Exploring the Use of Standardized Soil Moisture as a Drought Indicator

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ABSTRACT: Agricultural drought has traditionally been monitored using indices that are based on above-ground measures of temperature and precipitation that have lengthy historical records. However, the period-of-record length for soil moisture networks is becoming sufficient enough to standardize and evaluate soil moisture anomalies and percentiles that are spatially and temporally independent of local soil type, topography, and climatology. To explore these standardized measures in the context of drought, the U.S. Climate Reference Network hourly standardized soil moisture anomalies and percentiles were evaluated against changes in the U.S. Drought Monitor (USDM) status, with a focus on onset, worsening, and improving drought conditions. The purpose of this study was to explore time scales (i.e., 1–6 weeks) and soil moisture at individual (i.e., 5, 10, 20, 50, and 100 cm) and aggregated layer (i.e., top and column) depths to determine those that were more closely align with evolving drought conditions. Results indicated that the upper-level depths (5, 10, and 20 cm, and top layer aggregate) and shorter averaging periods were more responsive to changes in USDM drought status. This was particularly evident during the initial and latter stages of drought when USDM status changes were thought to be more aligned with soil moisture conditions. This result indicates that standardized measures of soil moisture can be useful in drought monitoring and forecasting applications during these critical stages of drought formation and amelioration.

SIGNIFICANCE STATEMENT: Drought is normally monitored by making inferences from temperature and precipitation observations. In this study, we explored whether soil moisture data would improve our ability to monitor evolving drought conditions. Results showed that soil moisture observations were drier than usual prior to U.S. Drought Monitor onset for nearly 80% of events and worsening drought weeks. For improving weeks, soil moisture observations were only slightly drier than usual or near normal. This was more pronounced in the initial and final few weeks of drought. This suggests that applications of soil moisture measurements to monitor and anticipate evolving drought conditions are best focused on the critical stages of drought formation and termination.

KEYWORDS: Drought; Soil moisture; Surface observations; Agriculture; Decision support

1. Introduction

The use of in situ soil moisture conditions as a drought indicator has been limited primarily due to the short period of record (i.e., fewer than 20 yr for most stations), which challenges efforts to standardize (Ford et al. 2016; Leeper et al. 2019) and evaluate the severity (i.e., 2nd vs 20th percentile) or rarity of soil moisture conditions. Standardization is crucial to drought monitoring because it minimizes localized impacts on soil moisture observations from topographic (i.e., slope), land cover (i.e., vegetation type and density), soil characteristics (i.e., soil type, porosity), and/or other factors that can make the observations less comparable across diverse hydroclimatic regions (Entin et al. 2000; Brocca et al. 2007; Coopersmith et al. 2016). This has led agricultural drought, which is defined as a soil moisture deficit sufficient to negatively impact vegetation health (Mkhabela et al. 2010; Panu and Sharma 2002), to traditionally be assessed using indices based on above-ground measures of temperature and precipitation (Torres et al. 2013). A review of drought indices from Heim (2002) and Zargar et al. (2011) identified the Palmer drought severity index (PDSI; Palmer 1965), crop moisture index (CMI; Palmer 1968), and standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano et al. 2010) as some of the more widely used indices for monitoring agricultural drought. The preference for these indices is based on the 30+-yr longevity of the temperature and precipitation datasets, which allow these measures to be standardized and broadly applicable across the United States. However, these indices can only approximate soil moisture conditions, which can lead to regional biases that require careful calibration (Alley 1984; Wells et al. 2004) and consideration when associating them with soil moisture deficits.

Numerical models, such as the North America Land Data Assimilation System (NLDAS; Xia et al. 2014), the National Water Model (Viterbo et al. 2020) and others, provide an opportunity to construct long-term soil moisture time series from retrospective simulations. These long-term time series allow modeled soil moisture observations to be standardized and used in drought monitoring applications (Mo 2011; Narasimhan and Srinivasan 2005). Narasimhan and Srinivasan (2005), for instance, used a 75-yr modeled soil moisture record to compute the soil water deficit index (SWDI) and apply it in

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TABLE 1. USDM drought category, description, and percentile range.

Category	Description	Indicator percentile range
None	No drought or abnormal dryness	31–100
D0	Abnormally dry	21–30
D1	Moderate drought	11–20
D2	Severe drought	6–10
D3	Extreme drought	3–5
D4	Exceptional drought	0–2

agricultural drought application. However, underlying assumptions in model physics and uncertainties in the forcing datasets (Bolten et al. 2010) can lead to offsets and biases in comparison with in situ soil moisture observations (Leeper et al. 2017). In addition, these uncertainties may not be consistent in time (Dirmeyer 2011), which can negatively impact efforts to standardize model soil moisture datasets.

Techniques to quantify soil moisture deficits from the short period-of-record lengths of in situ soil moisture datasets can be split into two types. The first attempts to leverage soil characteristics (i.e., wilting point and field capacity) to monitor the amount of water available to plants. These measures include plant available water (PAW) and fractional available water (FAW) recently described by Krueger et al. (2019) or the SWDI as previously noted (Narasimhan and Srinivasan 2005; Martínez-Fernández et al. 2016). Given the level of effort needed to properly estimate wilting point and field capacity from soil samples, these measures may be challenging to prescribe for well distributed or dense networks (i.e., more than 100 stations). For instance, this approach would be particularly challenging for remotely sensed datasets with global coverage. The second approach takes advantage of a sampling method first applied by Applequist et al. (2012) on hourly temperature observations to estimate climatological normal soil moisture conditions from short-term datasets (Leeper et al. 2019). This approach could be equally applied to both in situ and remotely sensed soil moisture datasets and has been found to reasonably estimate longer-term mean conditions when at least a 5–7-yr period of record is available (Leeper et al. 2019; Ford et al. 2016).

In this study, the recently released standardized soil moisture dataset from the U.S. Climate Reference Network (USCRN), which employs a moving 31-day sampling approach to estimate seasonally varying standardized soil moisture anomalies and percentiles at each station (Leeper et al. 2019). The standardized anomalies and percentiles provide two separate measures (i.e., deficits and rarity of a measure) from which to evaluate the soil moisture state from formation to amelioration of drought events. The USCRN is a high-quality reference network that monitors hourly soil moisture conditions at 5-, 10-, 20-, 50-, and 100-cm depths in addition to top (5 and 10 cm) and column (5, 10, 20, 50, and 100 cm) layer aggregates.

Soil moisture conditions can be a leading indicator of drought onset (Ford et al. 2015; Leeper et al. 2019), which is especially important to the detection of flash droughts (Ford et al. 2015; Otkin et al. 2018). Deficits at deeper depths (i.e., 50 and 100 cm) can be informative during long-lasting droughts that impact hydrological conditions (i.e., streamflow or reservoir levels). The purpose of this study was to evaluate how standardized soil moisture deficits evolve during drought events as described by the U.S. Drought Monitor (USDM), which is a composite index that considers drought conditions across the hydrological cycle (Svoboda et al. 2002). As a result, soil moisture conditions can be evaluated over drought episodes by depth to identify soil conditions (i.e., standardized measures and thresholds) that can serve as leading indicators of evolving drought status.

2. Data

a. USCRN

The USCRN is a network of 140 climate monitoring stations located across the United States, including Alaska and Hawaii (Diamond et al. 2013). Beginning in 2009, soil sensors capable to of monitoring both moisture and temperature conditions were installed at 113 stations across the contiguous United States at five depths: 5, 10, 20, 50, and 100 cm (Bell et al. 2013). A fraction (i.e., 20%) of stations within the USCRN network had insufficient soil depth or rocky substrate that prevented instrument installation at all five depths; at these sites only the 5- and 10-cm depths were instrumented. Similar to other primary variables in this network (i.e., air temperature and precipitation), three sets of Stevens Water Monitoring Systems, Inc., Hydra Probe sensors were installed at each depth to provide redundant hourly soil moisture observation for the station, which were averaged across each of the available depths. This redundancy was found to improve efforts to maintain the continuity of the record and evaluate sensor performance and health for quality control. Time series of both soil moisture and temperature conditions are quality controlled using both automated and manual methods. Note here that the sensor technology is not sensitive to frozen moisture, and as a result, sensor observations of soil moisture are automatically set to missing when soil temperatures approach freezing conditions (i.e., 0.5°C).

To evaluate soil moisture conditions prior to drought onset and periods of worsening and improving conditions, a recently developed USCRN standardized soil moisture dataset (Leeper et al. 2019) was utilized in this study. Leeper et al. (2019) used a 31-day moving sampling approaching over each yearday hour in the station's period of record to describe the hourly median (i.e., same hour over the 31 days) soil moisture climatologies for each station and depth as well as top (5 and 10 cm combined) and column (5 through 100 cm) layer aggregates. If a

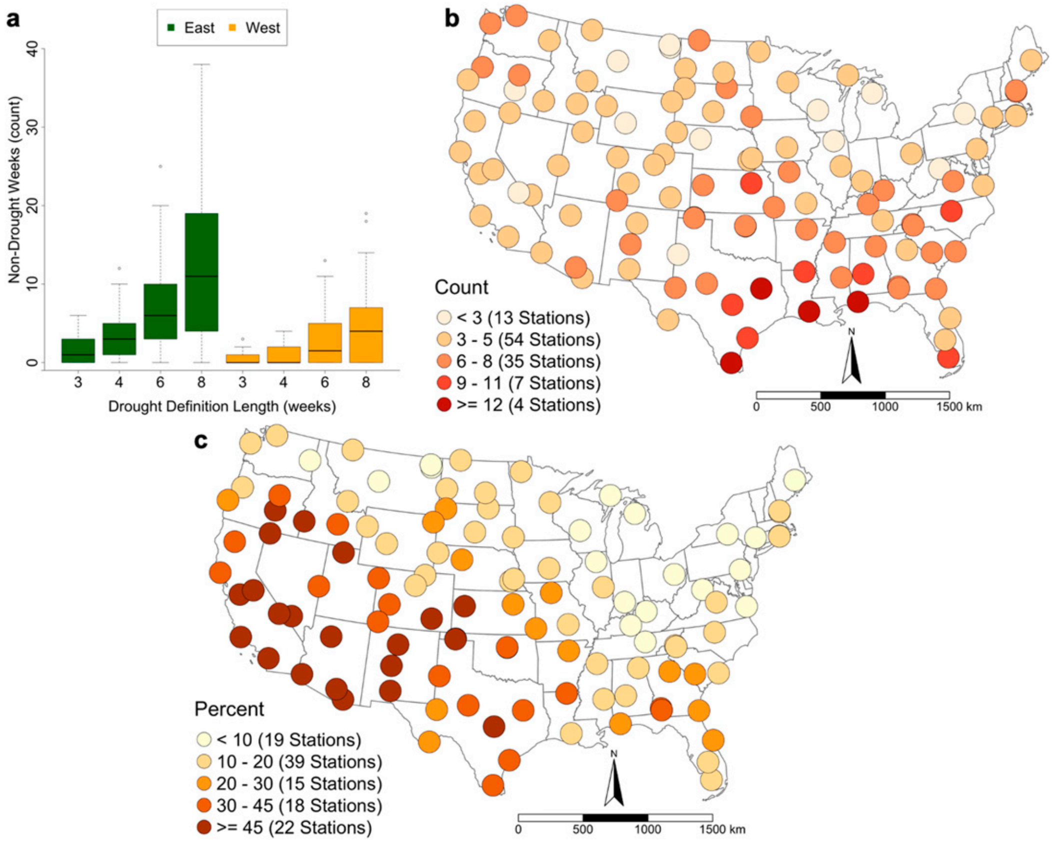

FIG. 1. Distribution of (a) nondrought weeks (D0 and none) within drought events for stations located east (green) and west (orange) of −105°W by gap length. Using the 3-week gap length to define drought events, (b) the count of drought events and (c) the percent of time within drought at USCRN stations from 2010 to 2019 are shown.

station had a 10-yr record for instance, the median would be evaluated from the 310 observations for a single hour that fall within the same 31-day calendar window across each of the 10 yr. The top and column layer aggregates were first evaluated as arithmetic means of the respective layer averages before median climatologies were evaluated. The combination of the 31-day sampling and moving window allowed for the evaluation of robust soil moisture climatologies that account for seasonal variations in soil moisture conditions.

These climatologies were used to evaluate standardized soil moisture anomalies and percentile conditions. The standardized anomalies were calculated by subtracting the median and dividing by the interquartile range (i.e., difference between the conditions for the 75th and 25th percentiles). The median climatology was found to be less sensitive to soil moisture outliers than mean conditions that were sensitive to precipitation events (Leeper et al. 2019). The percentiles were evaluated using an empirical cumulative distribution function that ranks standardized anomalies on a scale from driest (0) to wettest (100) conditions observed over the same 31-day calendar window in each year of the station's period or record. More information about and access to the hourly standardized dataset (climatologies, anomalies, and percentiles) are available online (https://www.ncdc.noaa.gov/crn/qcdatasets.html).

b. USDM

The USDM is produced through a collaborative effort among the National Drought Mitigation Center (NDMC), U.S. Department of Agriculture (USDA), and National Oceanic and Atmospheric Administration (NOAA) and is advised by federal, state, and local drought experts. Using geophysical observations (precipitation, temperature, streamflow, modeled soil moisture, vegetation state, etc.) and experts from the field, the USDM authors have manually generated weekly evaluations of drought conditions across the United States since 1999. These weekly maps characterize drought conditions using a categorical scale from none (no drought) to D4 (exceptional

TABLE 2. Thresholds used to evaluate the sensitivity and precision of soil moisture metrics by drought condition.

Soil moisture metrics	Condition	Thresholds
Standardized anomaly	Onset	0.0, −0.2, −0.4, and −0.6
Fractional hours ≤ 30th	Onset	0.15, 0.30, 0.45, and 0.70
Standardized anomaly	Worsening	0.0, −0.2, −0.4, and −0.6
Fractional hours ≤ 30th	Worsening	0.15, 0.30, 0.45, and 0.70
Standardized anomaly	Improving	0.0, 0.2, 0.4, and 0.6
Fractional hours > 30th	Improving	0.15, 0.30, 0.45, and 0.70

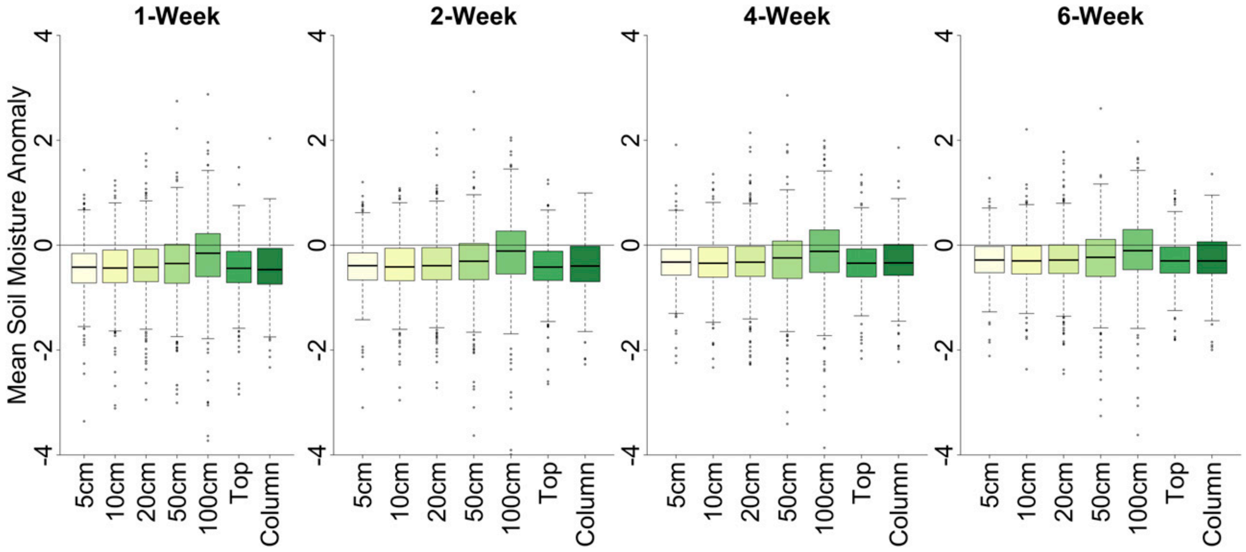

FIG. 2. Boxplots representing the 25th, median, and 75th percentiles of 1-, 2-, 4-, and 6-week averages of anomalous soil moisture conditions over the week prior to onset for the 5-, 10-, 20-, 50-, and 100-cm depths, along with top and column layer aggregates.

drought) as shown in Table 1. The USDM weekly maps (https://droughtmonitor.unl.edu/DmData/GISData.aspx) were intersected with USCRN (latitude and longitude) locations using geographic information system technology to generate time series of USDM conditions at each USCRN station. From the time series, drought events were defined to evaluate how standardized soil moisture conditions evolved prior to onset and during drought conditions. The method used to define drought events in this analysis is described in section 3a

3. Method

a. *Definition of drought events*

Drought-event start and end dates were defined for each station's location over the USDM period of record, from 2000 to 2019. From the weekly time series of USDM status, drought event start dates were determined as the first week drought status met or exceeded D1. End dates were identified as the last week that USDM status met or exceeded D1 followed by three or more consecutive weeks of D0 or none drought status.

The choice of minimum drought status (D1) to define the start and end dates was based on the consideration that D0, or abnormally dry status, was not a strong and consistent indicator of drought. The 3-week time requirement used to separate unique drought events was chosen based on a sensitivity analysis of gaps ranging from 3 to 8 weeks (Fig. 1). The 3-week criteria minimized the number of nondrought weeks (D0 and none) within drought events for stations located in both western and eastern regions of the contiguous United States (Fig. 1). Over the USCRN soil

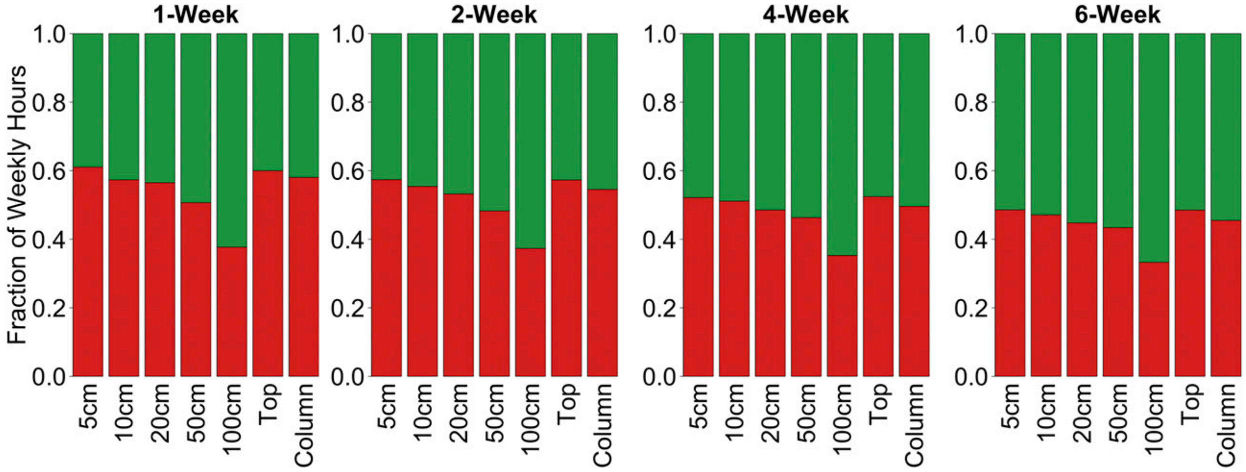

FIG. 3. The 1-, 2-, 4-, and 6-week mean fraction of abnormally dry hours (red) and nonabnormally dry hours (green) at each depth and layer aggregate.

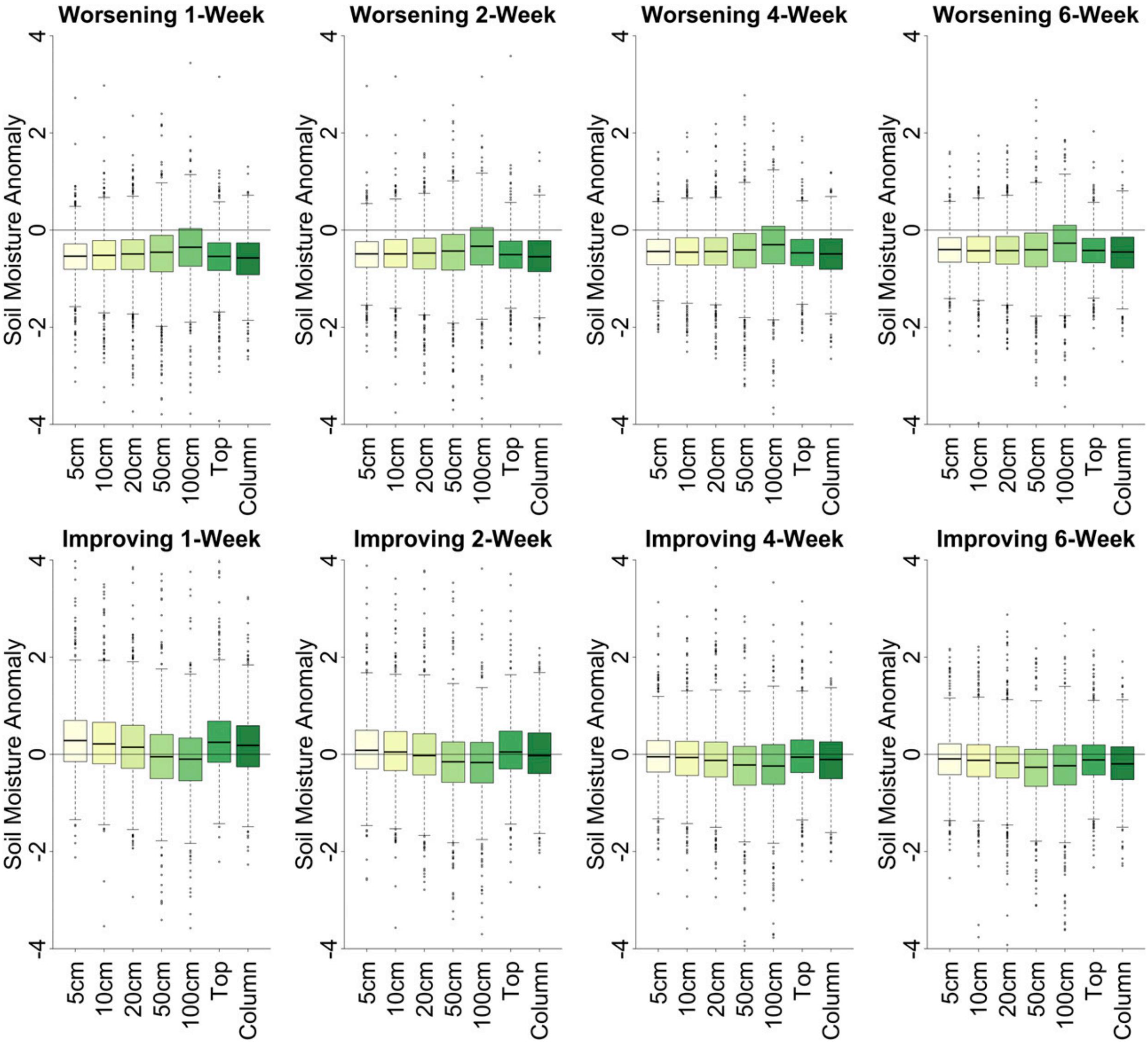

FIG. 4. As in Fig. 2, but for (top) worsening and (bottom) improving weeks within drought events.

moisture period of record from 2009 to 2019, this drought definition resulted in a total of 578 USCRN station drought events covering 15 022 station weeks in drought. Among the 113 stations, this averaged to five drought events per station with a mean event duration of 26 weeks. However, there were sharp contrasts between western and eastern stations with fewer, but longer-lasting drought events for stations located west of 105°W.

b. *Standardized soil moisture metrics*

The hourly standardized soil moisture measures (anomalies and percentiles) were aggregated over several weekly periods (1, 2, 4, and 6 weeks) to evaluate the importance of aggregation to variations in drought conditions. Regardless of aggregation length, all weekly periods ended at the same time and date, 1200 UTC Tuesday, to represent soil moisture conditions up to the valid date/time for each USDM map. For instance, if the USDM identified drought onset for a station on 21 January, the 1- and 2-week aggregation periods would be from 1100 UTC 15 January to 1200 UTC 21 January and from 1100 UTC 8 January to 1200 UTC 21 January, respectively. The standardized soil moisture anomalies were evaluated as arithmetic means of the hourly observations over these periods. Since soil moisture percentiles should not be averaged, these values were aggregated in two ways: the fraction of hours less than or equal to the 30th percentile, and the fraction of hours greater than the 30th percentile. These percentile metrics provide a measure of the fraction of hours meeting these conditions divided by the total number of nonmissing observations over the period. In other words, these are measures of the fractional time spent at abnormally dry states and at states wetter than abnormally dry over weekly periods based on the USDM D0

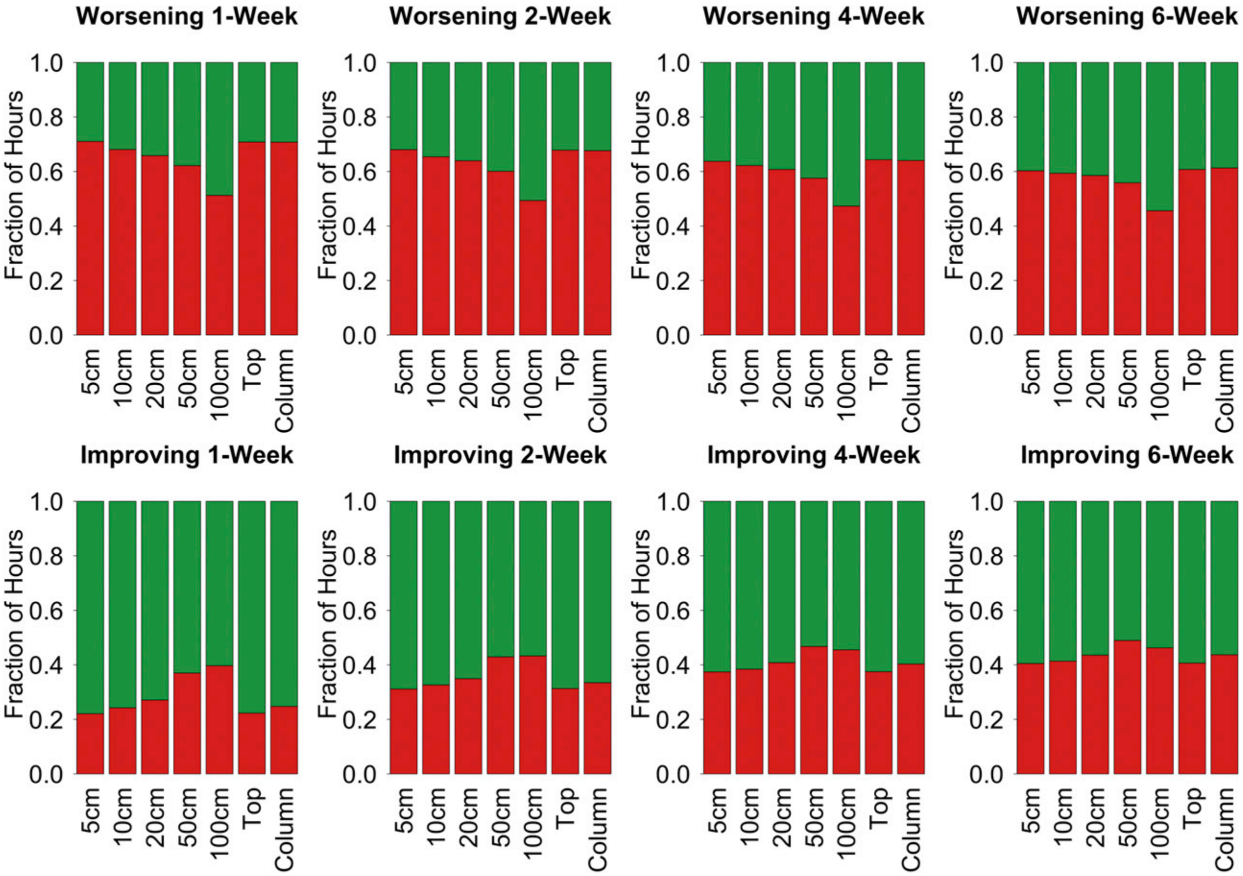

FIG. 5. Mean fraction of nonabnormally dry hours (green) and abnormally dry hours (red) over 1-, 2-, 4-, and 6-week periods ending for (top) drought-worsening and (bottom) drought-improving weeks.

(30th percentile) criteria. These three metrics (averaged standardized anomalies, and abnormally dry and not abnormally dry fractions) were generated for each depth (5, 10, 20, 50, and 100 cm) and layer aggregate (top and column).

To evaluate how soil moisture conditions varied with drought, the analysis was split into two parts. The first segment explored how the metrics varied in response to USDM identified drought events at USCRN stations across the United States. For drought onset and worsening USDM status (i.e., drought status increased), mean standardized soil moisture anomalies and the fraction of abnormally dry hours (≤30th percentile) were evaluated. For weeks when the USDM status improved (i.e., drought status decreased), attention was given to mean standardized soil moisture anomalies and the fraction of hours wetter than abnormally dry (>30th percentile). Focusing on drought onset and weeks of worsening and improving USDM status allowed for evaluations of typical soil moisture conditions at critical moments within drought evolution, and the range of these conditions across the United States by soil depth.

In the second part of this study, thresholds were identified to evaluate the association of these soil moisture metrics to changes in drought status. These thresholds provide a way to evaluate how successful an indicator these metrics are for drought onset, worsening, and improving status conditions by counting the times when a metric successfully indicated changes in drought status. In this study, three separate performance measures, sensitivity, precision, and their harmonic mean or accuracy (also known as *F* score), were selected to evaluate the depth, aggregation length, and measures of soil moisture deficits (anomalies and/or percentiles) that best align with evolving drought conditions.

For drought onset and worsening weeks, soil moisture measures were required to meet or dip below a threshold in Table 2 to be considered successful or a true positive (TP); otherwise, it was counted as a miss or false negative (FN). If soil moisture conditions met or dipped below a threshold when USDM conditions were static (neither worsening or onset), then it was counted as a false positive (FP). In a similar way, true positives, false negatives, and false positives were defined for improving drought weeks. However, in this case soil moisture measures were required to meet or exceed the respective thresholds in Table 2. Note here that FPs were not evaluated for weeks when drought status remained static at D4 conditions from week to week since it was the highest USDM category and conditions cannot

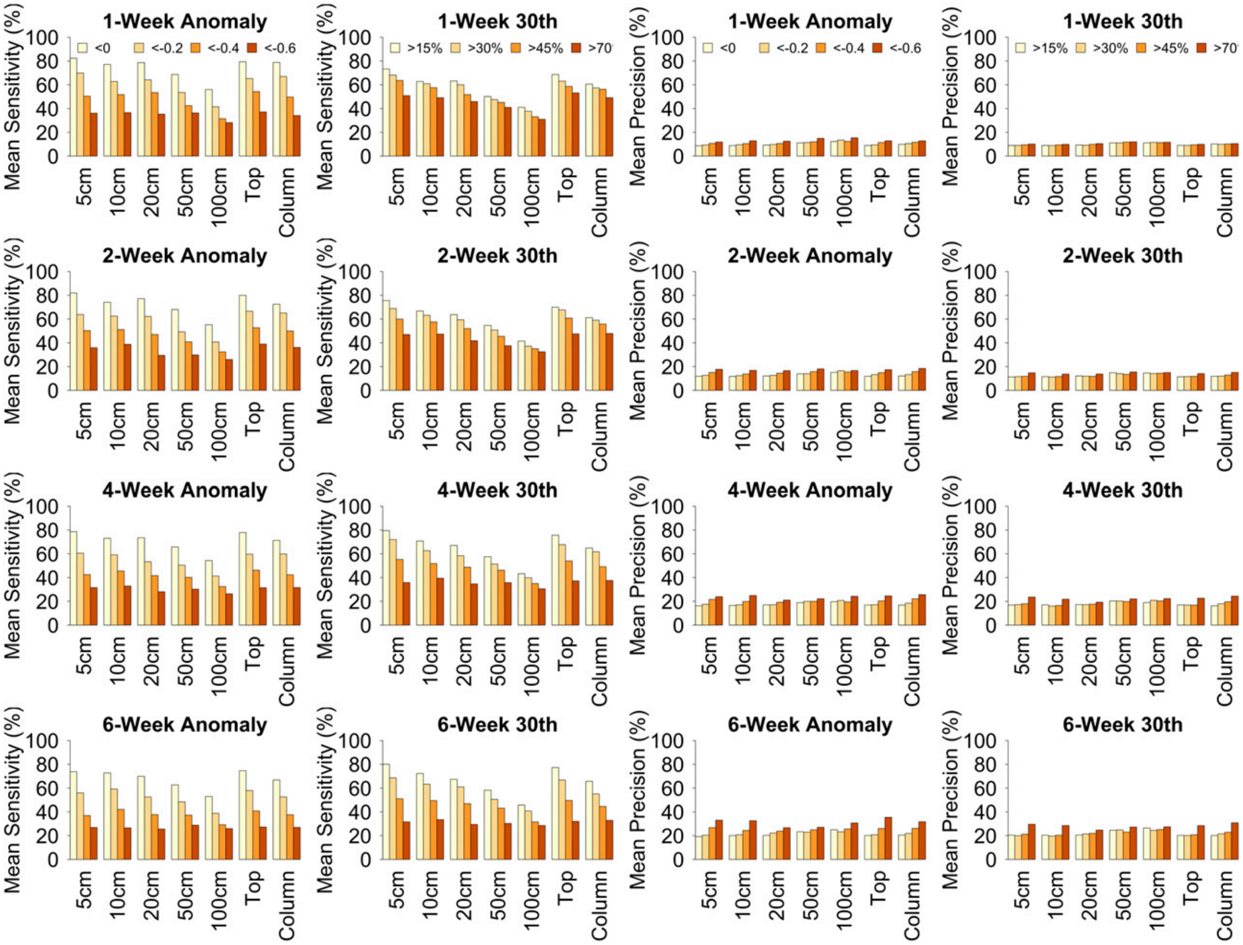

FIG. 6. Performance metrics (left),(left center) sensitivity and (right center),(right) precision for the (top) 1-, (top middle) 2-, (bottom middle) 4-, and (bottom) 6-week averaged standardized anomaly and fraction of hours below the 30th-percentile thresholds ending the week prior to drought onset.

worsen from that status. The three performance measures are defined as

$$\text{Sensitivity} = \frac{\text{TP}}{\text{TP} + \text{FN}}, \tag{1}$$

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}}, \quad \text{and} \tag{2}$$

$$\text{Accuracy} = \frac{2}{\text{Sensitivity}^{-1} + \text{Precision}^{-1}}. \tag{3}$$

These three performance measures provide various perspectives on how well the soil moisture metric can anticipate changes in drought conditions. Sensitivity measures how well the metrics performed during times when USDM status changed (i.e., onset, worsening, and improving) and penalizes the metrics that miss changes in USDM status (FN). Precision provides a slightly different perspective by including all conditions when a measure indicates drought change (i.e., equal or below a threshold for onset and worsening weeks and greater than a threshold for improving weeks). In other words, precision penalizes the measures for false alarms or when they indicate onset or worsening (i.e., ≤threshold) or improving (≥threshold) drought conditions that are not reflected by the USDM. Accuracy is a harmonic mean of sensitivity and precision, which equally weights the two separate performance measures to provide a composite score for the drought metrics. Ideally, a measure that can successfully anticipate changes in USDM status not only would meet the threshold when USDM status changes but would do so with fewer false alarms or FPs, resulting in a higher measure of accuracy.

4. Results

a. *Soil moisture conditions prior to onset*

Standardized soil moisture anomalies for all depths and averaging times (Fig. 2) indicated soil moisture conditions were dryer than usual over the week leading up to drought onset. For standardized soil moisture anomalies, the 5-,

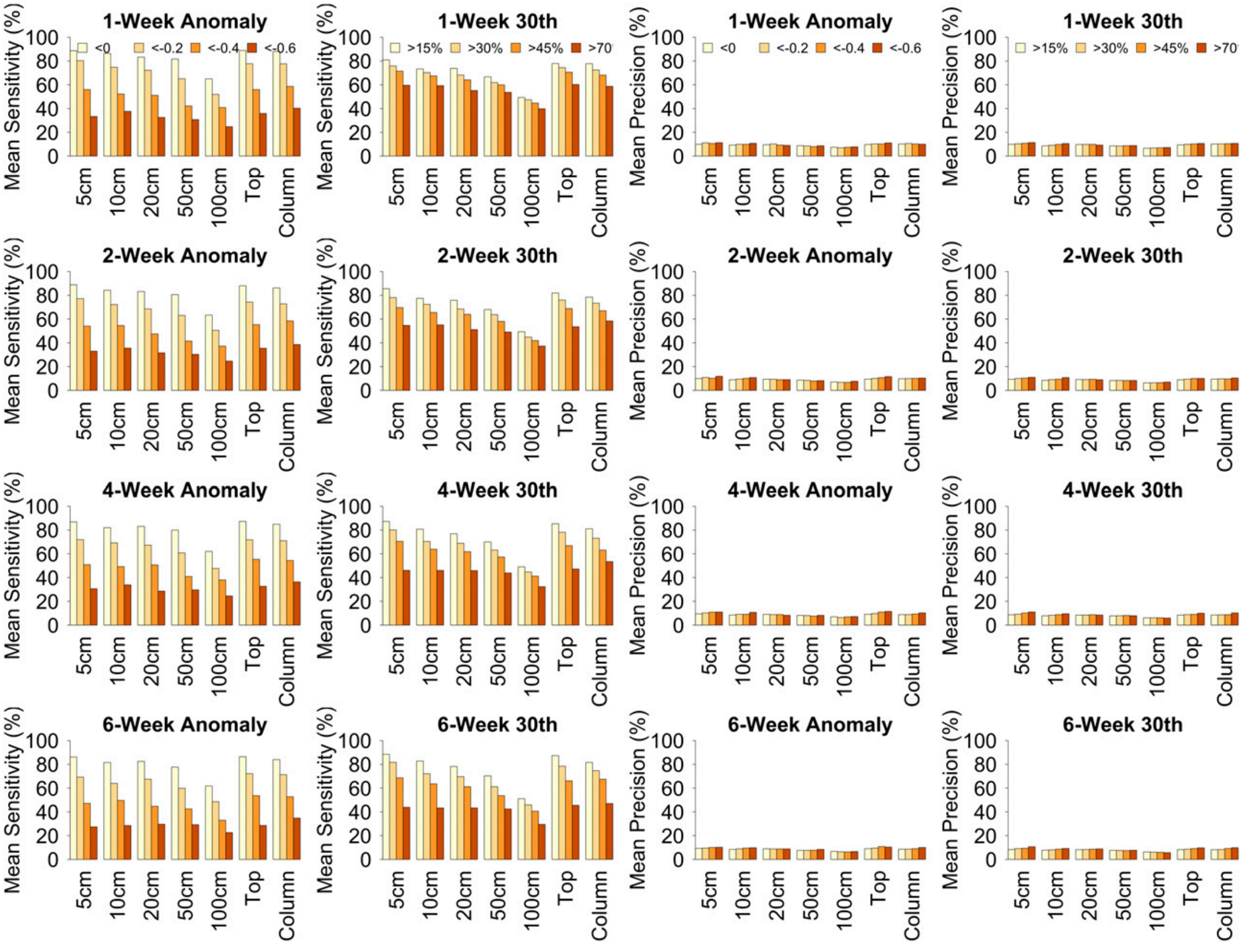

FIG. 7. As in Fig. 6, but for drought-worsening weeks.

10-, and 20-cm depths and top and column layers had similar sized negatively shifted anomaly distributions while the deeper depths (i.e., 50 and 100 cm) had anomaly distributions nearly centered on zero. This was particularly true for the 100-cm depth. The drying signal was seen at the surface first (5–20 cm) with D1 drought conditions established before dryness reached the deeper (50 and 100 cm) depths. As the averaging period increased, mean anomalous conditions were slightly less negative, with the top layer standardized anomaly mean increasing from −0.45 to −0.29 from the 1-week to the 6-week averaging periods. These results suggest that soil moisture conditions declined prior to drought onset with the decline more discernable at the upper-level depths (5, 10, and 20 cm) and shorter averaging times since they are impacted initially and with larger deficits before drought began.

The proportion of abnormally dry hours (soil moisture percentiles less than the 30th) prior to drought onset (Fig. 3) was greater than 0.5 or 50% of the week despite representing only a third of the distribution. However, this became less so with increasing depth and averaging period length. For instance, the top layer fractions reduced from 0.60 (60% of the hours) over the 1-week period to 0.48 (48%) for the 6-week duration, and from 0.61 to 0.38 between the 1-week duration at 5- and 100-cm depths, respectively. Once again, the fraction of abnormally dry hours, particularly for the upper-level depths, suggest that soil moisture conditions can be a leading indicator of drought onset. The small shift between 1- and 4-week distributions of the fraction of abnormally dry hours for the upper-level depths suggest that soil moisture conditions can indicate the potential of drought 1–4 weeks in advance of USDM D1 conditions.

b. Drought worsening and improving soil moisture conditions

Soil moisture anomalies were generally more consistently negative for worsening conditions at all depths (Fig. 4). The magnitude of the soil moisture deficits for worsening weeks diminished slightly with depth and averaging length. For the top layer, soil moisture anomalies ranged between −0.57 and −0.43 for the 1- and 6-week average periods.

Drought improving weeks were only slightly wetter or near normal soil moisture conditions for the upper levels (5, 10, and 20 cm) and shorter averaging periods with the top layer 1- and 6-week means reaching 0.24 and −0.15, respectively. At the deeper depths and longer averaging periods, differences

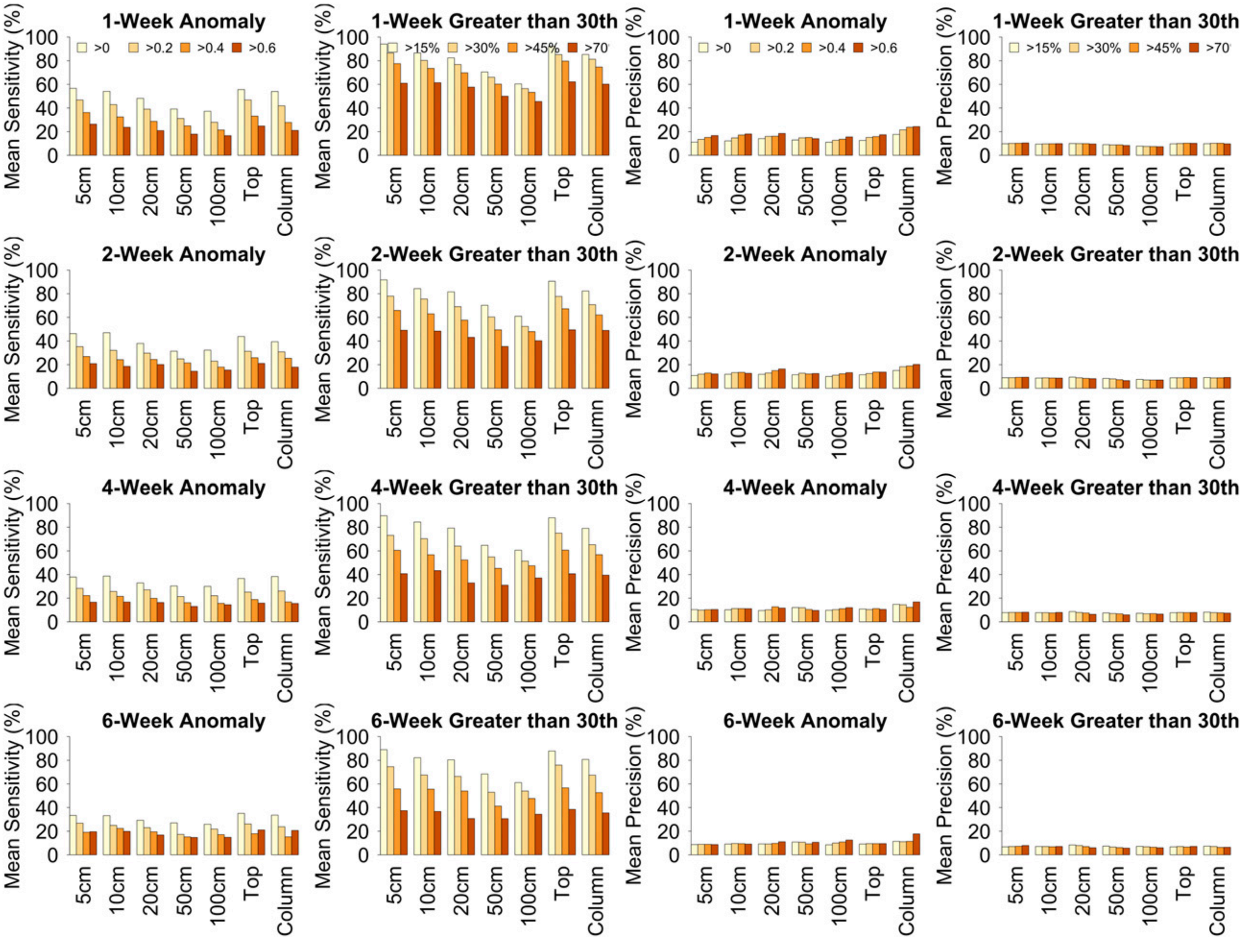

FIG. 8. As Fig. 6, but for drought-improving weeks.

between worsening and improving drought weeks were undiscernible with the 100-cm-depth 6-week mean for worsening (−0.44) and improving (−0.34) drought conditions only offset by −0.1. The dryer soil moisture conditions over longer averaging periods and deeper depths for drought-improving weeks were not surprising given the noted lag for deeper depths and the longer averaging times including worsening and or static drought conditions.

Soil moisture percentiles showed a greater distinction between worsening and improving drought weeks (Fig. 5). This was particularly true for the shorter-term averaging periods near the surface where the fraction of abnormally dry hours was much greater than the fraction of hours wetter than abnormally dry conditions (Fig. 5). For the 1-week top layer average, the fractional number of hours that soil moisture conditions were below the 30th percentile was 0.71 as compared with 0.29 for the number of hours above the 30th. Likewise, the 1-week top layer average for drought-improving weeks had a much greater portion of hours above the 30th (0.74) than below the 30th (0.26) percentiles. These differences diminished slightly with depth and to a greater extent with averaging length (Fig. 5), albeit more so for improving than worsening weeks. In fact, for the 6-week improving average the fraction of hours below the 30th (0.44) and greater than the 30th (0.56) were very similar.

c. *Performance of soil moisture metrics*

To evaluate the performance of soil moisture conditions as an indicator of drought monitoring, a series of anomalous and percentile thresholds were selected (Table 2) to assess the sensitivity and precision for drought onset, worsening, and improving weeks.

1) DROUGHT ONSET

For both standardized anomalies and fraction of hours below the 30th percentile, sensitivity was much higher than precision regardless of threshold, averaging length, or depth (Fig. 6). Nationally averaged onset sensitivities were generally greater for the upper-level depths and top and column layer aggregates with averaging length only slightly impacting sensitivity. This was particularly pronounced for the standardized anomalies. Excluding the deeper depths (50 and 100 cm), nearly 80% of the 578 USDM identified station drought events for this study had a negative soil moisture anomaly deficit (<0.0) for the 1-week average. This percentage declined

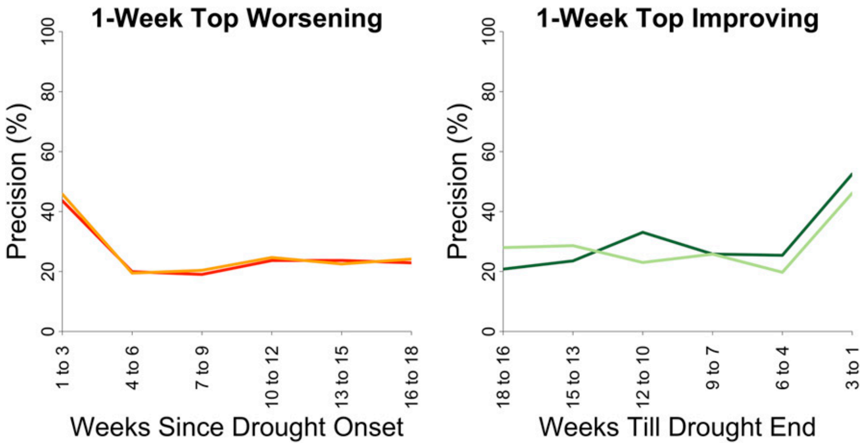

FIG. 9. One-week top layer precision for the (a) 0.15 threshold for fraction of hours below the 30th percentile (red) and 0.00 anomaly threshold (orange) by weeks since drought onset for worsening USDM weeks and (b) 0.15 threshold for fraction of hours above the 30th percentile (dark green) and 0.00 anomaly threshold (light green) by weeks until drought end for improving USDM weeks.

slightly to 75% for the 2-, 4-, and 6-week averaging lengths. As the threshold decreased from less than 0.0 to −0.6, the top layer sensitivity dropped from 79.4% to 37.1% of drought events having soil moisture deficits of this size prior to onset. The reduction in sensitivity for the larger magnitude thresholds were thought to be caused by the USDM reporting drought conditions prior to soil moisture deficits reaching those thresholds. Measures of precision were generally around 10% for the 1-week anomaly and 30th percentile fractions but increased to over 20% for the longer averaging lengths and lower thresholds. The lower levels of precision indicate that there were a number of false alarms or times when there were soil moisture deficits indicating drought onset, but no USDM drought was identified.

2) DROUGHT WORSENING AND IMPROVING WEEKS

Similar to drought onset, soil moisture anomalies and fraction of hours below the 30th percentiles had larger measures of sensitivity than precision for drought-worsening weeks. Of the 1,172 worsening station drought weeks, nearly 90% were preceded by a 1-week negative (<0.0) soil moisture anomaly for the upper level (5, 10, and 20 cm) and top and column level aggregates (Fig. 7). This reduced slightly to over 85% for the 2-, 4-, and 6-week averaging lengths with the steepest declines in sensitivity occurring with larger negative anomaly thresholds. Hours below the 30th percentile had less contrast among the fractional thresholds with the 1-week averaging period for the upper levels (5, 10, and 20 cm) and top and column aggregates dropping from a range of 75%–81% for the 15% threshold to 56%–60% at the 70% threshold (Fig. 7). In contrast, precision remained low (i.e., around 10%) regardless of threshold, depth, and aggregation length. This suggests while there are soil moisture deficits for a sizeable majority (over 80%) of drought-worsening station weeks, but it was also challenging to distinguish between USDM worsening and static drought weeks.

For improving drought weeks, there was some contrast in measures of sensitivity between the anomalies and fraction of hours above the 30th percentile (Fig. 8). Overall, the fraction of hours above the 30th had higher measures of sensitivity than standardized anomalies. For the 1-week 5-, 10-, and 20-cm depths and top and column layers, the fraction of hours above the 30th had sensitivities ranging between 52.2% and 90.7% as compared with 23.8%–58.1% for the standardized anomalies at the same averaging length and depths. Differences in

TABLE 3. The predominant threshold for standardized anomaly and fraction of hours below the 30th percentile by depth and averaging length for drought onset weeks.

Depth	Anomaly 1 week	Anomaly 2 week	Anomaly 4 week	Anomaly 6 week	Percentile 1 week	Percentile 2 week	Percentile 4 week	Percentile 6 week
5 cm	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15
10 cm	0.00	0.00	0.00	0.00	0.70	0.15	0.15	0.15
20 cm	0.00	0.00	0.00	0.00	0.70	0.15	0.15	0.15
50 cm	0.00	0.00	0.00	0.00	0.70	0.15	0.15	0.15
100 cm	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15
Top	0.00	0.00	0.00	0.00	0.70	0.70	0.15	0.15
Column	0.00	0.00	0.00	0.00	0.70	0.70	0.15	0.15

TABLE 4. As in Table 3, but for drought-worsening weeks.

Depth	Anomaly 1 week	Anomaly 2 week	Anomaly 4 week	Anomaly 6 week	Percentile 1 week	Percentile 2 week	Percentile 4 week	Percentile 6 week
5 cm	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15
10 cm	0.00	0.00	0.00	0.00	0.70	0.15	0.15	0.15
20 cm	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15
50 cm	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15
100 cm	0.00	0.00	0.00	0.00	0.70	0.70	0.15	0.15
Top	0.00	0.00	0.00	0.00	0.70	0.15	0.15	0.15
Column	0.00	0.00	0.00	0.00	0.70	0.45	0.15	0.15

sensitivity between the standardized measures of soil moisture were likely caused by the choice to use positive anomaly thresholds in this case. For instance, the same percentiles between the 31st and 49th would be considered a true positive for fraction of hours greater than 30th, but a false negative for the anomaly metrics since these percentiles would equate to a negative anomaly. In some regard, this provides an advantage of using percentiles during drought amelioration periods where slightly drier than usual soil moisture can indicate an improvement from even drier soil moisture conditions found earlier. Measures of sensitivity were found to be more responsive to the choice of threshold than averaging length for both anomalies and fraction of hours above the 30th percentile. Similar to onset and worsening drought conditions, measures of precision ranged between 6.2% and 11.2% and 4.3% and 5.4% for the 1-week soil moisture anomaly and fraction of hours above the 30th percentile, respectively.

5. Discussion and conclusions

The high levels of sensitivity suggest that the standardized measures of soil moisture conditions were generally in agreement with changes in USDM drought status (i.e., onset, worsening, and improving). For instance, standardized soil moisture anomalies and fraction of abnormally dry hours indicated drier conditions prior to onset for over 80% of all USDM drought events and worsening weeks, depending on the choice of threshold and averaging length. This was also the case for drought-improving weeks, albeit slightly less so for soil moisture anomalies, with up to 58% and 90% of the USDM improving weeks preceded by wetter anomalies and a greater fraction of wetter than abnormally dry hours, respectively.

However, the low levels of precision indicated that soil moisture conditions changed frequently and were not temporally aligned with changes in USDM status (i.e., false alarms). For onset, this included cases of drier than usual soil moisture conditions that did not lead to USDM drought events. Within drought events, the primary challenge was distinguishing static drought weeks (when USDM status remained unchanged) from worsening or improving drought weeks. These results may not be all that surprising given that the USDM is a composite index that considers other measures of moisture deficits across the time scales of the hydrological cycle beyond soil moisture (Svoboda et al. 2002). In addition, soil moisture provides a more quantitative measure of agricultural drought than the USDM, which allows it to capture any instance of drier than usual soil moisture conditions. This differs slightly from the USDM's convergence of evidence approach that favors more sustained and prominent drought conditions. This suggests that considering soil moisture conditions across a region (i.e., from multiple stations) may improve measures of precision with respect to the USDM than a single station.

There may also be times when the USDM status is more sensitive to measures of soil moisture conditions. To explore this further, standardized soil moisture measures of precision for worsening and improving weeks were evaluated by the number of weeks since drought onset and the number of weeks until drought termination (Fig. 9). In the initial weeks of drought onset, worsening drought week precision scores for the top layer improved from less than 10% (Fig. 7) to over 40% before trailing off as drought conditions persisted in time (Fig. 9a). Likewise, in the final few weeks of drought, precision measures for improving weeks reached nearly 50% as drought conditions abated. It should be noted that in these weeks' sensitivity measures remained relatively similar (high 80%) to those shown in Figs. 7 and 8. These results suggest soil moisture conditions were better aligned with USDM status change in the initial and waning weeks of drought evolution than during the interim period, which is presumably when drought authors were focused on other aspects of the hydrological cycle (i.e., evapotranspiration, streamflow, and reservoir level anomalies). These are particularly important findings for the drought monitoring and forecasting communities that may find soil moisture conditions a useful indicator of evolving drought conditions during the earlier and latter phases of drought evolution.

To further evaluate the response of sensitivity and precision to threshold selection, harmonic means of sensitivity and precision (F scores) were evaluated for each USCRN station depth, aggregation length, and standardized measure (anomaly and percentiles). From these evaluations, most station harmonic means ranged between 40% and 59%. For soil moisture anomalies, harmonics means were largest when using the 0.00 threshold for most stations for drought onset, worsening and improving drought conditions. The fraction of hours below the 30th percentile tended to have higher harmonic means for the 0.70 threshold for drought onset and worsening USDM weeks. For drought-improving weeks, the 0.15 threshold for the fraction of hours wetter than abnormally dry conditions was more commonly associated with stations in the eastern half of the

TABLE 5. The predominant threshold for standardized anomaly and fraction of hours above the 30th percentile by depth and averaging length for drought-improving weeks.

Depth	Anomaly 1 week	Anomaly 2 week	Anomaly 4 week	Anomaly 6 week	Percentile 1 week	Percentile 2 week	Percentile 4 week	Percentile 6 week
5 cm	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15
10 cm	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15
20 cm	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15
50 cm	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15
100 cm	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15
Top	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15
Column	0.00	0.00	0.00	0.00	0.15	0.15	0.15	0.15

United States as compared with the 0.70 threshold for western located stations. These results were mostly unchanged by averaging length as shown in Tables 3–5 and suggest that the choice of threshold may be more important for percentile frequencies.

An additional consideration that should be further evaluated is the sensitivity of these thresholds to specific drought mitigation and resiliency applications. In this study, we evaluated the choice of standardized soil moisture thresholds that best aligned with changes in USDM status; however, the selection of thresholds may vary by specific drought impact or application of interest. For instance, the timing of anomalously dry soil moisture conditions may be more important (i.e., crop pollination, snowpack melt) than the designation of USDM status change. This highlights an additional need for a localized historical analysis of past drought events, similar to the method applied at USCRN stations in this study, to support efforts to evaluate the importance of soil moisture and potentially other hydrological indicators (i.e., meteorological, agricultural, and hydrological) in specific drought monitoring applications.

In summary, USDM weekly status changes consisting of onset, worsening, and improving drought conditions were evaluated against all 5 native USCRN monitoring depths (5, 10, 20, 50, and 100 cm) as well as two aggregate levels, the top (5 and 10 cm) and column (5, 10, 20, 50, and 100 cm) layers. These analyses revealed that the top three levels (5, 10, and 20 cm) and top layer aggregate had very similar anomalous and hourly fractional distributions during drought onset, worsening, and improving conditions. This may be useful when combining standardized soil moisture measures from multiple networks and data sources that monitor the upper layers of the soil at differing depths. This also suggests that remotely sensed soil moisture datasets may be a useful indicator of drought evolution during the earlier and later phases of drought despite only detecting surface soil moisture conditions. The deeper depths (50 and 100 cm), as expected, lagged the shallower depths in both drying and moistening periods within a drought, and were not found to appreciably improve measures of sensitivity or precision in this study. The utility of deeper depths to monitor drought was hampered by the temporal lag, which can cause soil moisture conditions at those depths to become out of phase when drought conditions evolve in nonlinear ways (i.e., worsening conditions followed by improving, and worsening again). However, the deeper depths can be an indicator of drought persistence over a worsening phase, which may be useful in assessments of drought severity. The responsiveness of the upper-level depths to changes in drought status indicates that soil moisture observations from the upper levels (5–20 cm) of the soil would be more suitable for detecting the rapid intensification of flash drought, which is a designation applied to drought events that evolve rapidly (Otkin et al. 2018).

Networkwide thresholds for standardized anomalies and fraction of hours (both below the 30th and above the 30th percentile) were 0 and 0.15, respectively, for drought onset, worsening, and improving drought conditions. The high levels of sensitivity suggest that these standardized soil moisture metrics (i.e., anomalies and percentiles) and thresholds can be useful indicators of evolving drought conditions during the earlier and later phases of drought formation and amelioration when measures of precision were elevated. For onset, sensitivity measures for anomalies and fraction of hours below the 30th percentile varied little between 1- and 4-week averages, suggesting that soil moisture conditions can provide up to a 4-week lead time on drought formation for approximately 78% of USCRN drought events. Once drought had formed, standardized soil moisture measures became less successful as a direct indicator of USDM status change. While this study focuses on comparisons with the USDM composite drought measure, further research should evaluate how standardized soil moisture conditions compare with other measures such as vegetation stress, phenological development, or agricultural yields that are more directly tied to agricultural drought.

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Data availability statement. The standardized soil moisture dataset (https://doi.org/10.7289/V5H13007) from the U.S. Climate Reference Network (USCRN) used in this study is openly available from NOAA's National Centers for Environmental Information (https://www.ncei.noaa.gov/pub/data/uscrn/products/soilanom01/). The national drought status conditions used to define drought events were obtained from the National Drought

Mitigation Center at the University of Nebraska–Lincoln (https://droughtmonitor.unl.edu/), as described by Svoboda et al. (2002).

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