Flash Drought Characteristics and Prediction

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1. Introduction

Drought can develop and intensify in a short amount of time and result in major agricultural losses if they are not predicted and detected in a timely manner. Understanding the characteristics of flash drought events, when and where these events occur, their causes, and the prediction of the onset of such events on subseasonal timescales is of critical importance for impact assessment, disaster mitigation, and loss prevention. In this study, we define a flash drought event as a drought event with greater than or equal to two categories degradation in a 4-week period based on the U.S. Drought Monitor (USDM; Svoboda *et al.* 2002). We examine the characteristics of flash drought events, their temporal and spatial distributions, and distinctions from conventional, slowly-evolving drought based on rasterized USDM data from 2000 to 2017. We also identify a list of major flash drought events and investigate the causes leading to the rapid development using concurrent Phase 2 of the North American Land Data Assimilation System (NLDAS-2) data (Xia *et al.* 2012a and b). Unlike conventional drought, which is mainly driven by precipitation deficits, anomalously high evapotranspiration (ET) rates, caused by anomalously high temperatures (e.g., during heatwaves) and/or anomalously high incoming radiation, are usually present before the onset of flash drought. As a result, monitoring rapid changes in ET, along with precipitation (P) and soil moisture (SM), can provide early warnings of flash drought development. An experimental tool was created at NOAA's Climate Prediction Center (CPC) to predict the areas vulnerable for flash drought development using near real-time NLDAS-2 monitoring data, and has been used to support the operational production of CPC's Monthly Drought Outlook (MDO) since April 2018. We briefly introduce the tool in this paper and evaluate its performance during the 2018 warm season.

2. Flash drought characteristics

To analyze flash drought characteristics, we utilize historical USDM maps from 2000 to 2017. USDM maps are produced weekly in ArcGIS shapefile format through expert synthesis of various data sources, including precipitation, soil moisture, streamflow, snow water equivalent and snowpack, crop and vegetation conditions, and reservoir and groundwater levels (Svoboda *et al.* 2002). These data sources are coupled with inputs from local, state, regional, and federal levels (*e.g.*, local impact reports) to depict short- and long-term drought conditions. USDM maps contain valuable information of drought occurrence and severity, and are used by U.S. government agencies for official drought declarations. In order to use USDM as a data source for numerical analysis, we rasterized USDM maps into gridded outputs with 1/8 degree resolution covering the contiguous United States (CONUS).

Figure 1 shows the maps of drought occurrence percentage based on the rasterized 2000-2017 USDM data (the sample size is 939) for all 12 months. Drought can occur year-round and everywhere in the United States. However, some regions, such as Nevada, Arizona, and southern California, are more prone to drought than others, and drought occurrence is largely dependent on geographical location. In the maps, an east-west contrast is observed for all months, indicating that the western United States are more vulnerable to drought. Due to the slowly-evolving nature of drought, there are small variations among seasons. Yet, a slight increase in drought
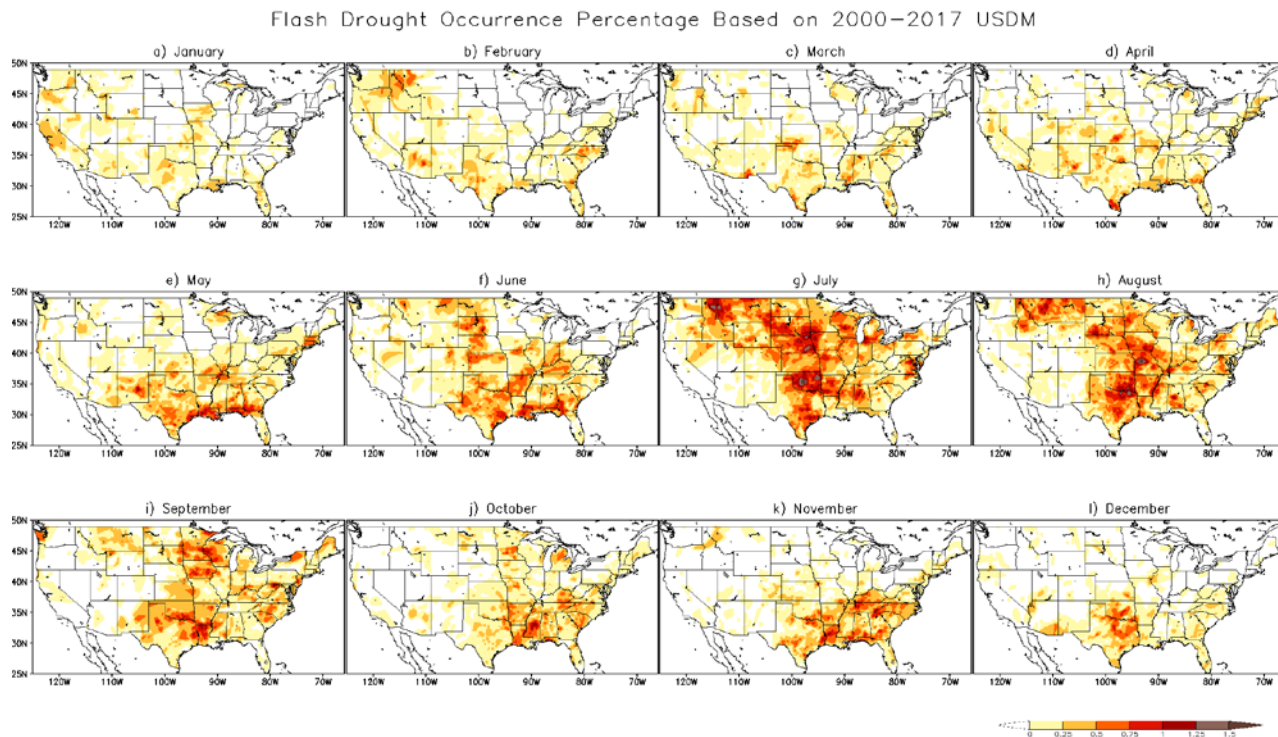
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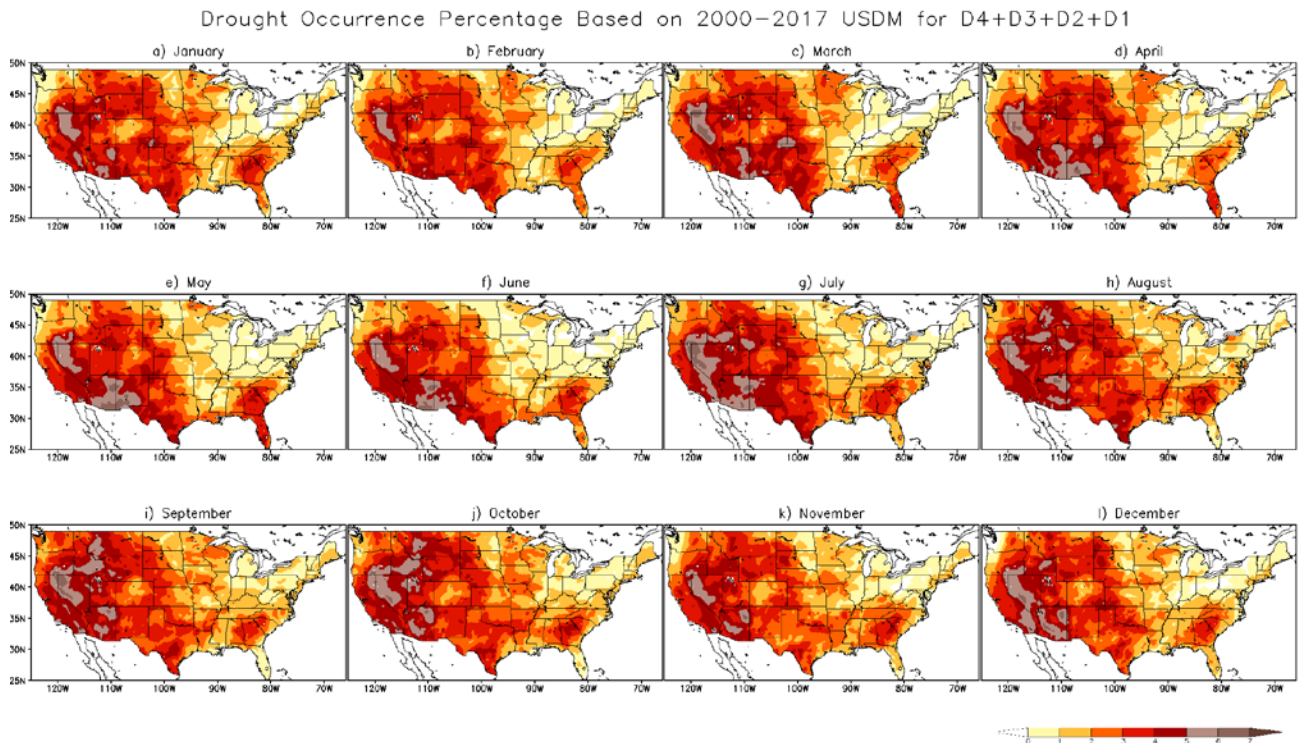
Fig. 1 Maps of drought occurrence percentage based on rasterized 2000-2017 USDM data for (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December.

occurrence appears over the central and southern United States during the warm season, implying that temperature (T) or its related quantities (e.g., ET) may play a role in drought manifestation in summertime.

Figure 2 presents the maps of flash drought occurrence percentage (the sample size is 935) for all 12 months. In this analysis, a flash drought event is defined as a drought event with greater than or equal to two categories degradation in a 4-week period based on USDM, and this figure shows when and where these events occurred. Clearly, flash drought has preferred seasons and regions to occur. Unlike conventional, slowly-evolving drought that can occur year-round, most events occurred in the warm season and over the central United States. This characteristic is very different from conventional drought driven mainly by precipitation deficits, suggesting that different approaches may be needed to predict flash drought. By cross-examining the spatial and temporal patterns of flash drought occurrence with T and ET climatological maps derived from 1981-2010 NLDAS-2 data (figures not shown), there is strong coherence between the flash drought occurrence maps and ET climatological maps. This result further suggests that flash drought development is more related to ET processes than T effects.

To illustrate how flash drought occurred over time, Figure 3 shows the time series of the fraction of area within the CONUS that experienced flash drought development from 2000 to 2017. It is seen that flash drought occurred frequently throughout the 18 years, although some years only have a small fraction of the CONUS experiencing flash drought development. During these 18 years, five years (*i.e.*, 2000, 2003, 2006, 2007, and 2012) had widespread fast development of drought, and four out of the five years (except 2003) occurred after or during an La Nina episode, indicating that the Southern Oscillation plays an important role in widespread flash drought development over the United States. The 2012 flash drought over the central Great Plains (Hoerling *et al.* 2014) is historic, with about 18% of the CONUS experiencing sudden deterioration of conditions at the peak of drought development. The significance of this drought (and the damages it caused) has led to the awareness of flash drought and motivated the inauguration of the MDO at CPC in 2013.

In order to investigate the antecedent conditions prior to the rapid development of drought, NLDAS-2 data of the five years with widespread flash drought development were gathered and analyzed. We looked at the

Fig. 2 Maps of flash drought occurrence percentage based on rasterized 2000-2017 USDM data for (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December.

time series of P, T, SM, ET, and runoff, their anomalies and standardized drought indices, as well as the evolution of these five droughts. The goal is to look for common features during the drought development phase. We found that all five droughts had sudden decreases in ET anomaly over the drought regions before onset. We also noticed sharp declines in SM anomaly associated with the sudden decreases in ET anomaly. Temperatures during the development periods were warmer than normal, due to heatwaves in the regions, and the 3-month standardized precipitation indexes were negative for all five droughts. These results, consistent with the findings by others (*e.g.*, Otkin *et al.* 2015 and Otkin *et al.* 2018), suggest that closely monitoring rapid changes in ET (a responding variable to T), along with P and SM conditions, can provide early warnings of flash drought development.

3. Flash drought prediction

Based on the findings above, we developed an experimental tool to predict areas vulnerable for flash drought development using near real-time NLDAS-2 monitoring data. The tool calculates the Rapid Change Index (RCI) proposed by Otkin *et al*. (2015) using 7-day mean ET anomalies. RCI is the accumulated magnitude of moisture stress changes (standardized differences) occurring over multiple weeks. Drought is likely to develop when RCI is negative. Because RCI changes with time, like all drought variables, it is difficult to capture drought developing signals by monitoring RCI maps. In order to create an intuitive drought prediction map that directly depicts drought tendency as the MDO, we count the number of occurrences that RCI is less than -0.5 over the last 30 days and plot the count maps with selected thresholds specifying P and SM conditions. The new tool started running on April 1, 2018 and has been providing real-time predictions (updated daily) to support MDO's production since then.

The top row of Figure 4 displays the new tool's predictions from April to September 2018. In these maps, yellow-to-red colors indicate areas with potential drought development or intensification. The higher the count, the more likely for drought to develop. In the end of April 2018, the new tool indicated that areas over eastern ND, northwestern MN, southern IA, and northern MO were vulnerable to flash drought development and verified well with USDM issued on 29 May 2018 (bottom row). The tool also suggested that drought may
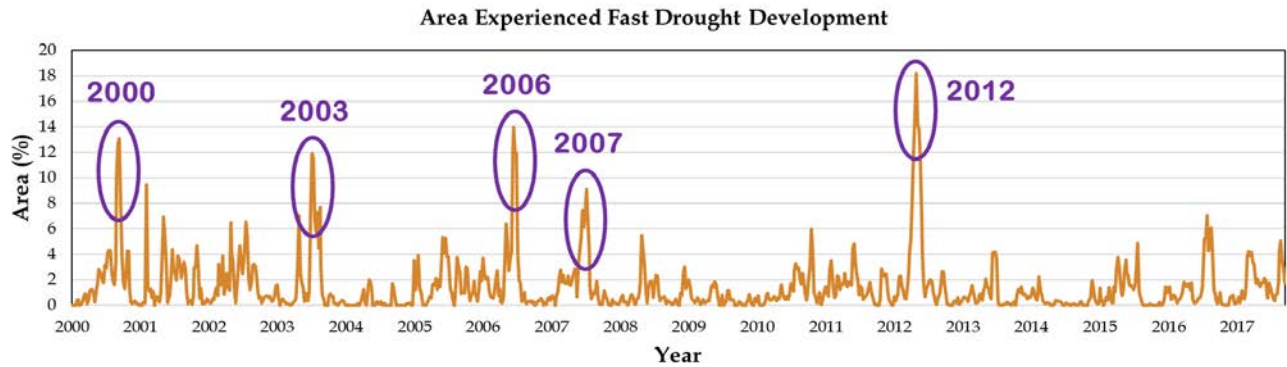
Fig. 3 Time series of the fraction of area within the contiguous United States experiencing flash drought development from 2000 to 2017.

intensify over KS, parts of OK, and northern TX; however, rainfall in May over this region (as forecasted) brought relief and improved drought conditions. Drought was not developed until June and July when heatwaves moved into the region. At the end of May 2018, the new tool indicated that flash drought may develop over western TX and LA, consistent with the MDO (third row). This prediction was verified by USDM on 26 June 2018 (bottom row). The new tool did not capture the drought development in New England and Pacific Northwest, as these two regions are not prone to flash drought. At the end of June 2018, the new tool again suggested widespread drought development over MO, AR, and eastern KS, as well as CO and UT. Aided by the heatwaves in this region, this prediction was successfully verified by USDM on 31 July 2018 (bottom row). However, the area over northeastern SD, in opposition to the development, was improved by rainfall that occurred in July. In August and September, wet conditions emerged over the MO/KS region and a series of rainstorms gradually erased the summer flash drought.

The interplay between precipitation and high temperature appears to be a challenge for flash drought prediction. The first stage of the tool is solely based on NLDAS-2 monitoring data and does not take into account forecast information. Therefore, it highlights areas with potential flash drought development if the current conditions persist into the next month. Predictions that meet this requirement (*e.g.*, areas over CO and UT for July prediction) are usually verified well. In the next stage, we will add CFSv2 forecast information into the tool to help restrain the development areas and provide potential drought improvement information.

4. Summary and Conclusions

We have examined flash drought characteristics using historical USDM and NLDAS-2 data. Unlike conventional drought that can occur year-round and everywhere in the United States, flash drought occurs mostly in the warm season and central United States. Instead of being driven by precipitation deficits, flash drought development is mainly driven by ET processes. By closely monitoring rapid changes in ET, along with P and SM conditions, we are able to predict areas vulnerable for flash drought development. An experimental flash drought prediction tool was created using the Rapid Change Index (Otkin *et al.* 2015) calculated from weekly changes of 7-day mean ET anomaly. The new tool started running on April 1, 2018 and has been used to support the operational production of CPC's Monthly Drought Outlook. Preliminary assessment of the tool shows promising results in predicting flash drought development, and the interplay between precipitation and high temperature appears to be a challenge for flash drought prediction. To improve the performance of the tool, we will add CFSv2 forecast information to help restrain the development areas and provide potential drought improvement information. A full-length technical paper (Chen *et al.* 2019) is in preparation to document details of the study of flash drought characteristics. Another paper will be written to document the methodology and assessment of the flash drought prediction tool once it is finalized.

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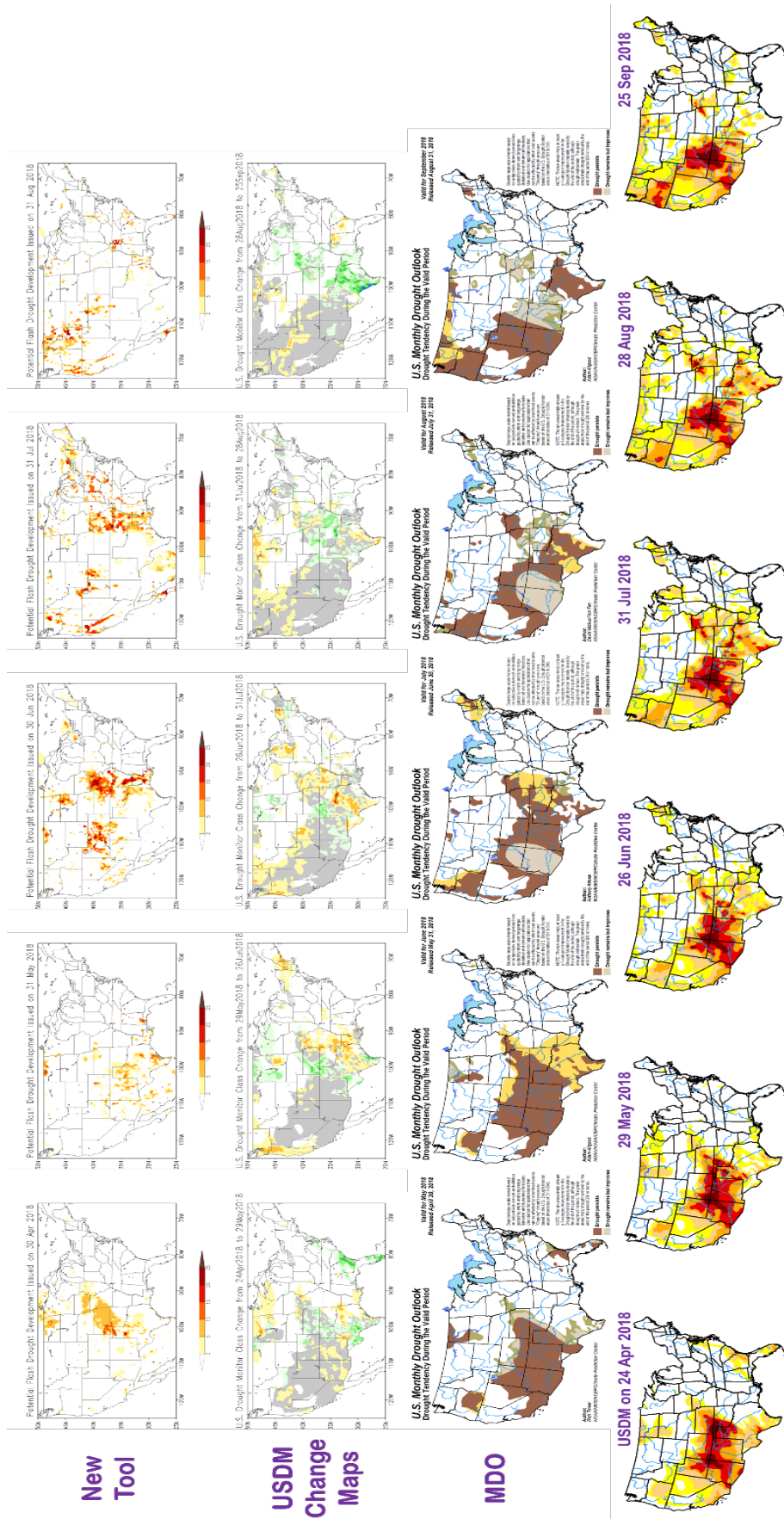
Fig. 4 Flash drought predictions during April-September 2018 and their verifications. Top row shows the predictions from the new tool, second row shows the USDM change maps, third row shows the predictions from the Monthly Drought Outlook, and fourth row shows the USDM maps at the end of each month.

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