

RESEARCH LETTER

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Key Points:

- In situ soil moisture detects flash drought earlier than U.S. Drought Monitor
- Four flash drought events in Oklahoma detected at 2–3 week lead using soil moisture
- Integrating soil moisture into drought early warning systems may aid in flash drought detection

Supporting Information:

- Supporting Information S1

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On the utility of in situ soil moisture observations for flash drought early warning in Oklahoma, USA

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Abstract Drought early warning systems are a vital component of drought monitoring and require information at submonthly time scales because of the rapidly evolving nature of drought. This study evaluates the utility of in situ soil moisture observations for drought early warning in Oklahoma. Soil moisture was used to identify drought events, and the results were compared with the U.S. Drought Monitor with respect to the identification of drought onset. Soil moisture observations consistently identify rapid-onset (flash) drought events earlier than the U.S. Drought Monitor. Our results show that soil moisture percentiles provide a 2–3 week lead time over the U.S. Drought Monitor based on five flash drought events that occurred in Oklahoma between 2000 and 2013. We conclude that in situ soil moisture observations are an important source of information for early warning of flash drought events in the Oklahoma.

1. Introduction

Drought is one of the most destructive and costly natural disasters, resulting in diminished agricultural production [Hatfield *et al.*, 2011; Mallya *et al.*, 2013; Zhang *et al.*, 2014], reduced water resources [van Dijk *et al.*, 2013; Shukla *et al.*, 2015], and deadly heat waves [Hoerling *et al.*, 2013; Schubert *et al.*, 2014]. In response, drought strategies are being developed worldwide, with a particular focus on comprehensive drought monitoring [Hayes *et al.*, 2011]. Historically, indices have been developed to characterize meteorological, agricultural, hydrological, and socioeconomic drought [Vicente-Serrano *et al.*, 2012]. The Standardized Precipitation Index (SPI) [McKee *et al.* 1993], for example, was recently recommended for characterizing meteorological drought worldwide [Hayes *et al.*, 2011].

One of the most comprehensive drought monitoring systems in the United States is the U.S. Drought Monitor (USDM), which was developed to track and communicate the severity and extent of drought across the United States [Svoboda *et al.*, 2002]. The USDM is updated weekly through an expert assessment of rainfall, streamflow, crop conditions, and local drought impact observations. Drought is classified by the USDM in one of four categories (D1 to D4), from moderate to exceptional drought, with additional separation between short-term and long-term drought impacts. The USDM also reports “abnormally dry” conditions (D0). Although the USDM is not the only measure of drought in the United States, it is frequently used as a benchmark against which other drought monitoring tools are evaluated [e.g., Luo and Wood, 2007; Gu *et al.*, 2007; Shukla and Wood, 2008].

Despite the utility of drought monitoring tools such as the USDM, they often have difficulty capturing rapidly evolving drought events commonly referred to as “flash droughts” [Senay *et al.*, 2008]. The rapid onset of flash droughts significantly reduces time available for impact preparation, potentially resulting in greater adverse agricultural and societal effects than a slowly evolving drought event [Otkin *et al.*, 2015]. Drought early warning systems therefore must integrate information that can be updated on weekly intervals to properly characterize flash drought events. Several remotely sensed drought indicators have been recommended for flash drought monitoring, including satellite-based evapotranspiration, soil moisture, and ground water storage [Pozzi *et al.*, 2013]. One example is the Evaporative Stress Index (ESI) [Anderson *et al.*, 2007], which measures evapotranspiration anomalies based on satellite thermal infrared imagery and a land surface energy balance model. A unique component of the ESI is the Rapid Change Index (RCI) [Otkin *et al.*, 2014] which characterizes accumulated moisture stress over long time periods and can be used to identify potential regions of drought development [Anderson *et al.*, 2013]. Recent studies have indicated that integrating the ESI and RCI into drought early warning systems could lead to more timely warnings and earlier drought mitigation [Otkin *et al.*, 2013, 2015].

Few studies have evaluated the utility of in situ soil moisture observations for drought early warning, despite the importance of soil moisture for meteorological and agricultural drought development. Previous studies have found that soil moisture anomalies are useful for characterizing drought onset and demise [Hunt *et al.*, 2009], particularly for rapid-onset drought monitoring [Mozny *et al.*, 2012]. However, in most regions of the world, the lack of spatially extensive soil moisture monitoring networks precludes the inclusion of soil moisture in drought monitoring systems. The purpose of this study is to evaluate the utility of in situ soil moisture for drought early warning using a dense network in the U.S. Southern Great Plains. Droughts captured by the soil moisture data are compared with concurrent USDM conditions. Although we analyze every drought during the study period (2000–2013), this paper specifically focuses on rapidly evolving or flash drought events.

2. Data and Methods

2.1. Soil Moisture

Soil moisture observations from the Oklahoma Mesonet (www.mesonet.org) [Illston *et al.*, 2008] are used to characterize drought conditions over the state of Oklahoma between 2000 and 2013. The Oklahoma Mesonet provides hourly observations of thermal matric potential measured by the Campbell 229-L sensor, from which volumetric water content ($\text{cm}^3 \text{cm}^{-3}$) is derived. Hourly volumetric water content observations are aggregated to daily resolution at the 45 Mesonet stations with the longest and most complete record. For each of these 45 stations, percentiles are estimated separately for each calendar month from the empirical cumulative distribution function of daily volumetric water content. The daily percentiles of volumetric water content are then aggregated to weekly averages. Therefore, a record of weekly soil moisture percentiles is generated for each Mesonet station separately. We then analyze weekly drought status at the climate division level by averaging weekly soil moisture percentiles for all stations within each of the nine Oklahoma climate divisions (supporting information Figure S1). Separating our analysis by climate division allows us to identify spatial patterns in the effectiveness of soil moisture drought early warning. The weekly climate division drought status is assessed based on soil moisture percentiles consistent with the USDM: conditions less (drier) than the 30th percentile are abnormally dry, less than the 20th percentile are moderate drought, less than the 10th percentile are severe drought, less than the 5th percentile are extreme drought, and less than the 2nd percentile are exceptional drought [Svoboda *et al.*, 2002]. The weekly soil moisture-based drought classification is then compared to the USDM. One limitation of this method is that Mesonet stations are unevenly distributed within and between the climate divisions. The Panhandle division has only one station with a data record of sufficient length and completeness, while the Central division has 10 adequate stations that are used to determine the soil moisture-based drought status. We acknowledge that the effectiveness of soil moisture as a drought early warning indicator will be influenced by the station distribution. However, this study requires a long-term, nearly serially complete soil moisture record, and so this limits the number of available stations. It is also worth noting that soil moisture percentiles are based on a short record (<20 years) relative to the precipitation percentiles (e.g., SPI) that are used by the USDM. This may influence the stability of the soil moisture percentiles.

Our analysis focuses on soil moisture measurements taken at 5 cm and 25 cm depths. The Oklahoma Mesonet also monitors soil moisture at 60 cm depth; however, these data contain many more missing values and therefore could not be used in this analysis. We assess the early warning capabilities of the 5 cm and 25 cm records separately to determine which is more effective for flash drought detection.

2.2. U.S. Drought Monitor

The USDM characterizes drought conditions for the entire United States on a weekly basis (droughtmonitor.unl.edu) and provides the percentage of each climate division that is classified in each drought category. We convert these percentages to a single drought status for each climate division by using the most intense drought category (D0 to D4) that encompasses at least 25% of that particular climate division. The weekly USDM-based drought status for each climate division is evaluated against the corresponding soil moisture-based status to determine the effectiveness of in situ soil moisture for drought early warning.

2.3. Drought Comparison

The onset of drought events depicted in the soil moisture record is evaluated against the USDM record in each climate division. We acknowledge that drought is a multifaceted phenomena and that each drought

event has a unique spatial extent, severity, and duration. However, because the focus of this analysis is to evaluate the utility of in situ soil moisture for drought early warning, we only examine drought onset. Drought events are identified both in the USDM record and soil moisture record based on event minimum criteria of duration and severity. For this analysis, we vary one event minimum criterion while holding the other constant. Minimum drought duration is varied from 4 to 6 weeks, while minimum severity is varied from abnormally dry (D0) to moderate drought (D1). We initially extended the duration criteria to 8 weeks and the severity criteria to severe drought (D2). However, in both cases very few soil moisture-based drought events emerged. The onset of a drought event is defined using the USDM as the first week in which a set of these conditions (i.e., four consecutive week duration of moderate drought) is met. For example, if the week of 4 July begins a streak of four consecutive weeks in which the USDM identifies moderate drought, then we use 4 July as the first week of USDM drought onset. We then determine the onset of the same event using the soil moisture record. If the drought onset in the soil moisture record is prior to onset in the USDM record, it is considered a true positive with regard to providing drought early warning. Drought events occurring in the soil moisture record with no corresponding USDM drought are considered false positives. Finally, drought events that occur in the USDM record with no corresponding drought in the soil moisture record, or a later drought onset in the soil moisture record, are considered false negatives. This analysis is completed separately for each of the nine climate divisions. For different combinations of drought conditions (duration and severity), the sensitivity and predictive value for positive results (PV+) are used to quantitatively assess the utility of soil moisture for drought early warning. Sensitivity evaluates the reliability of a positive soil moisture-based drought warning, and it is calculated as the ratio of true positive warnings to the sum of true positive and false negative warnings. The sensitivity should be interpreted as the percent of USDM-classified drought events that were correctly identified in the soil moisture record prior to the USDM identification. The PV+ measures the probability that a positive soil moisture-based drought warning is true, and it is calculated as the ratio of true positive warnings to the sum of true positive and false positive warnings. The PV+ should be interpreted as the percent of drought events correctly identified in the soil moisture record that were also identified in the USDM record (but at a later time).

The results of the soil moisture-based drought warning assessment are presented as follows: section 3.1 describes the overall accuracy of soil moisture-based drought warnings, while section 3.2 describes the effectiveness of soil moisture more specifically for flash drought early warning.

3. Results

3.1. Drought Early Warning Assessment

The onset (week) of drought based on the USDM is compared with the onset based on soil moisture. A drought event is defined based on both duration and severity criteria. Drought comparison statistics, including the number of drought events identified in the USDM record and the average lead time, maximum lead time, and minimum lead time for events correctly identified using the 5 cm and 25 cm soil moisture, are included in supporting information Table S1. A lead time of 1 week means the 5 cm or 25 cm soil moisture record identified the drought event 1 week before the USDM record. Drought comparison information is separated by duration/severity criteria into (1) D0 for four consecutive weeks, (2) D1 for four consecutive weeks, (3) D0 for six consecutive weeks, and (4) D1 for six consecutive weeks (Table S1). The number of drought events is relatively consistent across all climate divisions, with the exception of the longest-lasting, most severe events (D1/6 weeks), which never occurred in climate divisions 6 (east central) and 9 (southeast). The average lead times for the 5 cm measurements are consistently longest in the Panhandle climate division, ranging from 4 to 5 weeks. The average lead time for drought early warning in the other climate divisions ranged from 1 to 4 weeks. For the 25 cm soil moisture measurements, the Panhandle lead times are shorter, while lead times in west central, east central, and south central divisions are longer.

The effectiveness of soil moisture-based drought early warning is evaluated using the sensitivity and PV+ metrics. These are derived separately for the 5 cm and 25 cm soil moisture measurements, and they are evaluated separately for each climate division and drought duration/severity combination (Figure 1). The bars in each panel in Figure 1 represent the 5 cm sensitivity in dark blue, the 25 cm sensitivity in light blue, the 5 cm PV+ in green, and the 25 cm PV+ in yellow. The panels show drought comparisons for (a) D0/4 week events, (b) D0/6 week events, (c) D1/4 week events, and (d) D1/6 week events. For the vast

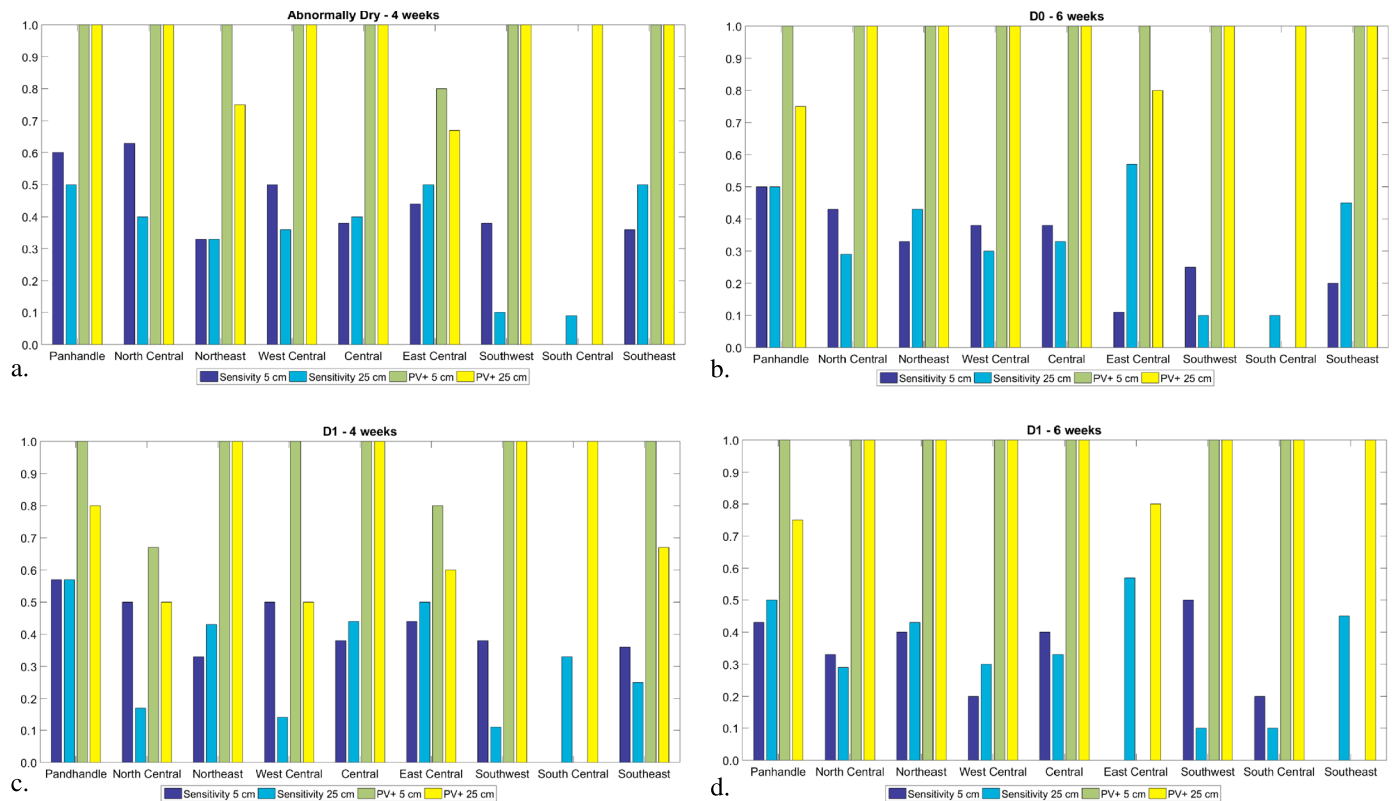


Figure 1. Drought onset comparison metrics, sensitivity (dark blue and light blue), and PV+ (green and yellow), between soil moisture percentiles and the USDM. Dark blue and green bars show metrics from 5 cm soil moisture, and light blue and yellow show 25 cm metrics. The bars are grouped by climate division, and each panel shows a different drought duration/severity criteria.

majority of drought duration/severity combinations and climate divisions, PV+ values at both 5 cm and 25 cm are perfect (equal to 1), meaning very few false positive warnings occur. Therefore, soil moisture-based drought warnings have a much higher probability of being correct than incorrect. The sensitivity results are much less consistent. When interpreting sensitivity, it is important to note the 0.5 mark, as sensitivity values exceeding 0.5 indicate the soil moisture record is able to provide early warning in more than half of the USDM drought events. Sensitivity of the 5 cm soil moisture record only exceeds 0.5 in the Panhandle and north central climate divisions. While at 25 cm, sensitivity exceeds 0.5 in the Panhandle and east central divisions. Over the four drought duration/severity criteria, 5 cm soil moisture has consistently higher sensitivity values than the 25 cm record in the north central, west central, and southwest climate divisions. On the other hand, 25 cm soil moisture has consistently higher sensitivity values than the 5 cm record in the northeast, east central, and southeast divisions. Although there is somewhat of a west-to-east difference in the sensitivity of 5 cm and 25 cm soil moisture, most sensitivity values are ≤ 0.5 . Interclimate division variability notwithstanding, we find that in situ soil moisture provides early warning for, at best, approximately half the drought events identified by the USDM.

3.2. Flash Drought Events

Our results suggest that soil moisture can provide some utility for drought early warning; however, the main limitation is the relatively high ($>50\%$) false negative observation rate. Because of their rapid evolution and lack of sufficient warning, we focus our analysis on flash drought events. We define a flash drought event in the USDM record as three category or more increase in drought severity over 8 or less weeks. In addition, we focused on flash drought events that affected at least five out of the nine Oklahoma climate divisions. Based on these criteria we identified five flash drought events between 2000 and 2013 in Oklahoma: (1) summer 2000, (2) summer 2001, (3) fall 2005, (4) early spring 2011, and (5) summer 2012. These events had a rapid onset and/or intensification in 8 weeks or less. We summarize the evolving drought conditions for each of these events and determine if the soil moisture record is able to provide early warning. The spatial extent and severity of each of these five flash drought events are depicted using weekly maps (Figures 2 and 3)

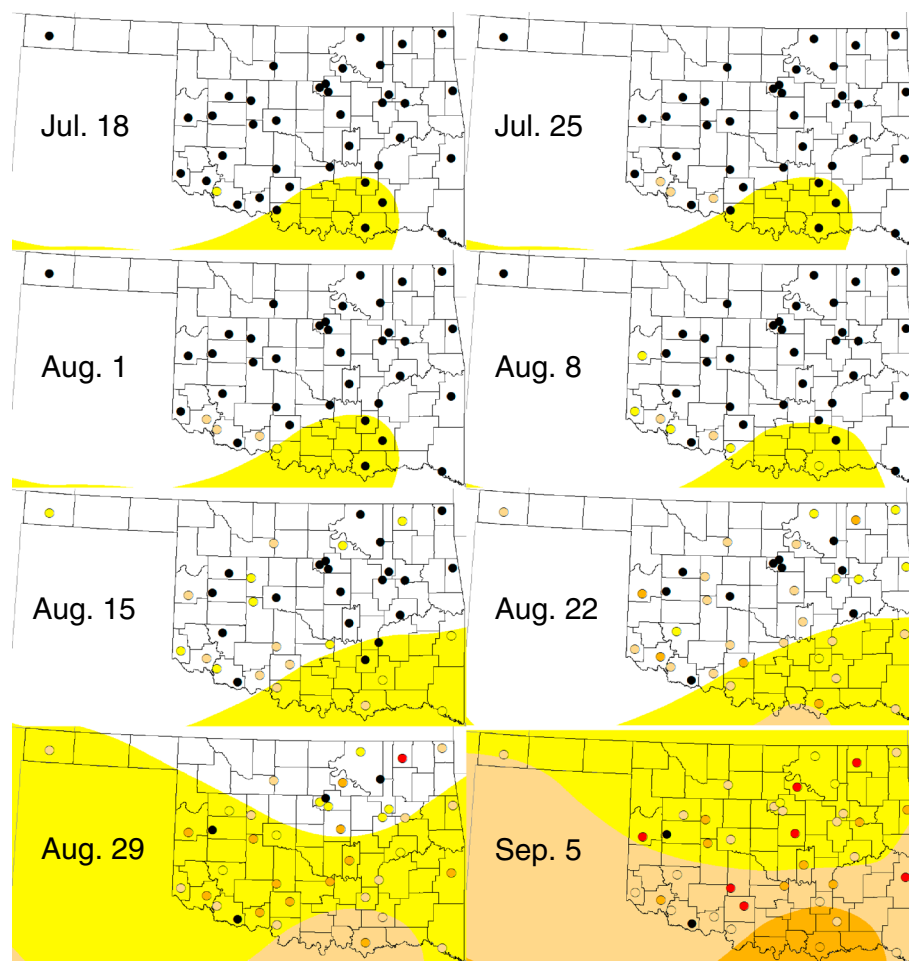


Figure 2. Drought maps depicting the summer 2000 event in Oklahoma. The shaded areas are the weekly USDM classifications, and the circles are Oklahoma Mesonet stations colored based on their drought classification.

to show the evolution of each event in the USDM and soil moisture records. These weekly maps show the areas of the state classified by the USDM in each drought category, overlaid by the Oklahoma Mesonet soil moisture stations, which are colored by their respective drought category. Areas of the state where soil moisture is determined to have utility for flash drought early warning are those where the soil moisture station(s) show drought prior to the USDM showing the same drought severity. The maps in Figure 2 (Figure 3) show the evolution of the summer 2000 drought (spring 2011 drought). Similar maps for the three other drought events are contained in the supporting information. We chose to focus on the 2000 and 2011 drought events, because they represent an event that was well captured by soil moisture (2000 drought) and an event that was not as well captured (2011 drought). The colored circles on the maps are based on the 5 cm soil moisture record; however, the 25 cm record was nearly identical.

The first flash drought event, as depicted by the USDM, developed in Oklahoma between late July and September 2000 (Figure 2). The event starts with a small portion of southern Oklahoma experiencing abnormally dry conditions, only captured by one soil moisture station. By the week of 15 August, several stations in the southwestern and central portions of the state show abnormally dry conditions to moderate drought, while the USDM depicts only abnormally dry conditions in the southeast corner. Between 22 August and 5 September, both soil moisture and USDM drought conditions intensify and move northward. Each week, soil moisture stations throughout the state depict drought conditions at least one category more intense than the USDM. In all but the south central and southeast climate divisions, the soil moisture record was able to capture intensifying drought conditions earlier than the USDM. Overall, the average soil moisture-based drought warning lead time for the summer 2000 flash drought was 2 weeks.

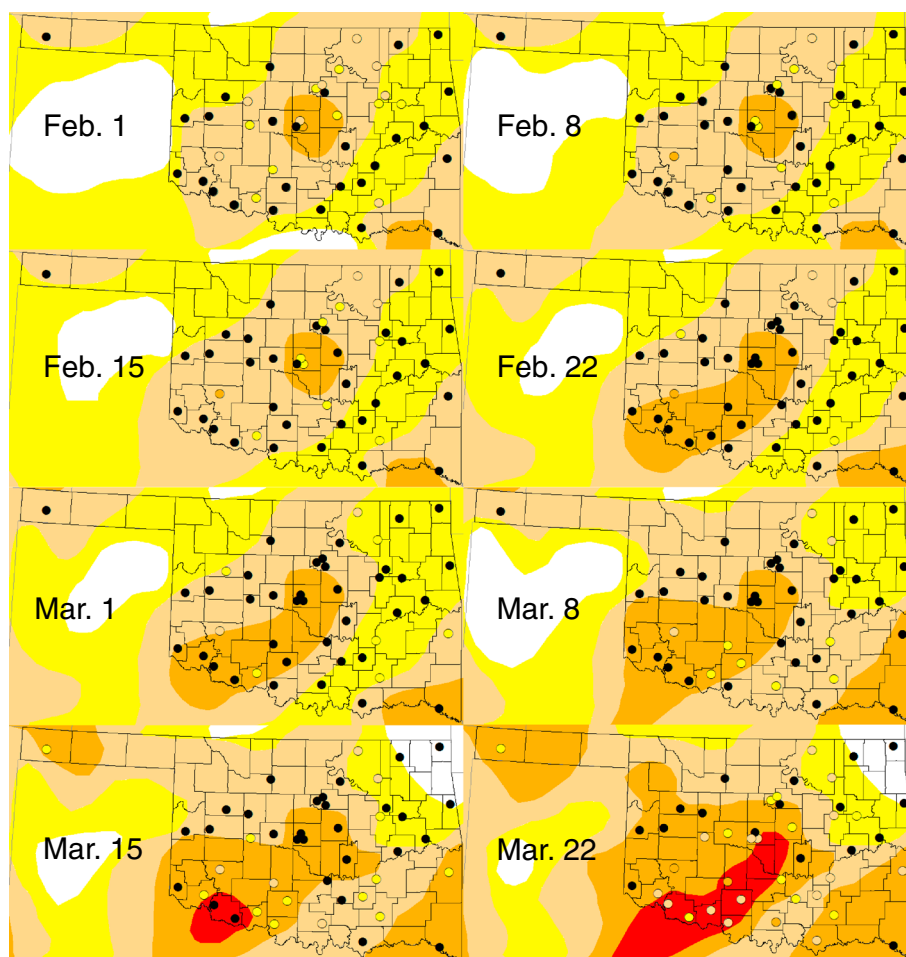


Figure 3. Drought maps depicting the spring 2011 event in Oklahoma. The shaded areas are the weekly USDMD classifications, and the circles are Oklahoma Mesonet stations colored based on their drought classification.

The second flash drought event started in June 2001. Maps depicting its evolution are in the supporting information (Figure S1). During the week of 19 June, several stations in the central portion of the state showed abnormally dry to moderate drought conditions, while only a very small part of the southwest corner experienced abnormally dry conditions as determined by the USDMD. Between the week of 26 June and 31 July, abnormally dry conditions spread to the northeast and intensified. Soil moisture stations in the central and northeastern parts of Oklahoma showed moderate to severe drought conditions prior to the USDMD. The soil moisture record was able to detect drought before the USDMD in the western and northern portions of the state, but it did not provide early detection in the southern and eastern portions of Oklahoma. The majority of soil moisture stations in the southeastern corner of the state did not even show abnormally dry conditions until the USDMD was depicting moderate drought. For the climate divisions in which soil moisture correctly identified the flash drought, the average event lead time was 2 weeks.

The third event started in October 2005 with moderate drought over most of the southeast corner of Oklahoma. Several stations in the central and eastern portions of the state, as well as the Panhandle, showed abnormally dry to severe drought conditions. The USDMD drought quickly intensified in southeast Oklahoma, and abnormally dry conditions spread throughout most of the state. As dry conditions evolved through November, soil moisture stations in most regions of the state showed more intense drought than was depicted by the USDMD. By the week of 6 December, the majority of the state was experiencing moderate drought with extreme drought in the southeast corner. The 5 cm and 25 cm soil moisture measurements were able to provide early warning of this flash drought event in all climate divisions except the southeast,

where drought conditions had persisted for multiple months. The average lead time for soil moisture early warning was 2 weeks, although the lead time varied by climate divisions.

The fourth drought event, starting in February 2011, was unusual in that the majority of the state had experienced abnormally dry or moderate drought conditions for a couple of months prior to the intensification (Figure 3). Therefore, although this event was classified as a flash drought, it evolved from a preexisting drought event that then experienced rapid intensification. By late February 2011, very few soil moisture stations showed any abnormally dry conditions; however, moderate to severe drought encompassed a large portion of the state. The event intensified to extreme drought in the southwest corner in mid-March, with inconsistent responses from the soil moisture stations. The soil moisture record did not provide any early warning of the flash drought event of spring 2011, most likely due to the preexisting drought conditions. The lack of effective soil moisture-based early warning for this particular event is in direct contrast with the previous three flash droughts and suggests that in situ soil moisture has utility for flash drought early warning when no drought or abnormally dry conditions already exist. However, the soil moisture record is less useful for providing a warning of a preexisting drought event rapidly intensifying.

The final flash drought event began in May 2012, with severe to extreme drought in most of the Panhandle and southwestern portions of Oklahoma. Despite these very dry conditions, the eastern half of the state was considered normal; however, several soil moisture stations in the central and eastern thirds of Oklahoma show abnormally dry to severe drought. Between May and late June in 2012, drought spreads eastward across the state with varied responses from the soil moisture stations. The flash drought event is correctly identified in the soil moisture record for the central, east central, south central, and southeast climate divisions. The lack of early warning in the western climate divisions is similar to the spring 2011 event, in which preexisting drought conditions intensified rapidly and were not captured in the soil moisture record. For the eastern half of the state, the average lead time was 3 weeks.

Soil moisture provided early warning of rapid drought onset and intensification in four of the five flash drought events that were assessed. The consistency with which soil moisture can capture these events depends on the preexisting conditions. Soil moisture is a better drought early warning indicator for drought events with a rapid onset, but it was less useful for drought events with rapid intensification. Overall, our results suggest that in situ soil moisture has utility for flash drought early warning in this region.

4. Discussion and Conclusions

A 13 year record of soil moisture percentiles from 45 stations across Oklahoma was used to determine the utility of in situ soil moisture observations for drought early warning. The onset of drought events in the soil moisture record was evaluated separately for each climate division against onset of the same events in the USDM. In general, low false positive soil moisture drought warnings are offset by high false negative rates. More specifically, drought warnings from both 5 cm and 25 cm soil moisture percentiles precede USDM classification of drought events for less than half of all drought events classified between 2000 and 2013. We focus on five specific events that exhibit rapid intensification or “flash droughts.” Soil moisture-based early warnings consistently precede USDM drought classifications by 2 to 3 weeks for four of the five flash drought events. The poor performance of the soil moisture as a drought early warning indicator for the spring 2011 event is attributed to the preexisting drought conditions that rapidly intensified. The fact that the soil moisture record was not able to capture the rapid intensification of drought in Oklahoma during the spring of 2011 suggests that soil moisture percentiles are more useful for capturing events that rapidly evolve from no drought or abnormally dry conditions than those that intensify from preexisting drought conditions.

There are a number of caveats to this study's methods and results, including the soil moisture data set used and the focus on drought onset. The Oklahoma Mesonet is unique in the United States with respect to its station density, spatial extent, and record (time) length. Therefore, the results are somewhat data set dependent, and additional analysis is required to determine the utility of other soil moisture networks that are less dense or have a shorter period of record for drought early warning. In addition, the spatial dimension of drought events could be better characterized if the in situ soil moisture were integrated into a gridded soil moisture or moisture stress product. To accomplish this, it may be useful to combine the ESI, which provides complete spatial coverage, with in situ soil moisture observations (only provide information at a discrete point) to develop a more comprehensive drought early warning system.

The results of this study highlight the utility of in situ soil moisture observations for providing early warning of flash droughts. One of the many conclusions from the World Meteorological Organization/United Nations Strategy for International Disaster Reduction Expert Meeting on Agricultural Drought Indices in 2010 was a need for establishment of soil moisture monitoring networks where they do not currently exist [Heim and Brewer, 2012]. This recommendation was born from the vital information that soil moisture provides for drought monitoring [Narasimhan and Srinivasan, 2005; Bolten et al., 2010]. In this study, we find that in situ soil moisture observations are able to capture the onset of flash drought conditions earlier than the current USDM monitoring system. Soil moisture percentiles are found to provide flash drought early warning in all nine of Oklahoma's climate divisions, suggesting that its utility is somewhat consistent across a relatively large region. Further evaluations are necessary to comprehensively quantify the ability and limitations of soil moisture observations for nationwide drought early warning. However, based on the results presented here, we conclude that in situ soil moisture observations provide important information for early warning of flash drought events in the Southern Great Plains of the United States.

Acknowledgments

The soil moisture data for this paper are freely available for from the Oklahoma Mesonet at http://www.mesonet.org/index.php/weather/daily_data_retrieval. The U.S. Drought Monitor information is available at <http://droughtmonitor.unl.edu/>. This work was supported by NSF grant AGS-1056796 to Texas A&M University. Finally, we would like to thank Trenton Franz and an anonymous reviewer for their helpful suggestions during the review process.

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