the rapid intensification of the 2012 drought is linked to the trend in the June-to-July seasonal transition (Fig. 10a, within the domain as outlined). Estimates in the percent of contribution in precipitation, upper-level streamfunction and T2m are also shown for comparison purposes. The precipitation pattern (Fig. 10b) is apparently closer to the PDSI pattern than streamfunction and T2m (Figs. 10c,d). The ratio of contributions in EF, soil moisture and PBL height (not shown) ranges between the ratios in precipitation and T2m. Combined, these features suggest a predominant effect of the precipitation reduction on drought intensification. Arguably however, the changing T2m and streamfunction (ridge) patterns did play an essential role as well, because the intensified ridge over the northwestern U.S. (contributing ~30% to in the ridge center) acts to induce subsidence in the central U.S., and this would further suppress rainfall through local feedbacks. It is important to note that these analyses assumed linearity and therefore further analysis is needed to capture the nonlinear interactions involved in the changing seasonal transition and its impact on recent drought events – this will require comprehensive model simulations to achieve.

## 6. Concluding remarks

In general, precipitation in the central U.S. decreased by about 25% during the June-to-July seasonal transition. Since 1979, this precipitation reduction in the central U.S. has become more severe, having decreased twice as much in recent years. Such a long-term change has potentially intensified recent events of summer drought. In particular, the analyses presented here indicated a marked resemblance between the June-to-July PDSI, precipitation, temperature and circulation shifts in their long-term evolution change and the 2012 "flash drought" – one which was characterized by a rapid expansion over the Central Plains in early summer. Approximately 30% of the drought intensification from June to July 2012 was estimated to be due to long-term changes (based on PDSI); this contribution seems more closely related to the increase in precipitation deficit (from June to July) and the subsequent reduction in soil moisture with enhanced sensible heat flux. At the larger scale, examination of T2m and tropospheric circulation change in the western U.S. indicated that dynamical forcing was present that enhanced subsidence while, at the same time, suppressing rainfall in the central U.S.

Even though the 2012 drought is seemingly unpredictable at seasonal time scales [*Hoerling et al.*, 2013b], this study did show systematic factors related to the drought development. One factor was land-atmosphere feedbacks over the U.S., i.e. the enhanced anticyclonic anomalies stationed over the western U.S. can lead to further reductions in precipitation and soil moisture in the Central U.S. In turn, the long-term changes in land surface moisture and temperature can sustain or amplify the evolution of the overlying anticyclonic circulation and precipitation deficit. In the long run, the land surface feedback to the atmospheric circulation anomalies is strong and can affect future drought expansion in the central U.S. These processes could help anticipate future drought in the central U.S., especially those that occur in spring and can worsen in summer.

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