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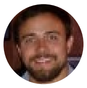

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Comparison of Drought Probability Assessments Based on Atmospheric Water Deficit and Soil Water Deficit

Guilherme M. Torres, Romulo P. Lollato, and Tyson E. Ochsner*

ABSTRACT

Methods that estimate the probability of agricultural drought using atmospheric data can be widely applied but have not been compared with actual drought occurrence indicated by soil moisture measurements. Our objectives were to develop a drought probability assessment method using long-term measurements of soil water deficits (SWDs) and to compare the resulting probabilities with those of an existing method based on atmospheric water deficits (AWDs). Fifteen years of daily precipitation, air temperature, and soil moisture measurements for eight locations across Oklahoma were used to calculate the probability (*P*) of water deficits sufficient to cause plant water stress for each day of the growing season. For the SWD method, the drought threshold was set at 50% depletion of the soil's total available water capacity. For the AWD method, the threshold was a 7-d cumulative AWD of 50 mm. Values of AWD were similar to calculated SWD for the 0- to 40-cm soil layer in the spring; however, AWD values seldom reached the drought threshold. Thus, drought *P* values calculated by the AWD method were unreasonably low and consistently lower than *P* estimated by the SWD method. The AWD method showed greater agreement with the SWD method when 37 mm was used as the AWD threshold or when the original 50-mm threshold was applied for a 15-d cumulative AWD. The new SWD method gave plausible and consistent results when applied to both the 0- to 40- and 0- to 80-cm soil layers and should be utilized when long-term soil moisture data are available.

Drought is a major cause of limited productivity in rainfed agroecosystems throughout the world, accounting for a large proportion of the crop losses and yearly yield variation of annual crops (Boyer, 1982). Drought costs are estimated to vary from US$6 to 8 billion yr^{-1} in the United States; however, single events can cause losses as high as US$39 billion (e.g., the 1987–1989 drought that affected the central and eastern states; Federal Emergency Management Assessment, 1997). Drought is a climatological event characterized by low precipitation and intensified by weather factors such as low atmospheric humidity, high wind speeds, and high temperatures (Federal Emergency Management Assessment, 1997). Different types of drought are recognized, including meteorological, agricultural, and hydrological drought, each with specific characteristics and magnitudes (Dziegielewski et al., 1991). Meteorological drought, which is defined as persistent below-average precipitation, can alter the seasonal replenishment of soil water, which may lead to agricultural drought. According to Mkhabela et al. (2010), agricultural drought is a deficiency in soil water that is severe enough to harmfully stress rangelands and pastures and to decrease crop production.

Accurate assessment of seasonal patterns in drought probability is important because if the crop cycle can be matched with periods when drought is less likely to occur, yield losses due to drought may be reduced (Purcell et al., 2003). Current drought probability assessment methods are typically based on long-term atmospheric data such as rainfall and maximum and minimum temperatures, on precipitation indices, or on a crop-specific drought index and typically do not consider site-specific soil properties (Keating and Meinke, 1998; Tsakiris et al., 2007). Methods that consider soil conditions have been proposed mainly to assess drought intensity (Palmer, 1965) or moisture accessibility for crop growth and development (Palmer, 1968), but no existing methods use actual soil moisture measurements to assess drought probabilities.

Purcell et al. (2003) suggested a method of drought avoidance assessment for summer crops based on long-term weather data. In this method, latitude, altitude, and long-term measurements of daily average wind speed and maximum and minimum temperatures are used to calculate reference evapotranspiration (ET_0). The cumulative ET_0 for the preceding 6 d and the day under consideration are summed (7-d total), and the 7-d cumulative precipitation is subtracted from this value, resulting in a 7-d cumulative AWD estimate for each day of the long-term record. From these AWD estimates, the drought probability for each day of the year (DOY) is determined. This method can be widely applied due to the availability of temperature and precipitation data, but it does not account for long-term water deficit accumulation or soil water storage (Purcell et al., 2003).

Soil physical properties such as texture and porosity influence the degree to which soil water is available for plant uptake, so a water stress threshold based on only soil water content would not be applicable across soil types. A more general

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Abbreviations: AWD, atmospheric water deficit; DOY, day of the year; ET_0, reference evapotranspiration; RAW, readily available water; SWD, soil water deficit; TAW, total available water.

threshold can be developed using the concept of total available water (TAW), which is the difference between the volumetric water content at field capacity and at the wilting point, multiplied by the thickness of the soil layer being considered (Allen et al., 1998). Water uptake by plants decreases considerably before the wilting point is reached, and therefore only a fraction of the TAW, varying from 0.3 to 0.7, is readily available water (RAW). When the RAW is depleted, water stress begins (Allen et al., 1998). We hypothesized that, when long-term soil moisture data are available, these concepts can be used to create SWD-based drought probability assessments, which are more reliable than those based on the AWD alone. The objectives of this study were to develop a drought probability assessment method based on long-term measurements of SWD and to compare the resulting drought probability assessments with those of an existing method based on the AWD.

MATERIALS AND METHODS

Long-term weather data were obtained for eight sites across the state of Oklahoma (Table 1) from the Oklahoma Mesonet, an automated network of 116 remote meteorological stations (McPherson et al., 2007). Sites were chosen to represent different annual rainfall amounts and soils across the state. The sites included Goodwell, Woodward, and Hollis with rainfall between 406 and 639 mm yr^{-1}; Acme and Stillwater with 788 to 881 mm annual rainfall; and Nowata, Lane, and Wister with >1000 mm of annual rainfall. Soil textures ranged from sandy loam to clay, with sand contents varying from 11 to 54% and clay contents from 6 to 57%.

Data sets were composed of 15 yr of observations (1996–2010) and contained daily values for maximum and minimum temperatures (T_{max} and T_{min}), precipitation, wind speed, and reference temperature difference (ΔT_{ref}) for three soil depths: 5, 25, and 60 cm. The ΔT_{ref} values, measured with 229-L heat dissipation sensors (Campbell Scientific), represent the increase in the sensor temperature after a 21-s heat pulse and were used to calculate the soil matric potential (ψ_m) (Illston et al., 2008). Sensors were installed under perennial vegetation; the dominant species varied by location but included bermudagrass [*Cynodon dactylon* (L.) Pers.], white clover (*Trifolium repens* L.), and tall fescue (*Festuca arundinacea* Schreb.).

The number of years used in statistical analysis of the climate is of great importance. In our analysis, we used 15-yr data sets for both the AWD and SWD methods because soil moisture data were not available before 1996. Our goal was to compare the methods using data collected from the location for the same period. Van Wart (2011) indicated that 15 yr of consecutive daily weather data were enough to achieve a coefficient of variation (CV) of 0.05 in the analysis of the yield potential of rainfed corn (*Zea mays* L.) systems in the U.S. Corn Belt, a variable that was associated with the mean annual rainfall. The period needed to achieve a CV of 0.05 was reduced to 12 yr when analyzing the yield potential of rice (*Oryza sativa* L.) systems in China. The results obtained by Van Wart (2011) led us to believe that the data used in this study is adequate. Following the methodology suggested by Purcell et al. (2003), missing data were not gap-filled and DOY 366 values from leap years were ignored.

Definition of the Growing Season

The growing season for warm-season crops is primarily limited by low temperatures, which restrict seed germination, plant emergence, and crop growth (Andrews, 1987). Therefore, the temperature limits of the growing season were determined for each location based on the probability (P) < 0.05 of the occurrence of $T_{min} < 0°C$, as suggested by Purcell et al. (2003). Probabilities were calculated as the number of years when $T_{min} < 0°C$ occurred, over the total number of observations for each DOY, using data from 1994 to 2010. The P values of $T_{min} < 0°C$ were plotted against DOY and regressed separately against the decreasing P values in the spring and the increasing P values in the fall. The resulting linear equations developed for each location were used to determine the respective DOYs when $P < 0.05$ of $T_{min} < 0°C$ occurred for the spring and for the fall.

Drought Probability Assessment Methods

The AWD approach followed the methodology suggested by Purcell et al. (2003). This method uses latitude, altitude, wind speed ($m\ s^{-1}$), T_{max}, and T_{min} to estimate daily ET_0 by the Penman–Monteith equation (Allen et al., 1998) as modified by the FAO. Altitude, latitude, T_{max}, and T_{min} were used to estimate

Table 1. Location and description of key weather variables for eight studied sites throughout the state of Oklahoma. Location of each site is specified by latitude, longitude, and elevation, and weather variables are average daily values for the entire year for mean temperature (T_{mean}) and total annual precipitation (Precip.) and the first and last day and duration of the growing season.

Site	Latitude	Longitude	Elevation	T_{mean}	Precip.	0°C T_{min} occurrence Last	0°C T_{min} occurrence First	Duration of season†
			m	°C	mm	——— DOY‡	———	d
Goodwell	36°36′ N	101°36′ W	997	13.3	406	120	281	161
Woodward	36°25′ N	99°25′ W	625	14.9	639	103	291	188
Hollis	34°41′ N	99°49′ W	497	16.2	616	94	298	204
Acme	34°48′ N	98°1′ W	397	16.2	788	101	295	194
Stillwater	36°7′ N	97°5′ W	272	15.5	881	106	293	187
Nowata	36°44′ N	95°36′ W	206	14.6	1033	104	290	186
Lane	34°18′ N	95°59′ W	181	16.5	1103	95	300	205
Wister	34°59′ N	94°41′ W	143	15.8	1119	108	290	182

† Duration of the growing season was defined as the period between the last (in spring) and first (in fall) occurrence of a minimum temperature of 0°C ($P = 0.05$).
‡ Day of the Year; first and last day of the growing season determined when P of $T_{min} < 0°C$ was <0.05.

the total solar radiation for each DOY, while the vapor pressure deficit was estimated based on the daily T_{max} and T_{min} (Allen et al., 1998). When wind speed measurements were not available, a value of 2 m s^{-1} was used, following the procedure suggested by Allen et al. (1998). The 7-d AWD was estimated for each DOY by calculating the 7-d running sum of ET_0 and subtracting the 7-d running sum of precipitation for each DOY. An AWD threshold of 50 mm was used to identify drought occurrence. Purcell et al. (2003) recommended this value assuming an effective rooting depth of 592 mm multiplied by 0.13, the difference between the soil water content at field capacity and the wilting point (average for 401 soils across the United States; Ratliff et al., 1983), and by 0.65, the assumed fraction of TAW depletion when plants start to suffer water stress (Ritchie, 1981; Ray and Sinclair, 1998). The drought probability for each DOY was then estimated as the number of times in which a 7-d AWD > 50 mm occurred on that DOY divided by the total number of observations for that DOY. Periods of relatively low drought probability were defined as those DOY with $P < 0.20$ of exceeding the AWD threshold. The same linear regression methodology used to define the growing season was applied to define the portion of the year with relatively low drought probability.

In the SWD approach, the soil matric potential (ψ_m) was used to calculate the volumetric soil water content (θ) for each depth according to the van Genuchten (1980) water retention curve. The van Genuchten parameters, including residual and saturated water contents (θ_r and θ_s, respectively, m^3 m^{-3}) and the empirical constants α (kPa^{-1}) and n (dimensionless) were estimated for the 5-, 25-, and 60-cm soil depths at each location using the ROSETTA pedotransfer function, Model H3 (Schaap et al., 2001). This model estimates the van Genuchten parameters based on the percentage of sand, silt, and clay and the bulk density, which we obtained for each site and depth from the Oklahoma Mesonet website. Volumetric soil water contents, calculated from data collected by 229-L sensors, resulted in root mean square errors of 0.066 and 0.052 cm^3 cm^{-3} when compared with independent θ measurements by gravimetric sampling or the neutron probe scattering technique, respectively (Illston et al., 2008).

The SWD for each soil layer (D) was estimated by multiplying the difference between the soil water content at field capacity (θ_{fc}), calculated using a ψ_m of −33 kPa (Veihmeyer and Hendrickson, 1931) and the calculated θ by the thickness of the soil layer (Δz):

$$D = \left(\theta_{fc} - \theta\right)\Delta z \qquad [1]$$

The soil layers were defined as ranging from 0 to 10 cm for the sensor at the 5-cm depth, from 10 to 40 cm for the sensor at the 25-cm depth, and from 40 to 80 cm for the sensor at the 60-cm depth. For each DOY, the 0- to 40-cm SWD (SWD_{40}) was determined by the summation of the D values for the first two layers, and the 0- to 80-cm SWD (SWD_{80}) was determined by the summation of the D values for all three layers.

The SWD threshold corresponding to plant water stress, and drought occurrence was specific to each site and each profile depth (40 or 80 cm). The thresholds were calculated as the readily available water (RAW), as suggested by Allen et al. (1998):

$$\text{RAW} = p\text{TAW} \qquad [2]$$

where p is the fractional depletion of TAW at which water stress begins. The TAW was calculated for each site and layer as the difference between θ_{fc} and the soil water content at the wilting point (θ_{wp}) multiplied by the layer thickness (Allen et al., 1998). A ψ_m of −1500 kPa was used to estimate θ_{wp} (Veihmeyer and Hendrickson, 1931). For the SWD_{40} method, the threshold was the sum of the RAW values for the first two layers, and for the SWD_{80} method, the threshold was the sum of the RAW values for all three layers. The value of p depends on the species and ranges from 0.3 to 0.7. We set $p = 0.5$ because this is a commonly used value for many crops (Allen et al., 1998). We note in passing that if $p = 0.5$ were used to set the threshold for the AWD method instead of the 0.65 value used by Purcell et al. (2003), the AWD threshold would become 38 mm.

The drought probability for each site for each DOY was then estimated as the number of times in which SWD exceeded the depth-dependent threshold on that DOY divided by the total number of observations for that DOY. Periods of relatively low drought probability were defined as those DOYs with $P < 0.20$ of exceeding the SWD threshold. The same linear regression methodology used to define the growing season was applied to define the portion of the year with relatively low drought probability.

Root mean square difference (RMSD) and the index of agreement (d) of Willmott (1981) were used to compare the AWD and SWD methods.

RESULTS AND DISCUSSION

Site Characteristics

The procedure for delineating the growing season for each site is illustrated in Fig. 1 using data from Hollis, OK. Based on the intersection of the regression lines with the line for $P = 0.05$, the growing season for Hollis was determined to be

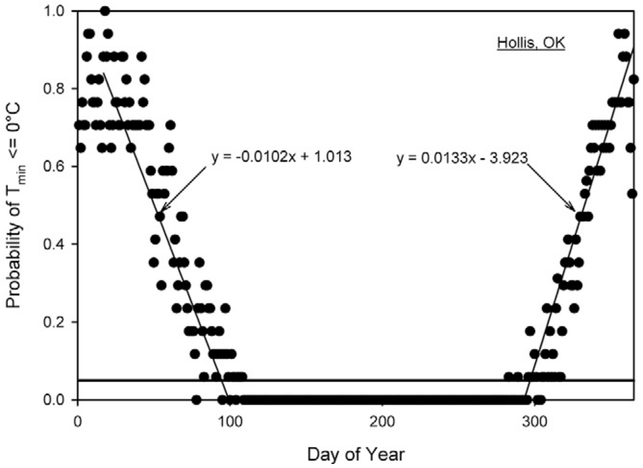

Fig. 1. Determination of the growing season for summer crops based on the 0.05 probability of occurrence of minimum temperatures (T_{min}) <0°C for each day of the year for 17 yr in Hollis, OK.

Table 2. Description of key weather variables for eight studied sites throughout the state of Oklahoma. Weather variables are mean daily values over the entire growing season for maximum (T_{max}) and minimum (T_{min}) temperatures, solar radiation at the soil surface (R_s), in addition to 7- and 15-d running sums of precipitation (Precip.), reference evapotranspiration (ET_0), and atmospheric water deficit (AWD, ET_0 – Precip.).

Site	T_{max}	T_{min}	R_s	7-d running sum Precip.	7-d running sum ET_0	7-d running sum AWD	15-d running sum Precip.	15-d running sum ET_0	15-d running sum AWD
	°C	°C	MJ m^{-2} d^{-1}	mm	mm	mm	mm	mm	mm
Goodwell	30.4	14.5	24.3	10.2	45.6	35.4	22.0	99.3	77.3
Woodward	29.3	16.1	21.5	16.2	38.6	22.4	34.7	85.2	50.5
Hollis	30.7	15.8	22.5	14.9	39.5	24.6	31.6	84.1	52.5
Acme	29.8	17.0	20.9	18.9	35.1	16.2	40.4	76.3	35.9
Stillwater	29.6	16.9	20.7	22.7	33.5	10.8	48.8	73.0	24.2
Nowata	28.5	15.9	20.6	25.5	32.3	6.8	54.5	67.6	13.1
Lane	29.4	16.8	20.4	22.1	28.5	6.4	47.2	58.9	11.7
Wister	30.4	16.2	22.0	22.9	31.6	8.7	48.8	66.6	17.8

from DOY 94 to 298. This delineation is similar to the growing season length of 210 d estimated by the Oklahoma Climatological Survey (2012). The growing season duration increased from 161 d at Goodwell, the second northernmost site, to 205 d at Lane, the southernmost site (Table 1). Mean annual precipitation ranged from 406 mm at Goodwell, the westernmost site, to 1119 mm at Wister, the easternmost site (Table 1).

Key weather variables averaged across the growing season are shown in Table 2. Growing season maximum temperatures and solar radiation values are similar to or slightly higher than those reported by Purcell et al. (2003) for the Mid-South region (Arkansas and Mississippi). In contrast, growing season precipitation values are generally lower than those in the Mid-South, indicating the drier climate, on average, in Oklahoma. Average growing season ET_0 values ranged from 28.5 mm wk^{-1} at Lane to 45.6 mm wk^{-1} at Goodwell, resulting in average 7-d cumulative AWDs ranging from 6.4 to 35.4 mm for these locations. The growing season AWD generally increased from east to west across the state.

Purcell et al. (2003) reported 7-d cumulative AWDs averaging 22.2 mm during the growing season in the Mid-South, a value more than twice as large as the AWD we observed in eastern Oklahoma (i.e., Nowata, Lane, and Wister). That larger AWD was apparently caused by overestimated ET_0 values. For example, the annual average ET_0 for Stuttgart, AR, was reported as 35.9 mm wk^{-1}, corresponding to 1867 mm yr^{-1}, whereas Scott et al. (1998) reported a value of 1141 mm yr^{-1} for the same location. The overestimation of the ET_0 values by Purcell et al. (2003) was caused by the inadvertent use of incident solar radiation instead of net radiation in the ET_0 calculations (Purcell, personal communication, 2012). The overestimation of ET_0 was compensated by the relatively high AWD threshold chosen by Purcell et al. (2003). Although the absolute values of ET_0 and AWD in Purcell et al. (2003) are incorrect, we believe there should be no changes in the major conclusions from their study. Reference evapotranspiration from the present study is in agreement with previous work performed in Greer County, Oklahoma, located approximately 70 km from Hollis. The reported ET_0 for the period 15 Apr. to 15 Sept. 2000 (corn growing season) was 41.4 inches, or 48.1 mm wk^{-1}, calculated using the Doorenbos and Pruitt (1977) method (Masoner et al., 2003). Our ET_0 calculations for Hollis for the same period accounted for 43.7 mm wk^{-1}, 10% lower than the values presented by Masoner et al. (2003). The Doorenbos and Pruitt method has been shown to overestimate ET_0 from 10 to 24% compared with the Penman–Monteith method used in our calculations (Fontenot, 2004).

Table 2 also shows the 15-d cumulative AWD for the study sites, ranging from 11.7 to 77.2 mm for Lane and Goodwell, respectively. When the 15-d summation period was used, the values of AWD were roughly double those from the 7-d summation period. This was expected because the magnitude of these variables should be affected by the period of summation (Purcell et al., 2003). Below we consider the effects of changing the summation period on the drought probability assessment by the AWD method.

Soil characteristics used to determine SWD thresholds for each location are presented in Table 3. Among the soil texture classes studied, sandy loam and silty clay loam soils comprised the soil textures with lowest and highest RAW, respectively. The mean RAW for the 0- to 10-, 10- to 40-, and 40- to 80-cm soil layers were 7, 22, and 27 mm, respectively. Averaged across soil textures, the mean θ_{fc} was 0.24 m^3 m^{-3}, while the mean θ_{wp} was 0.10 m^3 m^{-3}, with an average difference between θ_{fc} and θ_{wp} of 0.14. This is similar to the 0.13 suggested by Ratliff et al. (1983) and used by Purcell et al. (2003).

Water Deficits

Calculated SWD_{40} and SWD_{80} values were typically near zero in the winter, rose to moderate levels in mid-spring, and then climbed sharply in early summer. At Hollis, the long-term average SWD_{80} reached a maximum of 100 mm in early August (Fig. 2). Negative SWD values in the winter and spring indicate periods when the soil water content exceeded field capacity. Values of the 7-d cumulative AWD were similar to the calculated SWD_{40} during most of the spring and early summer for all the locations studied (e.g., Fig. 2). During mid and late summer, the AWD still displayed fluctuations similar to the SWD_{40} but with lower values, probably because the AWD does not account for deficits that accumulate beyond the 7-d time scale (Purcell et al., 2003). These results indicate that, during the spring, the 7-d AWD, determined from widely available data, can provide reliable estimates of the SWD_{40} determined from soil moisture measurements that are less often available. We are not aware of any prior studies comparing cumulative AWDs with calculated SWDs or showing the

Table 3. Description of soil physical properties for eight sites across the state of Oklahoma. For each location, the physical properties of soil water content at field capacity and at the wilting point, as well as total and readily available water are presented for three different soil depths (0–10, 10–40, and 40–80 cm).

			Soil water content		Available water	
Site	Soil depth	Soil texture	Field capacity†	Wilting point‡	Total§	Readily available¶
	cm		$m^3\ m^{-3}$		mm	
Goodwell	0–10	loam	0.24	0.09	14	7
	10–40	loam	0.25	0.10	43	22
	40–80	clay loam	0.26	0.11	59	29
Woodward	0–10	sandy loam	0.18	0.07	11	6
	10–40	loam	0.21	0.08	40	20
	40–80	loam	0.19	0.07	47	24
Hollis	0–10	silty clay	0.30	0.14	17	8
	10–40	clay	0.32	0.16	49	24
	40–80	silty clay	0.31	0.16	62	31
Acme	0–10	sandy loam	0.19	0.07	12	6
	10–40	sandy clay loam	0.27	0.11	48	24
	40–80	sandy clay loam	0.21	0.10	46	23
Stillwater	0–10	silty clay loam	0.35	0.14	21	10
	10–40	loam	0.25	0.09	47	24
	40–80	loam	0.25	0.10	62	31
Nowata	0–10	silty loam	0.25	0.07	18	9
	10–40	silty loam	0.26	0.07	55	27
	40–80	silty clay loam	0.27	0.13	57	28
Lane	0–10	sandy loam	0.15	0.06	9	5
	10–40	sandy loam	0.16	0.06	31	16
	40–80	sandy loam	0.15	0.06	37	18
Wister	0–10	silty loam	0.27	0.08	19	9
	10–40	silty loam	0.27	0.09	54	27
	40–80	silty loam	0.26	0.09	67	33

† Soil at field capacity was considered to have a matric potential of –33 kPa.

‡ Soil at the wilting point was considered to have a matric potential of –1500 kPa.

§ Total available water was calculated as the difference between field capacity and the wilting point.

¶ Readily available water was calculated as half of the total available water.

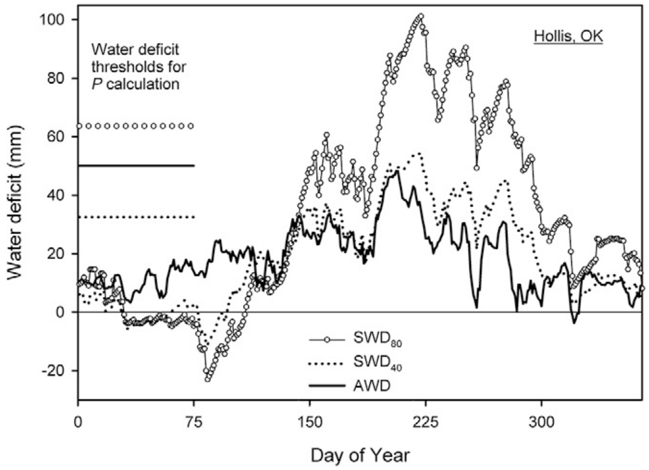

Fig. 2. Water deficit estimation by the atmospheric water deficit (AWD) method and soil water deficit methods for the 0- to 40- (SWD_{40}) and 0- to 80-cm depths (SWD_{80}), with corresponding water deficit thresholds. Averages of 15 yr for Hollis, OK.

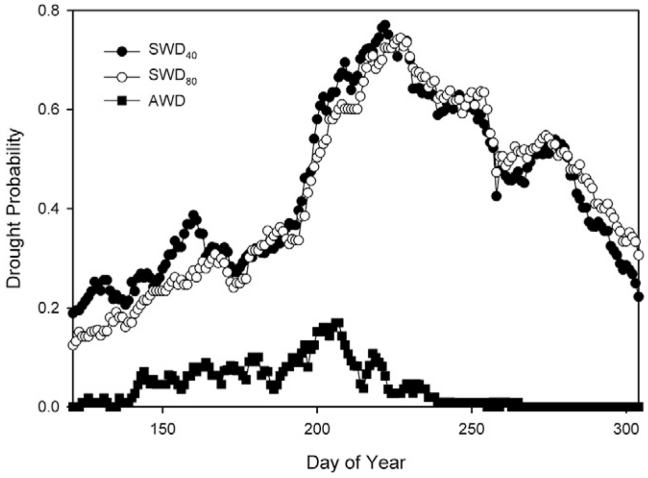

Fig. 3. Drought probabilities estimated by the atmospheric water deficit (AWD) method and soil water deficit methods for the 0- to 40- (SWD_{40}) and 0- to 80-cm depths (SWD_{80}). Average for 15 yr and eight sites in Oklahoma for Days of the Year (DOY) 121 to 304.

springtime correspondence between the two. Further research into this type of coupling across the soil–plant–atmosphere continuum is clearly warranted.

Another important feature depicted in Fig. 2 is that the mean AWD never reached the 50-mm threshold although Hollis has a hot and dry summer climate and is known to have high drought probability. This suggests that the 50-mm threshold was too high for the AWD method to accurately estimate drought *P* at this location. The same problem was observed at all the locations. The fact that Purcell et al. (2003) indicated reasonable probabilities of drought occurrence with this threshold may be explained by the prior observation that ET_0, and thus AWD, was overestimated in their study.

During the winter, soil moisture was typically replenished and values of AWD were greater than the actual SWD. The data from Hollis showed positive AWDs almost every DOY, whereas SWD_{40} and SWD_{80} indicated soil water recharge during winter and early spring (Fig. 2). This difference was a consequence of calculating the AWD based on ET_0, which assumes an actively transpiring grass surface. During the winter, the ET_0 estimates may not be applicable due to the reduced vegetative activity, and even the concept of ET_0 has limited validity under freezing conditions (Allen et al., 1998). The AWD and SWD methods in this study were intended to be used to evaluate drought probabilities for warm-season vegetation and should not be applied outside that growing season without additional research.

Drought Probabilities

The estimated drought probabilities were remarkably congruent between the SWD_{40} and SWD_{80} methods during the summer (Fig. 3), and the SWD-based drought probability seasonal patterns were consistent with general knowledge about drought in the region. Averaged across all eight sites, the drought probability in Oklahoma reached a maximum of 70 to 80% in the first half of August (Fig. 3). There was a tendency for the SWD_{40} method to estimate slightly higher drought probabilities in the spring and slightly lower probabilities in the fall than the SWD_{80} method (Fig. 3). This may be linked

Table 4. Threshold water deficits for each location for the atmospheric water deficit (AWD) and the soil water deficit for the 0- to 40- (SWD_{40}) and 0- to 80-cm depths (SWD_{80}), the first and last Day of the Year (DOY) and duration of the period with high drought probability ($P > 0.20$), low drought probability growing days in the spring and fall, and DOY and value of the highest drought probability for eight locations in Oklahoma.

Site	Method	Deficit threshold†	High drought probability period‡ First	High drought probability period‡ Last	Duration of water deficit	Low drought probability growing days in spring§	Low drought probability growing days in fall¶	Highest drought probability DOY	Highest drought probability P
		mm	DOY		d			DOY	P
Goodwell	AWD	50.0	143	230	87	23	51	200	0.64
	SWD_{40}	28.7	1	365	365	0	0	155	1.00
	SWD_{80}	58.0	1	365	365	0	0	145	1.00
Woodward	AWD	50.0	204	210	6	101	81	204	0.21
	SWD_{40}	25.4	132	353	221	29	0	222	1.00
	SWD_{80}	49.0	141	365	224	38	0	226	1.00
Hollis	AWD	50.0	187	208	21	93	90	203	0.42
	SWD_{40}	32.5	91	356	265	0	0	202	1.00
	SWD_{80}	63.6	129	359	230	35	0	220	1.00
Acme	AWD	50.0	na#	na	0	97	97	219	0.15
	SWD_{40}	29.9	156	326	170	55	0	216	0.92
	SWD_{80}	53.0	174	341	167	73	0	229	0.85
Stillwater	AWD	50.0	na	na	0	94	93	208	0.07
	SWD_{40}	34.0	187	284	97	81	9	223	0.64
	SWD_{80}	65.2	196	274	78	90	19	227	0.54
Nowata	AWD	50.0	na	na	0	77	76	0	0.00
	SWD_{40}	36.5	179	353	174	75	0	226	0.75
	SWD_{80}	64.8	183	356	173	79	0	217	0.66
Lane	AWD	50.0	na	na	0	102	103	0	0.00
	SWD_{40}	20.2	195	268	73	100	32	225	0.64
	SWD_{80}	38.7	202	266	64	107	34	227	0.50
Wister	AWD	50.0	na	na	0	91	91	208	0.07
	SWD_{40}	36.5	162	325	163	67	0	228	0.93
	SWD_{80}	69.8	160	345	185	65	0	222	0.93

† Soil water deficit thresholds fixed at 50 mm for AWD and determined as readily available water for SWD.

‡ First and last day of period with drought $P > 0.2$.

§ Low drought probability growing days in the spring refers to the number of days between the last occurrence of temperatures below 0°C ($P = 0.05$) and the first occurrence of a water deficit greater than the adopted threshold ($P = 0.2$). When P of drought was <0.2 throughout the growing season, the number of low drought probability growing days in the spring was calculated as the duration of the growing season divided by two.

¶ Low drought probability growing days in the fall refers to the number of days between the last occurrence of drought $P > 0.2$ and the first occurrence of temperatures below 0°C ($P = 0.05$). When P of drought was <0.2 throughout the growing season, the number of low drought probability growing days in the fall was calculated as the duration of the growing season divided by two.

\# na, not applicable; drought $P < 0.2$ throughout the growing season.

to the seasonal deepening of the active root water uptake zone throughout the year, depleting the 40- to 80-cm layer toward the end of the season. Linear regression of the SWD_{40} vs. SWD_{80} drought probabilities from Fig. 3 resulted in a slope of 0.90, an intercept of 0.003, and an r^2 of 0.89 ($P < 0.001$). Thus, the drought P estimates were largely independent of depth, producing similar results despite the fact that actual SWD values were different between depths as shown in Fig. 2.

The probabilities of drought for the 15 yr averaged across eight sites were substantially lower for the AWD method than the SWD methods (Fig. 3), even though the actual AWD values were similar to the SWD_{40} values during the spring. This again implies that the original 50-mm threshold used to define drought in the AWD method was too high, hence the P of drought was lower than the SWD method. Based on the AWD method, the statewide drought probability peaked in the second half of July between 10 and 20%. That estimate is inconsistent with general knowledge about drought patterns in the region and with prior estimates of drought probabilities in nearby states (Purcell et al., 2003).

The thresholds used at each location for the SWD_{40} and SWD_{80} methods are shown in Table 4. Recall that these thresholds were obtained based on RAW, whereas the AWD method used a fixed 50-mm threshold. Thresholds for SWD_{40} were consistently less than 50 mm across all locations, ranging from 20.2 mm in a sandy loam at Lane to 36.5 mm in a silty loam at Wister and Nowata. The lower drought probability estimates of the AWD method were largely due to its higher threshold. Thresholds for SWD_{80} were usually >50 mm, varying between 38.7 mm at Lane and 69.8 mm at Wister. Because the actual SWD values were also higher when summed to a depth of 80 cm, reasonable probabilities of drought occurrence were estimated by this method despite the greater thresholds.

The SWD-based drought probability assessments identified critical periods during the year when water stress is likely. Following Purcell et al. (2003), we used the $P > 0.20$ level to define the portion of the year with relatively high drought probability. Table 4 shows the first and last day of high drought probability, the duration of the period of high drought probability, and the number of low-drought-probability growing days in the spring and fall for each method for the eight locations. The SWD-based methods produced plausible drought probability assessments, which were generally in line with expectations for these sites. Averaged across locations, SWD_{40} indicated drought beginning approximately 11 d earlier and ending 5 d earlier than SWD_{80}. At Goodwell, Woodward, and Hollis, the periods of low drought probability in the spring were less than 40 d in duration. Forty days is generally not sufficient time to produce a crop, so these results are consistent with the fact that, when summer crops are grown at these locations, they are typically irrigated. The remaining five sites had from 55- to 107-d periods in the spring with low drought probability based on the SWD methods, with the longest period occurring at Lane. These results are consistent with the fact that short-season, rainfed summer crops are part of the agricultural systems near these locations. The majority of days with low drought probability occurred during the spring rather than the fall. None of the sites in this study had more than 34 growing days with low drought probability in the fall according to the SWD methods. The highest drought probabilities occurred between DOY 202 and 229 (late July to mid-August) for all sites except Goodwell, which experienced the highest drought probability around DOY 150 (late May).

The AWD method indicated later occurrence and earlier disappearance of the periods of high drought probability than the SWD methods at Goodwell, Woodward, and Hollis (Table 4). In the other five locations, which had higher rainfall, the AWD method indicated that the *P* of drought was never >0.2, which contradicts general knowledge about the climate of the region and the results obtained by the SWD methods. The AWD values for these locations rarely reached the 50-mm threshold. The underestimation of drought probabilities by the AWD method is obviously undesirable when assessing drought probability for summer crops because it indicates favorable conditions when, in fact, serious drought stress is likely.

Refining the Atmospheric Water Deficit Method

The advantage of the AWD method is that the required data are available for more sites than those that have the long-term soil moisture data required for the SWD methods. Thus, we sought to refine the AWD method. To find a better fit between the AWD and the SWD methods, two different approaches were used. First, the AWD threshold was reduced from 50 to 37 mm. This value was cited by Purcell et al. (2003) as the minimum soil water deficit at which Mid-South farmers typically schedule their irrigations (Cahoon et al., 1990). A similar threshold (38 mm) is obtained if a fractional depletion of 0.5 in Eq. [2] is chosen instead of the 0.65 value chosen by Purcell et al. (2003), all other assumptions remaining unchanged. Better agreement between the AWD- and SWD_{80}–based drought probabilities resulted at all sites, as confirmed by lower RMSD and *d* values when 37 mm was used as the AWD threshold (Table 5).

Purcell et al. (2003) also suggested possible adjustments to the model including the calculation of AWD based on a 15-d running sum instead of 7-d running sum. This second refinement was tested using 50 mm as the AWD threshold. Further improvement in the agreement between the AWD- and SWD_{80}–based drought probabilities was achieved with this approach (Table 5). The RMSD decreased for all sites except Stillwater and Lane, where the 7-d running sum and 37-mm threshold still resulted in lower RMSD. It is important to remember that RMSD and *d* complement each other because no single measure of agreement can properly define model performance, hence more than one measure of performance should be reported (Willmott, 1982). This can be verified by noting the higher *d* for Stillwater when the 15-d sum was used for the AWD method. Thus, for seven of eight sites, using a 15-d cumulative AWD and a threshold of 50 mm led to the best performance among the three variants of the AWD method we evaluated. At the warmest site, Lane, a 7-d sum with a 37-mm threshold performed best.

Table 5. Comparison between drought probabilities estimated by the soil water deficit method for the 0 to 80 cm depth (SWD_{80}) and by the atmospheric water deficit (AWD) method using different drought thresholds (50 and 37 mm) and running sums of water deficit (7 and 15 d). Statistical measures were root mean square difference (RMSD) and Wilmott's index of agreement (*d*).

	RMSD†			*d*‡		
	7-d sum		15-d sum	7-d sum		15-d sum
Site	50 mm	37 mm	50 mm	50 mm	37 mm	50 mm
Goodwell	0.66	0.33	0.11	0.17	0.30	0.57
Woodward	0.53	0.36	0.26	0.46	0.55	0.67
Hollis	0.52	0.34	0.25	0.48	0.58	0.67
Acme	0.45	0.32	0.26	0.58	0.65	0.71
Stillwater	0.23	0.19	0.20	0.32	0.54	0.71
Nowata	0.35	0.25	0.17	0.37	0.56	0.83
Lane	0.19	0.16	0.31	0.22	0.72	0.62
Wister	0.53	0.39	0.27	0.46	0.27	0.76

† Model's fit improves as RSMD approaches zero.

‡ Model's fit improves as *d* approaches unity.

Figure 4 shows the 15-yr *P* of drought averaged across the eight locations as estimated by the SWD method and the two modifications to the AWD method described above. The 7-d running sum of AWD using a threshold of 37 mm resulted in drought probabilities that closely followed those of the SWD_{80} method in the beginning of the growing season, as the *P* of drought increased (Fig. 4A). Beginning in early summer, however, the AWD-based probabilities diverged from the SWD-based probabilities and became unreasonably low. When using the 15-d AWD with a 50-mm threshold, the AWD method resulted in somewhat higher drought probabilities than the SWD_{80} method in the beginning of the growing season and somewhat lower probabilities late in the growing season (Fig. 4B). Although both modified AWD methods in Fig. 4 resulted in lower drought probability estimates than the SWD_{80} method late in the growing season, the differences were smaller when using the 15-d AWD with the 50-mm threshold. It appears that, to best match drought probabilities based on the SWD, increasing summation periods and thresholds would need to be used in the AWD method as the season progressed. For example, the 7-d AWD and 37-mm threshold could be used to calculate drought probability in the beginning of the growing season, with a switch to the 15-d AWD and 50-mm threshold at some point near the middle of the season. Further research would be needed to

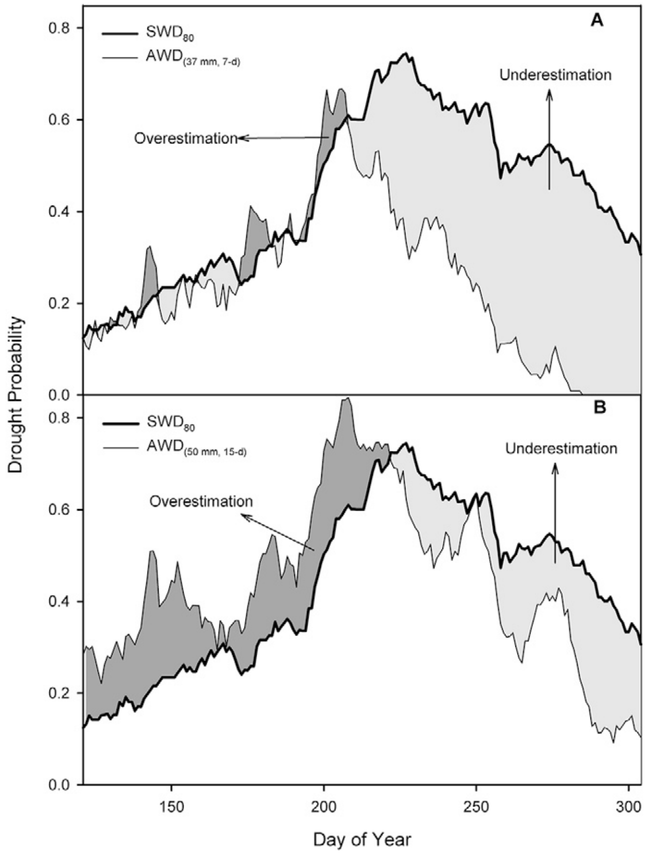

Fig. 4. Drought probabilities based on the soil water deficit method for the 0- to 80-cm depth (SWD_{80}) compared with two different modifications of the atmospheric water deficit (AWD) method: (A) a 7-d cumulative AWD using a water deficit threshold of 37 mm, and (B) a 15-d cumulative AWD using a water deficit threshold of 50 mm. Average for 15 yr and eight sites in Oklahoma for Days of the Year (DOY) 121 to 304.

define and validate such a "sliding" AWD approach. Another modification, using a threshold of 37 mm with a summation period of 15 d, resulted in much greater drought probabilities throughout the growing season for all the locations and therefore is not shown.

CONCLUSIONS

The new SWD-based methods presented here represent the first known application of data from a long-term, automated soil moisture monitoring network to the problem of quantitative drought probability assessment. The Oklahoma Mesonet is one of the oldest such networks in the world, so the opportunities for these types of analyses are just now emerging. The Soil Climate Analysis Network of the USDA-NRCS (Schaefer et al., 2007) is of similar longevity and offers the potential to extend this analysis across the United States, as will the more recent NOAA Climate Reference Network. Similar networks are emerging around the globe. There is a clear need to develop and apply conceptual frameworks and analyses, like the SWD methods presented here, to translate the growing wealth of soil moisture data into useful knowledge.

The SWD method gave plausible and consistent estimates of drought probability when applied to both the 0- to 40- and 0- to 80-cm soil layers and should be utilized when long-term soil moisture data are available. The 7-d AWD values were similar to the SWD values for the 0- to 40-cm layer in the springtime, an interesting fact that has not been previously reported. The 7-d AWD values were lower than the SWD values for the 0- to 40-cm layer toward the end of the growing season, perhaps due to longer term soil water deficit accumulation. The original AWD method as proposed by Purcell et al. (2003) resulted in lower drought probabilities compared with the SWD method at all eight sites studied. Improvements were obtained when adjustments were applied, either by reducing the AWD threshold from 50 to 37 mm or by increasing the AWD summation period from 7 to 15 d. Further research is needed to determine the relationship between the selected drought thresholds and actual drought impacts such as crop yield reduction. The calculated soil moisture values provided a sound empirical basis for evaluating refinements to an atmospheric method for assessing drought probabilities in Oklahoma. The refinements to the AWD method presented here should be applied when using that method for locations that lack long-term soil moisture data.

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