A COMPARISON OF THE EARLY TWENTY-FIRST CENTURY DROUGHT IN THE UNITED STATES TO THE 1930S AND 1950S DROUGHT EPISODES

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The early twenty-first century drought in the United States ranked as one of the most severe droughts of the last 120 years.

The United States was plagued by severe drought during 2012, when several regional droughts [see Figs. 1 and ES1; more information can be found in the online supplement (https://doi.org/10.1175/BAMS-D-16-0080.2)] expanded to form a national-scale [contiguous United States (CONUS)] drought. Record heat (especially during the growing season) exacerbated the drought conditions. For some regions (i.e., the southern Great Plains and Southeast), the 2012 drought was a continuation of drought that began in 2011 (southern Plains) or earlier (Southeast, West; Fig. ES1). Furthermore, the 2011–12 drought was only part of a larger-scale drought episode that affected parts (especially from California to New Mexico) or all of the United States for much of the first decade of the twenty-first century (Fig. ES1).

According to the U.S. Drought Monitor (USDM; Svoboda et al. 2002), which is the current standard for operational drought monitoring in the United States, 2012 began with 31.9% of the CONUS experiencing moderate (D1) to exceptional (D4) drought. Unusually dry and hot weather during the following months resulted in the expansion of drought to encompass 65.5% of the CONUS by 25 September, which is the greatest extent in the 1999–present USDM record (USDM 2014). Drought persisted through the end of 2012—stretching from the West Coast to the Mississippi Valley (with another drought epicenter in the Southeast) on 1 January 2013, covering 61.1% of the CONUS in the D1–D4 categories. The large area and spatial pattern of the 2012 drought prompted some, at the time, to draw comparisons to the expansive droughts of the

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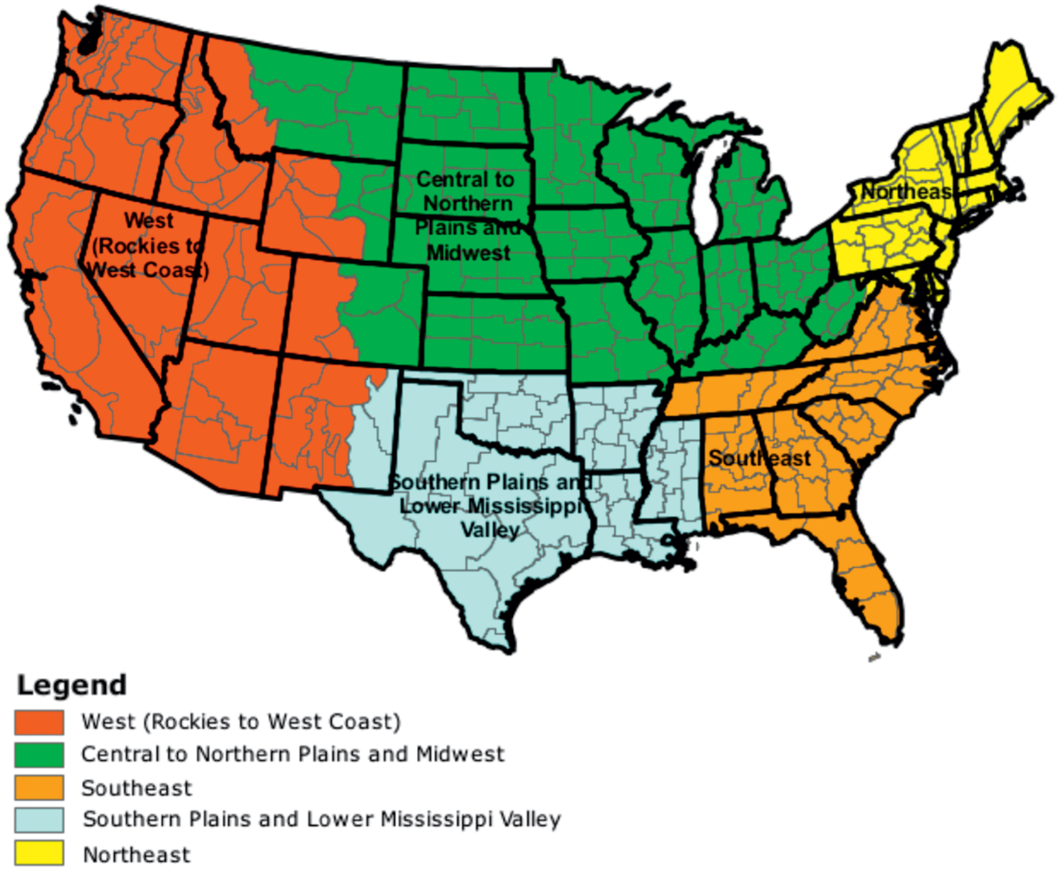


Fig. 1. Regions referred to in this paper: West (Rocky Mountains to West Coast), central to northern Plains and Midwest, southern Plains and lower Mississippi Valley, Southeast, and Northeast.

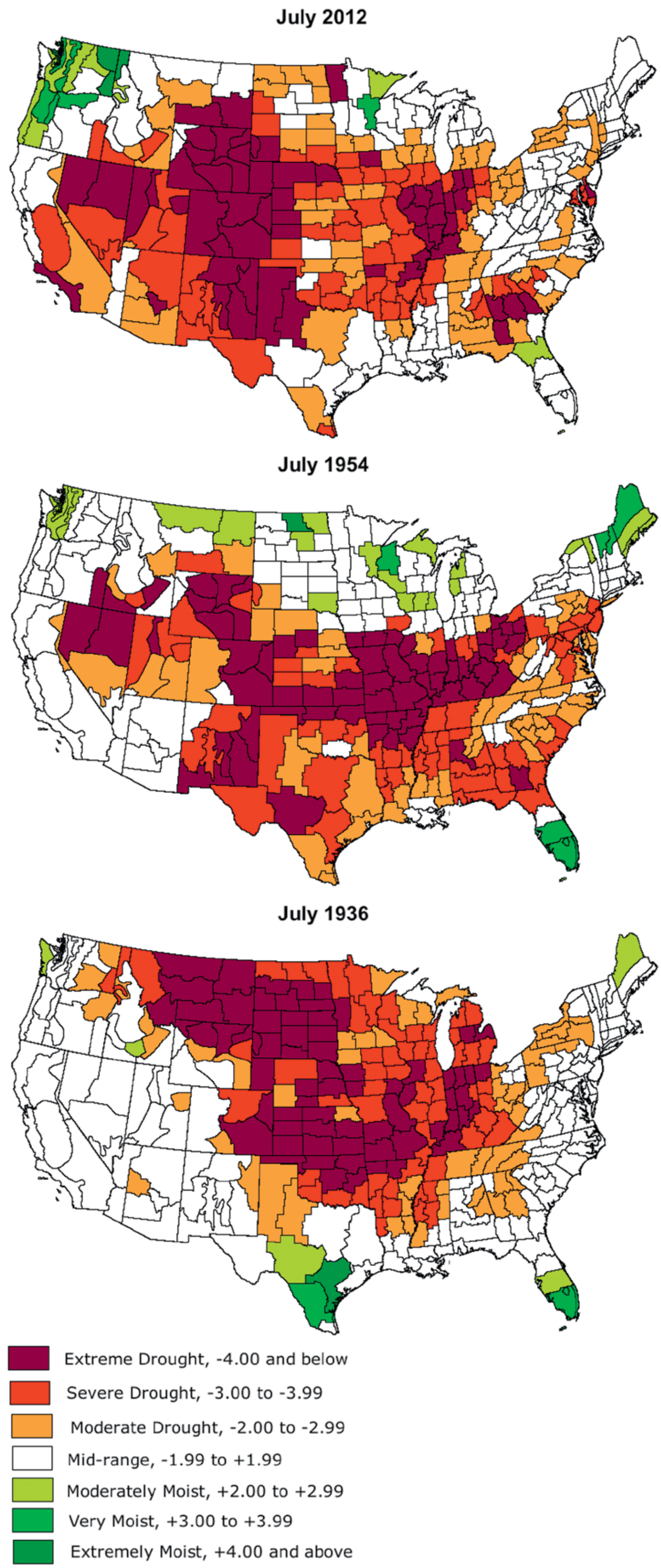
Dust Bowl and 1950s decades (Fig. ES2). In fact, a mean absolute difference comparison of Palmer drought severity index (PDSI) values resulted in July 1954 being the closest historical analog to July 2012 in terms of severity and spatial pattern, with July 1936 being the second closest historical analog (Fig. 2).

Records were set in 2011–12 by several climate measures (Hoerling et al. 2013a, 2014; Karl et al. 2012; NCEI 2011, 2012b, 2012c; Nielsen-Gammon 2011), and the drought had severe and widespread agricultural, hydrological, and economic impacts (Benfield 2013; Gutzmer 2013; MRCC 2012; Rice 2013; USDA 2013a,b; USGS 2013). Wildfires swept across the West (NCEI 2012a), with the amount of forested burned area in the western United States, and associated fuel aridity, the highest in 2012 compared to any other year since at least 1979 (Abatzoglou and Williams 2016).

Drought waxed and waned during other years of the last decade in the Southeast, southern Plains, central to northern Plains, and West (USDM 2014; Fig. ES1). At times, these regional droughts expanded to produce a national-scale drought, with 40% or more of the CONUS experiencing D1–D4 conditions several times since 2000, culminating in the record drought area of 2012 (USDM 2014). In other words, for the period 2000–14 (i.e., since the inception of the USDM), 40% or more of the CONUS experienced D1–D4 conditions for 25% of the time and 20% or more of the CONUS experienced D1–D4 conditions for 86% of the time.

The drought during the 2000–14 period fits into an even bigger picture. Evapotranspiration results from a complex interaction between solar radiation, humidity, temperature, and wind (Sheffield et al. 2012). Higher temperatures increase evapotranspiration and can intensify drought, causing quicker onset and higher intensity (Trenberth et al. 2014). Consequently, there is concern that future changes in climate resulting from increasing global temperatures may lead to more frequent, longer, and severe drought in the United States and other parts of the world (Breshears et al. 2005; Sheffield and Wood 2011; Sheffield et al. 2012; Rupp et al. 2012; IPCC 2013; Trenberth et al. 2014). In the United States, the slow spring and summer melting of the mountain snowpack built up during the winter normally provides an important source of water during the dry season in the West. The warming trend in the West over the twentieth and early twenty-first centuries has produced significant changes in this hydrology (Mote et al. 2005) with concurrent impacts to vegetation (Breshears et al. 2005; Mote et al. 2005). Global studies of past drought found regional trends of conflicting sign, including increasing dryness or drought in East Asia, the Mediterranean, and West Africa and decreasing dryness or drought in central North America and northwest Australia (Hartmann et al. 2013, p. 215), and so past changes in drought and exactly how a warming climate will affect future drought vary depending on location. Hartmann et al. (2013) summarized changes (trends or variations) during the twentieth and early twenty-first centuries in atmospheric circulation features such as the midlatitude jet streams and associated storm tracks, semipermanent pressure centers (subtropical highs and midlatitude lows), Walker and Hadley circulations [which are related to El Niño–Southern Oscillation (ENSO)], and monsoon circulations. They concluded that there is evidence for a poleward shift of storm tracks and jet streams, and a widening of the tropical belt, since the 1970s. Changes in these circulation features can affect the physical mechanisms that cause drought and thus the frequency, intensity, and location of droughts.

The physical mechanisms behind the 2000–14 drought varied depending on region and year. The 2012 drought in the central Plains resulted from atmospheric conditions (large-scale subsidence and reduction in Gulf of Mexico moisture transport) that developed



► **Fig. 2. PDSI maps for (top) Jul 2012, (middle) Jul 1954, and (bottom) Jul 1936. The difference in climate division PDSI values between Jul 2012 and every preceding Jul in the 1900–2012 period was computed; Jul 1954 had the closest spatial pattern (i.e., minimum mean absolute difference of PDSI values) to Jul 2012, followed by Jul 1936.**

in situ suddenly over the central United States due to internal atmospheric variability (Hoerling et al. 2013a). For the southern Plains and Southeast, the 2012 drought was a continuation of unusually dry conditions that began in late 2010 and continued through much of 2011 and that have been linked, in part, to La Niña conditions (Hoerling et al. 2013a,b, 2014; Seager et al. 2014). La Niña is one mode of the equatorial Pacific Ocean's ENSO variability. Herweijer et al. (2007) related the occurrence of North American drought (especially in the western United States) to interannual ENSO variability. The La Niña episodes during mid-1998–early 2001, mid-2007–mid-2008, and mid-2010–early 2012, as well as mid-1954–mid-1956, were coincident with peaks in national drought area. Herweijer et al. (2007) also noted, in their paleoclimatic study of tree rings, that several multidecadal "megadroughts" have occurred in North America during the past millennium, most notably between the eleventh and fourteenth centuries, and that these are related to ENSO variability.

The USDM statistics date back only to late 1999, and many of the latest soil moisture and other drought models extend back only 50–60 years, which does not allow comparison of the current drought to the record droughts of the 1930s and, in some cases, 1950s. There are macroscale hydrologic runs that have been extended back to the 1920s using gridded data [see Xiao et al. (2016) for a study in the Pacific Northwest]. The climate division dataset, consisting of Palmer drought indices [PDSI, Palmer hydrological drought index (PHDI), and Palmer *Z* index] and the standardized precipitation index (SPI), represents a continuous record of drought in the United States from 1900 to the present (Heim 2002). This paper utilizes this unique dataset to compare the 2011–12 drought and 1998–2014 national drought decade to the national-scale droughts of the twentieth century.

DATA. The primary datasets used in this analysis are the nClimDiv climate division dataset (Vose et al. 2014; Guttman and Quayle 1996) and U.S. climate extremes index (USCEI; Gleason et al. 2008) component station data maintained by the National Oceanic and Atmospheric Administration/National Centers for Environmental Information (NOAA/NCEI). The nClimDiv dataset consists of monthly precipitation and mean temperature data from January 1895 to present for 344 climate divisions in the CONUS. It is based on a gridded dataset derived from the Global Historical Climatology Network-Daily (GHCN-D; Menne et al. 2012) dataset using climatologically aided interpolation and addresses deficiencies that existed in the previous version of the climate division dataset. Other monthly divisional variables and indices are derived from the temperature and precipitation data, including Palmer drought indices, SPI, and heating and cooling degree-days. Regional and CONUS-wide values derived from the climate division dataset were computed by area weighting the divisional values.

The Palmer methodology[1] utilizes precipitation as the water supply component and temperature to derive the water demand component (evapotranspiration) in the drought equation and employs a simple two-layer model for soil moisture (Palmer 1965). Standardized indices (PDSI, PHDI, Palmer *Z* index) derived from these variables take on negative (positive) values for drought (wet spell) conditions. The calibration period 1931–90 is used to maintain interagency consistency in operational drought monitoring. The PHDI is used as a hydrological drought index and has a strong inertial component. The PDSI is used as a meteorological drought index and can change more rapidly than the PHDI because of a real-time probability factor (Palmer 1965; Heim 2002), which makes it less desirable for near-real-time drought monitoring. Consequently, the PDSI was modified by Heddinghaus and Sabol (1991) to develop the operational PDSI that is used by NOAA agencies for near-real-time drought monitoring and is used hereafter as a drought metric. The first 5 years of record (1895–99) of the Palmer model involve model spinup (Guttman 1991) and were discarded from subsequent analysis. The Palmer model uses the Thornthwaite model for potential evapotranspiration (PE), which may overemphasize the magnitude of change in PE under global warming studies (Dai 2011; Sheffield et al. 2012) but plays a nominal role over the historical record.

The USCEI integrates a set of climate extremes indicators that measure the fraction of the area of the CONUS experiencing extremes (upper or lower 10th percentile, depending on variable) in monthly mean surface temperature, daily precipitation, and drought and moisture surplus (monthly PDSI). The upper and lower 10th percentiles are computed based on the USCEI's period of record (1910–present). The USCEI source datasets include nClimDiv, U.S. Historical Climatology Network (USHCN; Karl et al. 1990), and

[1] Jacobi et al. (2013) identified a discrepancy in the code utilized by NCEI to compute the Palmer drought indices. Palmer indices computed using revised code that addressed this discrepancy (www.ncdc.noaa.gov/sotc/national/2013/03/supplemental/page-7/) were utilized in this study.

GHCN-D datasets. The following USCEI components were used in this study: seasonal or annual values of the percent area with average maximum temperature or minimum temperature much above normal (upper 10th percentile) or much below normal (bottom 10th percentile), percent area with seasonal or annual precipitation derived from extreme (equivalent to the highest 10th percentile) 1-day precipitation events, percent area with a much greater than normal (highest 10th percentile) number of days with precipitation in the season or year, and percent area with a much greater than normal (highest 10th percentile) number of days without precipitation in the season or year.

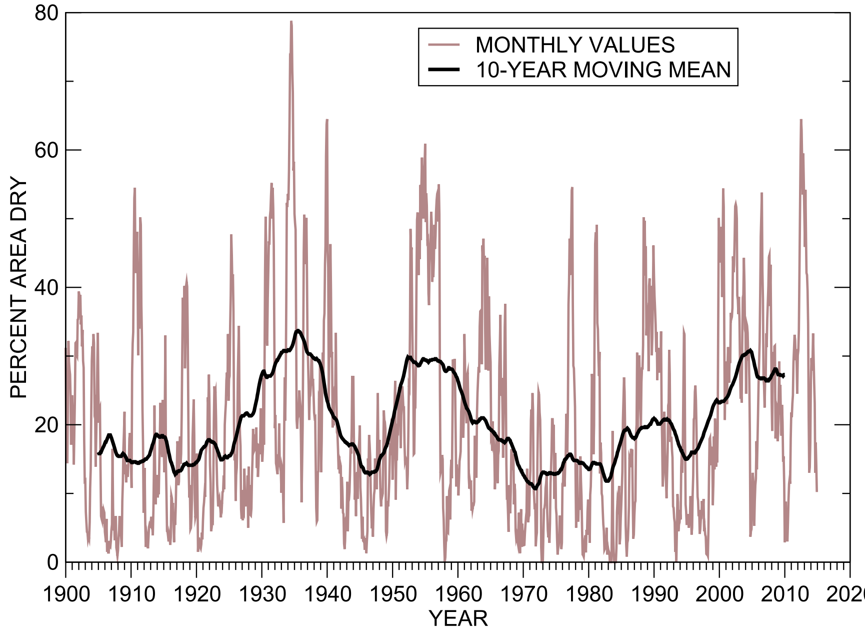


Fig. 3. Percent area of the CONUS experiencing moderate to extreme drought (PDSI ≤ −2.00) conditions, Jan 1900–Dec 2014. The thick black curve is a 10-yr moving-mean filter.

ANALYSIS. *Spatial coverage.* The percent area of the CONUS experiencing moderate to extreme drought (PDSI ≤ –2.00) from 1900 to 2014 is shown in Fig. 3. Major peaks in drought area occurred in the 1930s, 1950s, 1980s, and late 1990s–2012. The 2012 drought area peaked at 64.5% in July [the largest value for the 1998–2014 period (consistent with the USDM)], exceeded the peak area of the 1950s drought (60.9% in January 1955), and was the largest drought coverage since January 1940 (also 64.5%; the 1930s drought peaked at 78.8% of the CONUS in July 1934 and is the period-of-record maximum). The 10-yr moving average in Fig. 3 filters out the year-to-year variations and suggests that these variations have something of a cyclic nature [see also Fig. 2 in Heim (2015)].

Drought has a markedly regional character (Fig. ES1). Month-to-month and year-to-year variability in weather patterns can result in one or more regions experiencing drought while other regions experience "normal" or wet conditions (see Fig. ES3). A drought could be considered to be "national scale" in extent when it affects multiple regions or affects a large part of the country. Some researchers have used severity area duration curves to discuss historic CONUS droughts (e.g., Andreadis et al. 2005). A visual inspection of a time series showing the percent area of the CONUS experiencing moderate to extreme drought (Fig. 3) reveals that several drought episodes affecting large parts of the country have occurred in the United States during the twentieth and twenty-first centuries. The beginning and ending times of regional droughts can be readily determined, but determining the start and end points, duration, and significance of national drought episodes is not trivial. Wallander and Ifft (2012) defined a national-scale drought in the United States as one for which over 50% of agricultural land is exposed to moderate or greater drought. Sheffield and Wood (2011) examined droughts globally and defined a large-scale drought as a spatially contiguous area of at least 500,000 km^2 having low soil moisture. In the current analysis, the frequency of percent area above various thresholds (deciles from 10% to 70%) was examined, and persistence (consecutive months) above two thresholds (10% and 20%) was considered. Using the 10% area threshold for consecutive months, 40 drought episodes are evident from 1900 to 2014 with lengths ranging from 6 to 86 consecutive months. Using the 20% area threshold, 27 drought episodes are evident with lengths ranging from 6 to 58 months. This approach yields drought episodes in every decade, but a drop below the threshold area for even 1 month will result in a new drought episode, which tends to break into smaller episodes what would otherwise be a larger coherent drought episode.

Consolidation of these objective results (see supplemental information) produces a drought history consisting of 13 major drought episodes (Table 1), 11 of

TABLE 1. Drought and wet spell statistics for 13 drought episodes (beginning and ending month and year) during the period 1900–2014; total number of months in the period (total), percent area of the CONUS experiencing record dry PHDI (record area), percent of time the monthly drought area was beyond seven indicated thresholds, and the maximum (max) and average (mean) drought and wet spell percent area.

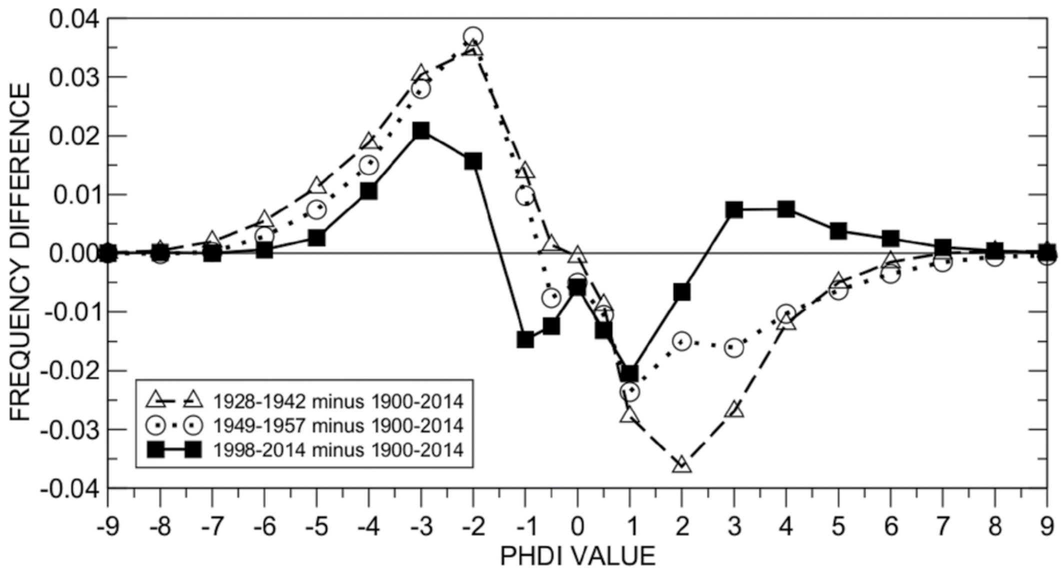
Drought episode	Total	Record area	Percent of time monthly drought area							Drought extent		Wet spell extent	
			>10%	>20%	>30%	>40%	>50%	>60%	>70%	Max	Mean	Max	Mean
Jan 1900–May 1905	65	2.1	88%	66%	32%	0%	0%	0%	0%	39.4	23.1	34.6	18.6
Oct 1908–Nov 1911	38	3.1	100%	55%	47%	32%	8%	0%	0%	54.5	28.4	38.4	18.5
Jul 1913–May 1915	23	0.0	87%	22%	4%	0%	0%	0%	0%	33.0	16.3	37.7	21.9
Dec 1916–Jan 1919	26	0.4	96%	50%	38%	15%	0%	0%	0%	40.8	23.8	36.6	14.4
Jan 1924–Oct 1926	34	7.7	97%	65%	29%	12%	0%	0%	0%	47.7	24.6	29.9	15.4
Jul 1928–May 1942	**167**	**31.3**	**96%**	**62%**	**38%**	**28%**	**17%**	**5%**	**3%**	**78.8**	**29.7**	**60.5**	**14.7**
Jul 1949–Sep 1957	**99**	**13.1**	**99%**	**72%**	**48%**	**44%**	**20%**	**1%**	**0%**	**60.9**	**33.3**	**47.1**	**15.1**
Sep 1958–Jan 1962	41	0.6	95%	46%	2%	0%	0%	0%	0%	33.2	18.5	47.2	17.6
Aug 1962–Jun 1967	59	3.8	100%	66%	36%	12%	0%	0%	0%	47.1	26.4	46.8	13.8
Jan 1976–Jan 1978	25	4.5	100%	60%	36%	28%	8%	0%	0%	54.6	27.7	30.0	15.1
May 1980–Jan 1982	21	0.0	100%	62%	38%	14%	0%	0%	0%	49.1	27.0	34.3	16.3
Apr 1987–Nov 1992	68	4.7	99%	74%	46%	15%	1%	0%	0%	50.2	28.3	43.2	17.5
Jun 1998–Dec 2014	**199**	**30.8**	**92%**	**71%**	**44%**	**21%**	**10%**	**1%**	**0%**	**64.5**	**28.7**	**53.8**	**20.8**

which covered 10% or more of the CONUS for 90% or more of the time (the 1900–05 and 1913–15 episodes covered 10% or more for 88% and 87% of the time, respectively). The three longest episodes are July 1949–September 1957 (1950s drought), July 1928–May 1942 (1930s Dust Bowl drought), and June 1998–December 2014 (the current drought; data through 2014 were analyzed for this study, but the drought was ongoing into 2015). The current drought episode can be subdivided into three distinct drought periods (using 10% area as the criteria): June 1998–September 2004, July 2005–December 2009, and September 2010–December 2014. The 1930s drought can also be subdivided into three distinct drought periods: July 1928–April 1933, June 1933–April 1938, and August 1938–May 1942. Unlike the 1930s and current drought episodes, the 1950s drought expanded and stayed at a relatively large spatial extent for most of the drought episode (especially from late 1953 to early 1957), although technically it could be subdivided into two periods when the spatial extent dipped below 10% in July 1950. Each of these three decadal drought episodes had a maximum drought extent greater than 60% and lasted 99 months or longer (Table 1; Fig. 3). The 1930s drought was the most expansive at its peak, but the 1950s drought had the greatest mean drought area (Table 1), indicating that it was the most severe (in terms of area) for the longest period.

As noted earlier, some regions might experience wet conditions while others are undergoing severe drought. On the national scale, this phenomenon could appear as an increase in wet spell area concurrent with a large drought area. Table 1 contains statistics for wet spell area (PDSI ≥ +2.00) as well as drought area (also see Fig. ES3). Not only did the 1930s drought have the largest peak drought area (79.9%) of these 13 drought episodes, it also had the largest peak area of wet spell conditions (60.5%); however, its average wet spell area was the third smallest (14.7%). The 2-yr drought of July 1913–May 1915 had the largest average wet spell area (21.9%), but the current drought had the second largest (20.8%).

Severity. Frequency distributions of divisional PHDI values were computed for several periods by counting the number of climate division months having PHDI values in each of 21 bins[2] then dividing by the total number of division months in the period. Subtraction of the period of record frequencies from the frequencies of each drought episode (Fig. 4, top) provides a description of the severity characteristics of each drought. The PHDI was used instead of the

[2] The bins were patterned after Palmer's (1965) drought (and wet spell) classifications and included −0.5 to +0.5, −1.0 to −0.5 (and +0.5 to +1.0), −2.0 to −1.0 (+1.0 to +2.0), −3.0 to −2.0 (+2.0 to +3.0), −4.0 to −3.0 (+3.0 to +4.0), −5.0 to −4.0 (+4.0 to +5.0), −6.0 to −5.0 (+5.0 to +6.0), −7.0 to −6.0 (+6.0 to +7.0), −8.0 to −7.0 (+7.0 to +8.0), −9.0 to −8.0 (+8.0 to +9.0), and ≤−9.0 (≥+9.0).



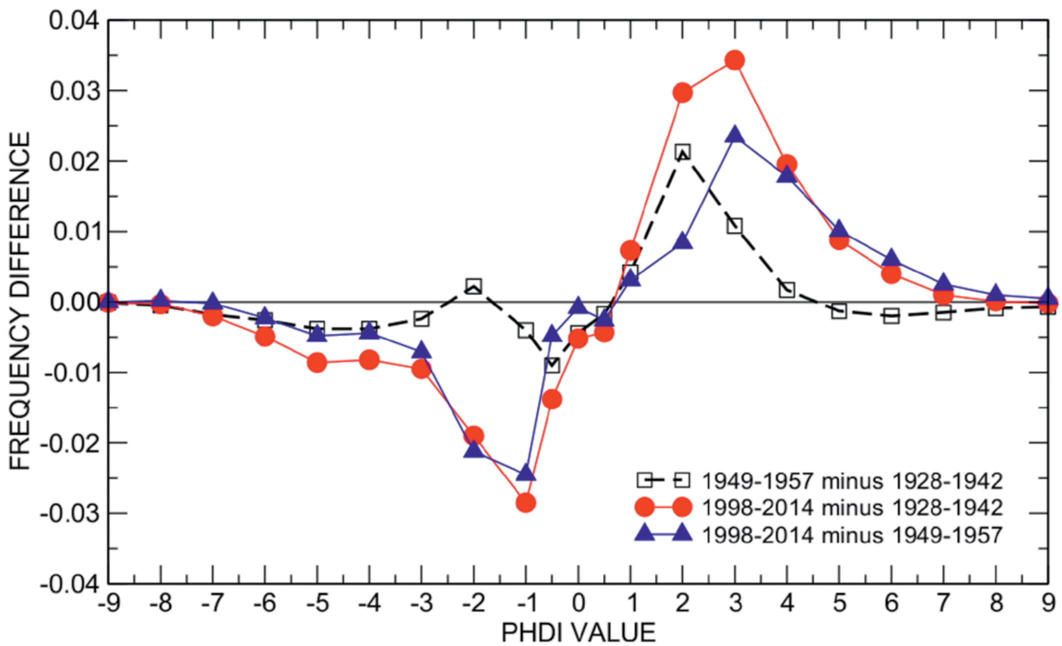


Fig. 4. (top) Difference in frequency distribution between each drought episode—1928–42 (dashed line with triangles), 1949–57 (dotted line with circles), and 1998–2014 (solid line with squares)—and the entire period of record (1900–2014). (bottom) Difference in frequency distribution of PHDI for the three major drought episodes: 1998–2014 minus 1949–57 (blue triangles), 1998–2014 minus 1928–42 (red circles), and 1949–57 minus 1928–42 (black squares).

PDSI because of the operational variability of the PDSI. As expected, each of the three major drought episodes had a greater frequency of drought (negative PHDI values) than the period of record base frequencies, with the 1930s drought having the greatest difference in relative frequencies, followed by the 1950s drought then the 1998–2014 drought (Fig. 4, top). There were fewer occurrences of wet conditions during the 1930s and 1950s droughts, with the 1930s having the greatest difference in relative frequencies. The 1998–2014 drought period had fewer mild wet PHDIs (+0.5 to +2.0) but more severe to extremely wet conditions (PHDI > +2.0; Fig. 4, top); it also had fewer mild droughts (–2.0 < PHDI ≤ –1.0). The 1998–2014 drought period had a "wetter" character compared to the 1950s and 1930s drought periods (Fig. 4, bottom). Also noteworthy are the differences between the 1930s and 1950s droughts. The 1950s drought had more mild to extreme wet conditions, but the 1930s drought had more frequent and

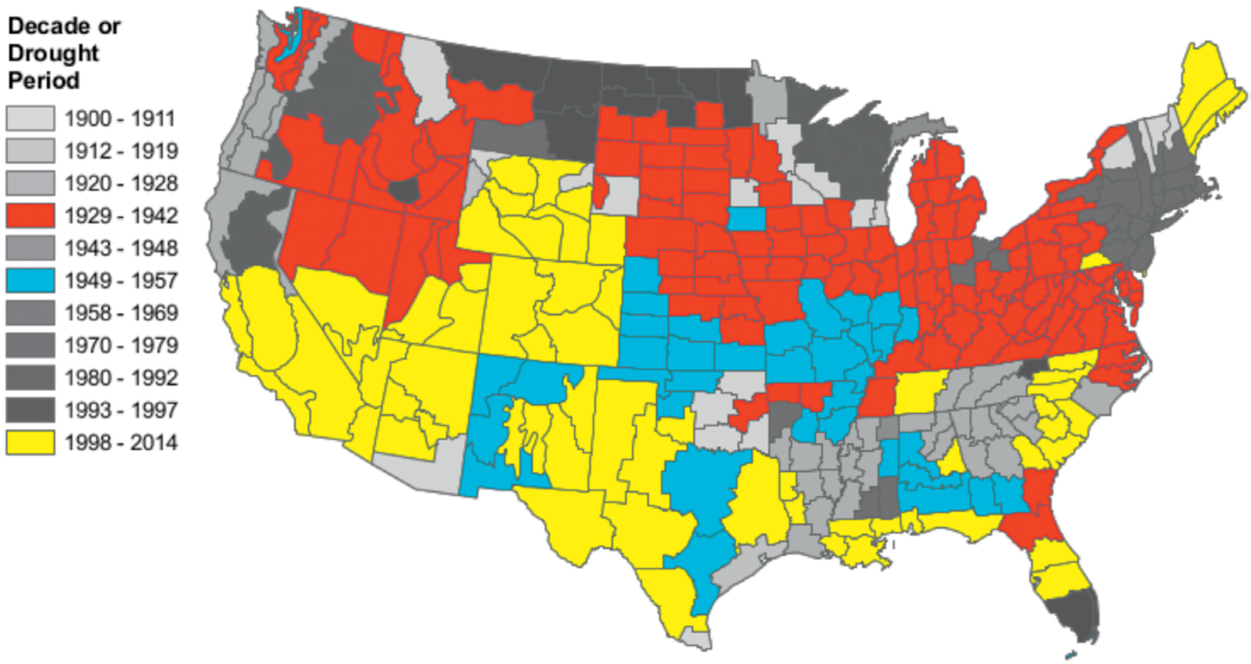


Fig. 5. Spatial pattern of occurrence of record dry PHDI, by decade or drought period.

widespread dry conditions and more extremely wet conditions (PHDI ≥ +5.0), although the frequencies and frequency differences for these extremely wet conditions were small.

The percent area of the CONUS experiencing record dry PHDI is shown in Table 1. A PHDI value was considered tied if it was within 0.05 of the lowest value. Only a few (18 out of 344) climate divisions had tied values, and this amounted to a percent area of about only 3.2%. Every drought episode except 1913–15 and 1980–82 experienced record drought somewhere. August 1934 was the single month with the greatest percent area in record drought (10.8%), followed by August 2002 (8.2%), September 1956 (9.5%), September 2011 (3.8%), August 1988 (3.4%), August 2011 (3.2%), February 1931 (3.2%), and January 1931 (3.0%). A total of 31.3% of the country experienced record drought during the 1930s episode, 13.1% during the 1950s episode, and 30.8% during the 1998–2014 drought period. The 1930s is the drought of record for a large contiguous region stretching from the East Coast to the Midwest and includes large areas in the central and northern Plains and the West and part of the Southeast (Fig. 5). The drought of record for much of the Southeast occurred in the 1920s. The 1950s is the drought of record for an area from the southern Plains to central Plains and Ohio Valley and part of the Southeast. The areas of the 1930s and 1950s droughts of record were obviously larger before the 1998–2014 drought became the drought of record for large parts of the southern Plains, West, and Southeast.

Duration. The PHDI for a climate division becomes more negative as dry conditions continue and becomes less negative during wet weather. If the PHDI becomes less negative (wetter) than a threshold value, it constitutes a break in the drought for that division at that time. Maximum drought length is defined as the total number of consecutive months from the time the PHDI value went below (was more negative than) a threshold value (–2.0 for moderate drought) to the time it went above the threshold. These maximum drought lengths were categorized into 10 bins.[3] For each of the three major drought episodes (1930s, 1950s, and 1998–2014), the number of droughts in each of these 10 bins was divided by the total number of droughts in the drought episode to compute a relative frequency (percentage) for each bin. This was also done for the period of record. This conversion of drought duration counts to relative drought duration frequencies allows comparison of the drought episodes and period of record (the actual numbers of droughts are not being compared). The period of record is characterized by a greater frequency of short-term (1–3 months) droughts than the three drought episodes (Fig. 6), which is expected since it incorporates wet spells as well as drought episodes, and local droughts that occur during widespread wet spells will likely not last very long. Each of the three

[3] The maximum drought durations were binned into these 10 categories: 1–3, 4–6, 7–12, 13–24, 25–36, 37–48, 49–60, 61–72, 73–84, and 85+ months.

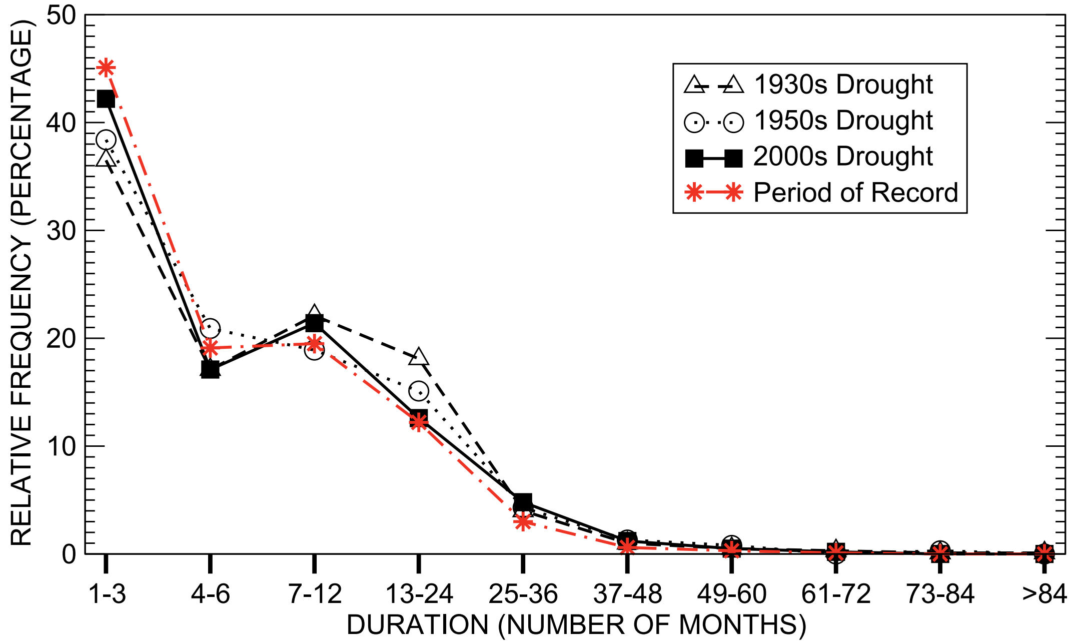


Fig. 6. Relative frequency distribution of maximum drought length for moderate to extreme droughts by drought episode—1928–42 (dashed line with triangles), 1949–57 (dotted line with circles), and 1998–2014 (solid line with squares)—and for the period of record (red dashed–dotted line with asterisks).

major drought episodes was characterized by more short droughts (1–3 months) than longer droughts, and each showed a tendency for a decreasing frequency of longer droughts, except for an uptick in frequency of 7–12-month drought duration for the 1930s and 1998–2014 episodes. The 1998–2014 episode had a greater relative frequency of shorter (1–3 months) droughts and smaller relative frequency of longer (13–24 months) droughts compared to the 1930s and 1950s episodes. The 1930s episode had relatively fewer short-term (1–3 months) droughts and relatively more frequent 1–2-yr (13–24 months) droughts than the 1950s or 1998–2014 episodes. The 1950s episode had a greater relative frequency of half-year (4–6 months) droughts and relatively fewer 1-yr (7–12 months) droughts than the other two episodes.

Significant drought episodes appear to be characterized by both large extent (Fig. 3) and long duration (Fig. 7). The longest scaled-area-averaged drought duration (37.3 months) for the 1998–2014 drought episode occurred in November 2003. The longest such drought duration (38.4 months) for the 1930s drought episode occurred in March 1935. The 1950s drought episode had the longest such drought duration (56.0 months) in the period of record, in February 1957.

Water supply versus water demand. Drought occurs when the balance between water supply and water demand is disrupted (Heim 2002). This disruption can occur when water supply (precipitation) decreases (WMO 1992; AMS 1997) or when water demand (here, evapotranspiration or PE estimated from temperature) increases, exacerbating drought conditions (AMS 1997). Human demand (for industrial or domestic use) is not considered here.

The CONUS area-averaged annual temperature has increased over 1901–2014, with the last decade warmer than all previous decades and 2012 ranking as the warmest year in the period of record. Consequently, of the three major drought episodes, the 1998–2014 episode nationally averaged warmer than the 1930s or 1950s episodes (Table ES1).

Precipitation during the wet season is more important for regional drought development or cessation than anomalous precipitation during the dry season. In fact, the failure of wet-season precipitation is crucial for regional drought development. Precipitation amount is an important input variable for drought models that compute soil moisture or evapotranspiration, but the geographical and seasonal variation in precipitation amount makes it more useful for hydrologic (e.g., flood) monitoring than for drought monitoring. For historical drought comparison, precipitation should be converted into a form that relates it to frequency of occurrence. By normalizing the variations in precipitation for location and season, the SPI (McKee et al. 1993) relates precipitation more readily to the USDM percentile categories. For operational drought monitoring purposes, an SPI value of –1.0 corresponds to moderate drought (USDM D1). NOAA agencies compute SPI operationally for seven time scales (1, 2, 3, 6, 9, 12, and 24 months), six of which are considered here. Of the three major drought episodes, the 1950s had the largest average percent area dry (SPI ≤ –1.0)—and the 1998–2014 episode had the smallest average percent area dry—for all time scales (Table ES1). Conversely, the 1998–2014 episode had the largest average percent area wet (SPI ≥ +1.0) at all time scales, and the 1950s had the smallest average percent area wet at all time scales. The 1930s and 1950s drought episodes were increasingly characterized by long-term dryness (6–24 months) relative to short-term dryness (1–3 months), while there was little difference by time scale for the 1998–2014 drought episode (Table ES1). Autumn and summer were the driest seasons (largest percent area with 3-month SPI ≤ –1.0) with winter the least dry season for the 1930s episode, and autumn was the driest season with spring and winter the least dry seasons for the 1950s episode. Conversely, for the 1998–2014 episode, autumn is the least dry season while winter and spring are the driest (Table ES2).

The warmer temperatures during the 1998–2014 drought resulted in more PE. On an annual basis (partial years were excluded from the annual calculation), the 1998–2014 drought averaged 760.3 mm PE, the 1930s drought averaged 744.3 mm, and the 1950s drought averaged 730.3 mm. But these differences are due more to the dominance of the 1998–2014 drought during the spring and autumn seasons than the other seasons (Table ES2). The average summer value for PE during the 1930s is very close to the value for 1998–2014, and evapotranspiration is essentially shut down across most of the CONUS during the winter.

The USCEI components based on daily precipitation were used to compare the three drought episodes on a finer (daily) temporal scale (Table ES3). The 1930s drought episode experienced a larger occurrence (larger average percent area) of days without precipitation, and smaller occurrence of days with precipitation, on an annual and seasonal basis than the 1998–2014 episode. The daily USCEI component data are consistent with the 3-month SPI in that autumn was the driest season for the 1950s drought.

When broken down by region (Fig. 1), the 1998–2014 episode had more days with precipitation than the other two episodes for all regions except the southern Plains to lower Mississippi Valley (Table ES4). The 1930s drought episode experienced a larger occurrence (larger average percent area) of days without precipitation than the other two episodes, and the 1998–2014 episode had the smallest days without precipitation component, for all regions except the southern Plains to lower Mississippi Valley. The differences in mean percent area with PHDI ≤ –2.0 between drought episodes indicate that the 1998–2014 episode had the largest mean drought area for the

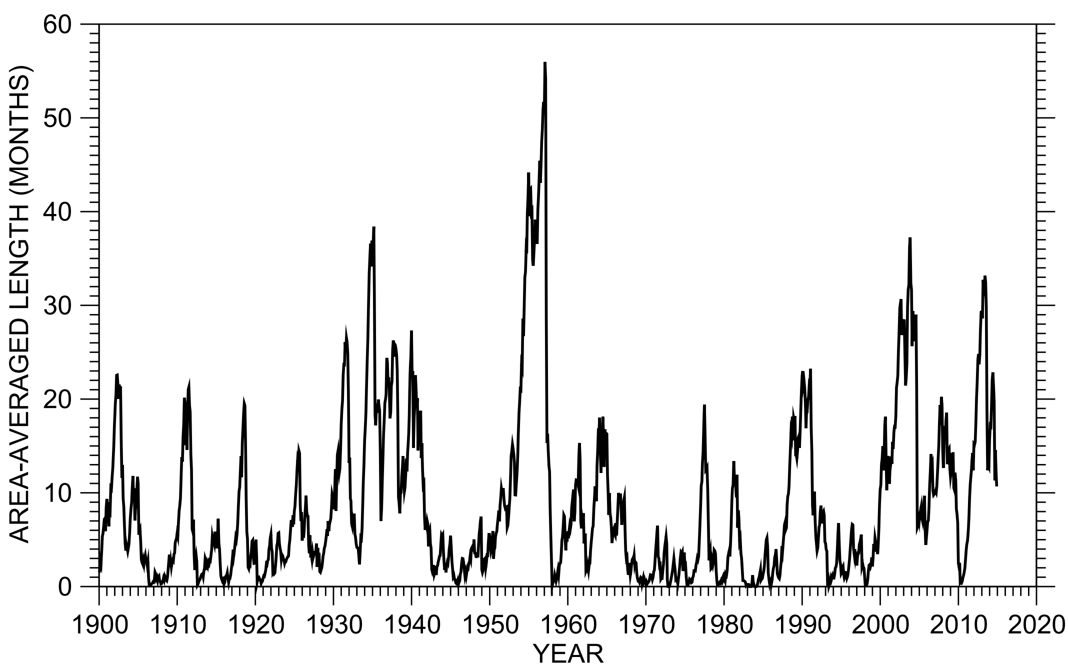


Fig. 7. Area-averaged length (months) of droughts for each month from Jan 1900 to Dec 2014, with drought threshold PHDI ≤ −2.0, weighted by the area of those climate divisions experiencing drought and scaled by the total area of the CONUS experiencing drought for each given month.

Southeast and the West and suggest an increasing trend for these regions. The opposite is true for the Northeast region and central to northern Plains and Midwest region. The 1950s episode had the greatest mean drought area for the southern Plains to lower Mississippi Valley region. The 1998–2014 episode was regionally significant in the Southeast, West, and southern Plains to lower Mississippi Valley. The differences in mean percent area with PHDI ≥ +2.0 between drought episodes indicate that the 1998–2014 episode had the largest mean wet area for the Northeast region and central to northern Plains and Midwest region and suggest an increasing trend for these regions; these results agree with the regional trends in total precipitation reported in Melillo et al. (2014).

SUMMARY AND IMPLICATIONS. Using operational NOAA datasets that span the twentieth and twenty-first centuries, this study has shown how several regional droughts merged to form a national-scale drought in the United States during 2012 that reached an intensity and areal coverage that, based on the Palmer drought index, standardized precipitation index, and U.S. climate extremes index components, rivaled the great drought episodes of the twentieth century. Objective criteria (percent area in drought) were used to identify 13 national drought episodes in the 1900–2014 record, with the 1930s (July 1928–May 1942), 1950s (July 1949–September 1957), and current (June 1998–December 2014) drought episodes being the three longest. Comparison of these three major drought episodes using various criteria contrasts the current drought with the previous droughts, thus putting it into a historical perspective.

The 1998–2014 drought episode is the warmest and "wettest" (more wet conditions in some regions concurrent with dry conditions in others) of the three drought episodes, is characterized more by short-duration dryness than long-duration dryness, has the greatest variability in moisture conditions across time (month to month) and space (Fig. ES3), and has lasted the longest. Its peak area was second in size to the 1930s drought episode. The 1930s and 1950s drought episodes were characterized relatively more by intense long-duration dryness than short-duration dryness. The 1950s drought was the most severe in terms of area for the longest period and had the lowest month-to-month variability in moisture conditions. The seasonal character of dryness is different, with autumn and summer the driest seasons for the 1930s episode, autumn the driest season for the 1950s episode, and winter and spring the driest seasons for the 1998–2014 episode.

Researchers have identified the physical mechanisms of the atmosphere that gave rise to the 2012 drought (large-scale subsidence and reduction in Gulf of Mexico moisture transport) and contributed to the 1998–2014 drought episode (recurrence of La Niña conditions). Other researchers have concluded that changes in climate are affecting changes in circulation features that affect the physical mechanisms that cause drought and thus the frequency, intensity, and location of droughts.

The implications of these climatic changes and their effect on the physical mechanisms that give rise to drought are significant. Even if the 1998–2014 drought episode itself is not the result of a changing climate, the increase in temperatures and associated changes in the hydrologic cycle have affected the characteristics of the drought. The increased frequency of drought in the western United States during 1998–2014 and the increasing temperature trend over the last three decades are creating (and will continue to create) significant hydrological and water supply concerns for the inhabitants and industry of the western United States (Mote et al. 2005; Cook et al. 2014, 2015). North America has a millennial-scale history of droughts, some of which dwarf the 1930s, 1950s, and 1998–2014 drought episodes in intensity and duration (Herweijer et al. 2007), and droughts are expected to continue to occur regardless of any changes in climate.

These issues have generated concern for water resource managers and decision-makers. Drought response has generally been *reactive* in terms of crisis management, which results in poor allocation of resources and disproportionate economic losses (Sivakumar et al. 2011, 2014a,b; Wilhite 2005). In recent decades, these concerns over drought have shifted the focus to a more *proactive* approach relying on risk management to reduce the impacts during future drought events and minimize economic losses (Wilhite 2000; Birkmann et al. 2011; McNutt et al. 2013; Wilhite et al. 2014; WMO/GWP 2014). Several states implemented drought plans[4] and Congress has expressed interest in national drought policy (Folger and Cody 2014). At the urging of western state governors, Congress established in 2006, and reauthorized in 2014, the National Integrated Drought Information System (NIDIS) as a multiagency system under the leadership of NOAA (NIDIS 2006). NIDIS was developed to enable society to respond proactively to short-term and sustained drought through improved monitoring, prediction,

[4] The National Drought Mitigation Center (NDMC) keeps an up-to-date list online at http://drought.unl.edu/Planning/DroughtPlans/StateDroughtPlans/CurrentStatePlans.aspx.

risk assessment, and communication. This proactive attention to drought at the state and national levels will go a long way toward enabling society and industry to prepare for, endure, and recover from the impacts of drought. But if the nature of drought is changing, then drought plans may need to be adjusted to accommodate these changes. Water resource managers and decision-makers may need to consider plans that can respond to increasing moisture extremes at *both* ends of the scale (droughts *and* floods)—at the same time.

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