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RESEARCH ARTICLE

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Characterizing U.S. drought over the past 20 years using the U.S. drought monitor

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Abstract

The main challenge of evaluating droughts in the context of climate change and linking these droughts to adverse societal outcomes is a lack of a uniform definition that identifies drought conditions at a location and time. The U.S. Drought Monitor (USDM), created in 1999, is a well-established composite index that combines drought indicators across the hydrological cycle (i.e., meteorological to hydrological) with information from local experts. This makes the USDM one of the most holistic measures for evaluating past drought conditions across the United States. In this study, the USDM was used to define drought events as consecutive periods in time where the USDM status met or exceeded D1 conditions over the past 20 years. This analysis was applied to 5 km grid cells covering the U.S. and Puerto Rico to characterize the frequency, duration, and intensification rates of drought, and the timing of onset, amelioration, and other measures for every drought event on record. Results from this analysis revealed stark contrasts in the evolution of drought across the United States. Over the western United States, droughts evolved much slower, resulting in longer-lasting but fewer droughts. The eastern United States experienced more frequent, shorter-duration events. Given the slower evolution from onset to drought peak, flash droughts, which made up 9.8% of all droughts, were less common across the western United States, with a greater frequency over the southern United States. The most severe drought event on record was the 2012 drought, when more than 21% of the United States experienced its largest number of weeks at or above extreme (D3) drought conditions. The availability of historical drought events would support future societal impacts studies relating drought to adverse outcomes and aid in the evaluation of mitigation strategies by providing a dataset to local decision makers to compare and evaluate past droughts.

1 | INTRODUCTION

Drought is a natural and complex phenomenon that is defined as a reduction of moisture within the hydrological cycle below normal levels that, over time, can have wide-ranging and cascading societal effects on agriculture, water quality, industry, and human health (Riebsame *et al.*, 1991; Wilhite, 2000; Heim, 2002; Sugg *et al.*, 2020). In the United States (U.S.), 18 of the past 20 years have had drought-induced agricultural losses (i.e., crop yields and livestock) exceeding a billion dollars, with an adjusted average loss of $6.97 billion and 26 heat stress-related deaths per year (NOAA, 2021). In addition, there are well-known drought impacts on forest fire fuel and combustibility that influence not only the acreage burned, but also the intensity, severity, and frequency of forest fires (Littell *et al.*, 2016). However, there are less well understood impacts of drought on water quality (i.e., harmful algae blooms), human health (i.e., Valley Fever, Lyme disease) and critical infrastructure (i.e., electrical grid, industrial productivity) that can result in secondary or indirect societal impacts, such as the loss of electricity service, industrial cooling capacity others (Sugg *et al.*, 2020). These impacts are only expected to worsen as populations in water-limited environments continue to grow and the demand for water from energy, industry, and agriculture (i.e., irrigation) increases (Mishra and Singh, 2010). When combined with expected anthropogenic changes in climate that may exacerbate drought conditions (Williams *et al.*, 2020), the proportion of society vulnerable to drought is likely to increase over time.

Since droughts are not a preventable phenomenon, efforts to reduce societal impacts of drought have focused mostly on the development of mitigation plans that, when implemented, improve a region's resilience to drought. One of the challenges of developing successful mitigation strategies is that drought impacts can vary by event due to differences in exposure brought on by the timing of onset, peak severity, and the rate of intensification (i.e., flash droughts) combined with specific regional and seasonal vulnerabilities (Barker *et al.*, 2019). Therefore, successful mitigation strategies are often best developed locally through interactions and coordination between local, state, regional, and national stakeholders and governments (Smith *et al.*, 2016) which allow these plans to prioritize key infrastructure and focus on communities most vulnerable to drought.

Mitigation and planning efforts can be greatly benefited by national assessments of historical drought conditions (Mishra and Singh, 2010; Spinoni *et al.*, 2015; Caillouet *et al.*, 2017; Heim, 2017; Barker *et al.*, 2019; Askarimarnani *et al.*, 2020). Asong *et al.* (2018) evaluated historical drought patterns across Canada using the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano *et al.*, 2010), in part to improve efforts at developing sustainable water management planning. In a similar way, a 250-year record of the Standardized Precipitation Index (SPI; McKee *et al.*, 1993) was evaluated across Ireland (Noone *et al.*, 2017) and combined with newspaper archives to help establish links between historical droughts and societal impacts. In the U.K. (Barker *et al.*, 2019) and France (Caillouet *et al.*, 2017), historical drought conditions were documented using 100+ year simulations of standardized streamflow to establish the full range in plausible hydrological drought scenarios. Spinoni *et al.* (2015) considered both meteorological and hydrological forms of drought in their analysis of the most severe European events based on a composite measure of drought that combines the SPI, SPEI, and the Reconnaissance Drought Index (RDI; Tsakiris and Vangelis, 2005).

In the U.S., many of the historical drought analysis have focused on the evaluating important regional differences in drought frequency and duration. Diaz (1983) and Karl (1983) both applied statewide historical (1800s to 1990s) measures of the Palmer Drought Severity Index (PDSI; Palmer, 1965) that reveal drought conditions over the interior west were more persistent and severe. Also using PDSI, Heim (2017) compared the early 21st century drought episodes to the those of the 1930s and 1950s using operational NOAA databases (PDSI, SPI, and components of the U.S. Climate Extremes Index). In addition, Williams *et al.* (2020), using a paleo version of PDSI based on tree rings, revealed that the 19-year period from 2000 to 2018 was cumulatively the most severe drought period since 1500 in the western U.S. Others have explored historical U.S. drought conditions based on hydrological drought measures using modelled streamflow and soil moisture (Andreadis *et al.*, 2005) and surface runoff (McCabe *et al.*, 2017).

These historical drought analyses provide important context when evaluating a drought indicator over time; however, comparing the historical U.S. drought patterns among the studies can result in contrasting drought frequency, severity, and duration perspectives. For instance, McCabe *et al.* (2017) found that runoff-based measures of droughts resulted in shorter-lived and more frequent drought events in the Western U.S. in contrast to longer-lived droughts over much the same regions in Diaz (1983) and Karl (1983). Andreadis *et al.* (2005) found similar contrasts between their drought analyses based on modelled soil moisture and runoff, which showed that runoff was more responsive to precipitation than soil moisture. As a result, droughts based on measures of runoff were found to recover more quickly or were even less severe if short wet spells were embedded within the event as was the case for the 1930s and 1950s droughts. These results indicate that the outcome of historical drought analyses are sensitive to the selection of the drought indicator and how droughts are defined (McCabe *et al*., 2017).

Unfortunately, there is little agreement in the literature on the most appropriate drought index and aggregation time to assess a given outcome (Bachmair *et al*., 2016), and there are growing numbers of possible drought indices for each of the drought types (meteorological, agricultural, and hydrological) as noted in Heim (2002) and Zargar *et al*. (2011). Efforts to address these limitations have focused on combining reports of drought impacts and drought indices to model the most appropriate indicator and aggregation time scale (e.g., Stagge *et al*., 2015; Bachmair *et al*., 2016). In Europe, Stagge *et al*. (2015) and Bachmair *et al*. (2016) found important differences in SPI and SPEI monthly aggregation times that best aligned with reported impacts in the agricultural (1–3 months), hydropower generation (6–12 months), and water supply (combination of 1–3 and 6–12 months) sectors. These studies, using only the SPI and SPEI, found that the relevant aggregation times varied by country, with water supply constraints related to regional sources of water access (i.e., surface or subsurface water; Stagge *et al*., 2015).

The choice of the most appropriate index from which to evaluate historical drought events will depend on the specific impact of interest and the availability of data used to derive the drought metric, in addition to spatial extent, temporal availability, scientific clarity, and other aspects (Steinemann and Cavalcanti, 2006). However, it may not always be clear which drought metric or set of metrics best align with specific drought impacts (e.g., human health, water infrastructure). In these situations, composite measures like the U.S. Drought Monitor (USDM), that combine moisture conditions from multiple indices may be more beneficial to a broader community than a single drought metric. The USDM, which was established in 1999, blends information from available drought indicators across the hydrological cycle (i.e., meteorological, agricultural, hydrological) with information from local experts (Svoboda *et al*., 2002). This integrated approach makes the USDM one of the most holistic measures of drought conditions across the U.S., Puerto Rico, U.S. Virgin Islands, and U.S. Affiliated Pacific Islands. In addition, the index is widely used from academia research and informing decision makers and policy experts to aiding in the declaration of disasters areas as well as delivering billions of dollars in economic assistance to agricultural communities through the Livestock Forage Disaster Program (LFP) and others.

The purpose of this study is to define and characterize a high spatial and temporal resolution climatology of recent U.S. drought conditions from 2000 to 2019 based on the published weekly USDM maps. This analysis will be one of the first efforts to evaluate regional differences in drought formation (i.e., timing of onset and termination) and evolution (i.e., duration, severity, and rates of intensification/amelioration) that includes Alaska, Hawaii, and Puerto Rico. In addition, the methods used will allow for the climatology to be updated regularly in the future. It is anticipated that the use of a broadly accepted historical analysis of drought (used by both academics and policy makers) will not only be useful in evaluating current and future hydrological indicators and seasonal drought forecasts, but also provide additional context on drought characteristics (i.e., their timing of onset, peak intensity, duration, etc.) to improve drought monitoring, mitigation efforts, and disaster recovery programs.

TABLE 1 USDM categories and corresponding drought indicator percentiles

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

2 | DATA

The USDM is produced through a collaborative effort of the National Drought Mitigation Center (NDMC), U.S. Department of Agriculture (USDA), National Oceanic and Atmospheric Administration (NOAA), and local experts (Svoboda *et al*., 2002). Using geophysical observations (e.g., precipitation, temperature, stream flow, soil moisture, vegetation state, and others) and information from local experts in the field, the USDM authors have generated weekly evaluations of drought conditions across the U.S. operationally since January 4, 2000. The USDM authors combine this information based on a "convergence of evidence" approach. The geophysical data and drought indicators are converted into a percentile-based format that relates them to their local history. These objective data and indicators are then integrated subjectively based on the intensity and importance of the conditions they indicate ("converge to"). The seasonal and geographical appropriateness of the data and indicators is of key importance during this process. The inputs are assimilated by the author into a composite measure that categorizes conditions into six levels of severity ranging from no drought (None) to exceptional (D4) drought (Table 1).

A gridded 5 km daily precipitation dataset based on the Global Historical Climatology Network (GHCN; Menne *et al.*, 2012) was used to evaluate precipitation conditions during phases of drought intensification and amelioration. The daily version of the gridded dataset referred to as nClimGrid-d contains spatially interpolated station observations of temperature and precipitation from GHCN (Vose *et al.*, 2014) between January 1, 1951 to present. This dataset was only recently developed and was not used as an input to the USDM process until 2020. Therefore, it provides a somewhat independent high resolution precipitation dataset available at daily time scales that can be easily synced with USDM's weekly drought index. For precipitation, only grids with measurable precipitation (greater than 0.1 mm) were spatially interpolated, with the daily sums forced to match monthly totals (Vose *et al.*, 2014). More information about nClimGrid-d can be found from Vose *et al.* (2014), and the dataset is publicly available at https://www.ncei.noaa.gov/pub/data/daily-grids/.

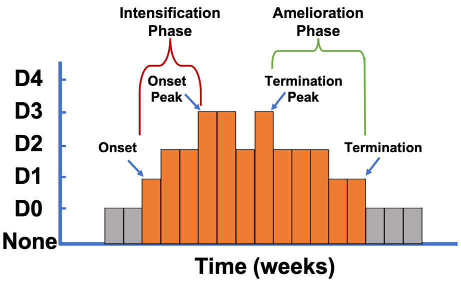


FIGURE 1 Schematic representation of an theoretical drought event (orange) with onset occurring the first week of D1 conditions, onset and termination peak defined as the first and last week of peak USDM status over the drought event, respectively, and drought termination defined as the last week of D1 conditions followed by 3 weeks or more of D0 or none status. Intensification and amelioration phases were denoted in red and green brackets demarking the weeks between onset to onset-peak and termination-peak to termination [Colour figure can be viewed at wileyonlinelibrary.com]

3 | METHODS

The weekly drought maps from the USDM were placed on a 5-km-resolution grid that aligned with nClimGrid-d. To ensure the consistency of the resolution across higher-latitude grids in Alaska, the grid was created using an Albers Equal Area projection, resulting in 374,309 cells that span the USDM regions. For the 2000–2019 period, 1,044 weekly files were placed on this grid to provide a high-spatial-resolution dataset from which to define and characterize drought events across the U.S. The weekly USDM gridded files used in this study are publicly available at https://www.ncei.noaa.gov/pub/data/nidis/geojson/us/usdm-tiff/albers-equal-area/.

A time series of weekly USDM drought status (Dx value) at each grid cell was generated from the gridded dataset and used to identify non-overlapping drought events, as outlined in Leeper *et al.* (2021). Based on their approach, a drought event was defined as beginning on the first week the USDM status meets or exceeds moderate drought (D1) conditions and ends the last week the USDM status meets or exceeds D1, followed by three or more consecutive weeks of abnormally dry (D0) or

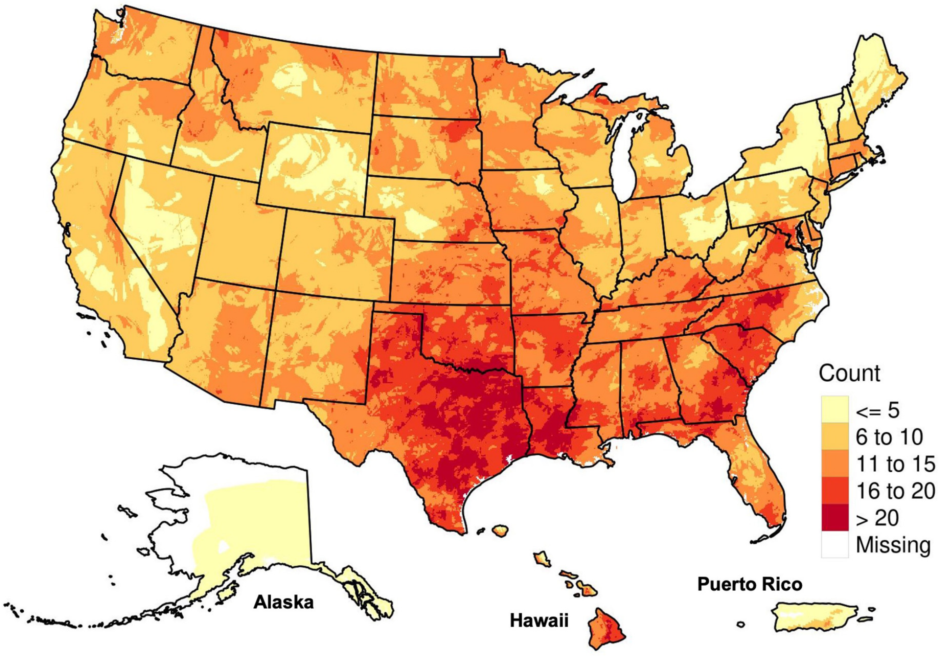


FIGURE 2 Drought event counts from 2000 through 2019. Areas never experiencing a drought event were set to missing [Colour figure can be viewed at wileyonlinelibrary.com]

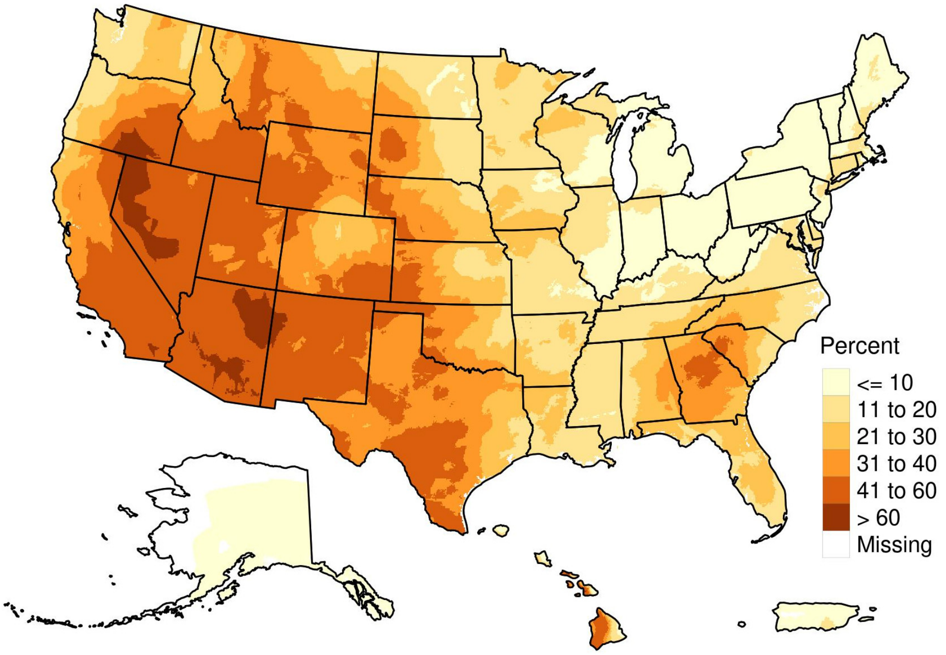


FIGURE 3 Percent of time spent in D1 or greater drought status from 2000 through 2019. Areas never experiencing a drought event were set to missing [Colour figure can be viewed at wileyonlinelibrary.com]

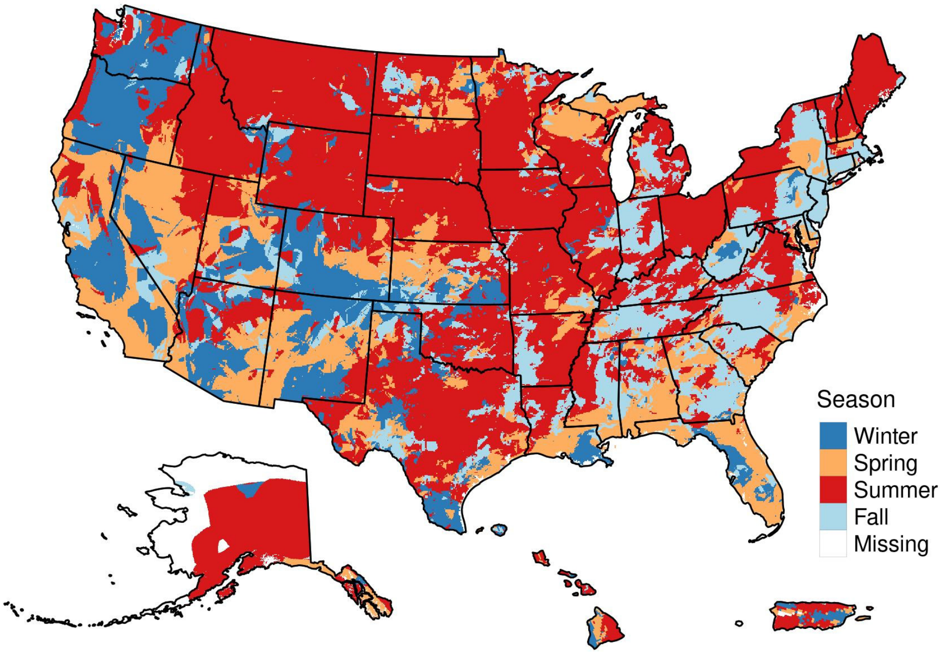


FIGURE 4 The mode of seasonal drought onset for all drought events from 2000 through 2019. Areas never experiencing a drought event were set to missing [Colour figure can be viewed at wileyonlinelibrary.com]

None conditions (Figure 1). While this allows events to incorporate a few weeks with D0 (0.44% of weeks in drought) or in rarer cases None (0.005% of weeks in drought) drought conditions, periods of time were identified when the USDM drought conditions over a grid cell were persistent enough to become drought events. These drought events were then analysed to evaluate the frequency and duration of drought episodes as well as critical moments in the evolution of drought as denoted in Figure 1. The moments include the timing of onset and termination, as well as the periods of time when drought conditions were intensifying (from onset to the first week of peak drought status) and ameliorating (the last week of peak drought status to drought termination) referred to as onset-peak and termination-peak, respectively. It should be noted here that not all drought events will have a maximum USDM status exceeding moderate drought (D1) conditions, which makes it challenging to identify the onset peak and termination peak weeks. In those cases, the drought events were excluded from analyses requiring onset and termination peak weeks, such as

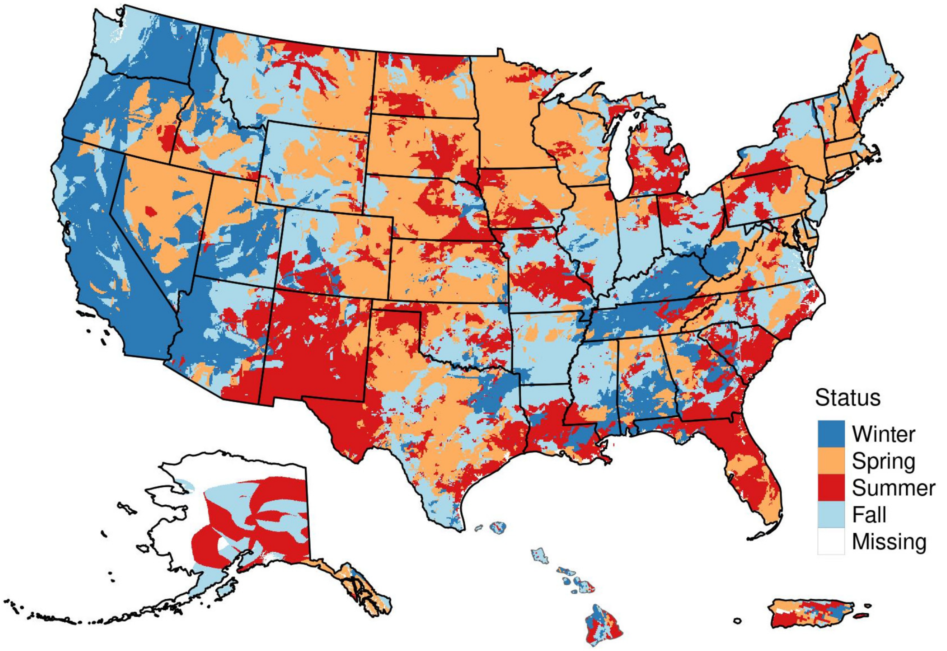


FIGURE 5 The mode of seasonal drought termination for all drought events from 2000 through 2019. Areas never experiencing a drought event were set to missing [Colour figure can be viewed at wileyonlinelibrary.com]

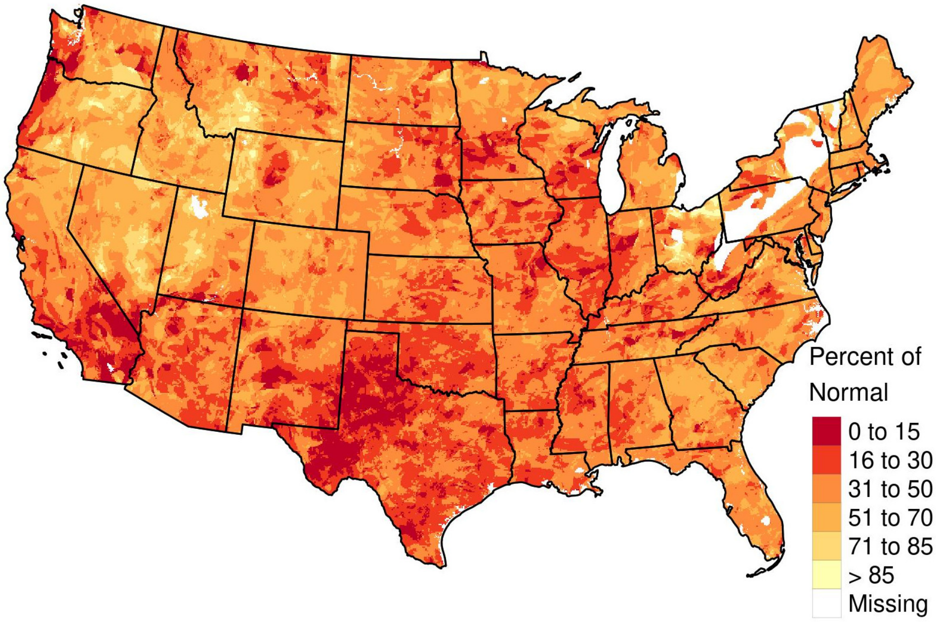


FIGURE 6 Median percent of normal precipitation from drought onset to the peak onset. This analysis excluded drought events that had peak status conditions less than D2 with areas having no drought events greater than D2 identified a s missing [Colour figure can be viewed at wileyonlinelibrary.com]

the median days from onset to onset peak or accumulated precipitation from termination peak to termination. Other analysis excluding D1 peak drought events include the median days from onset to onset peak and termination peak to termination. In addition, the U.S. Virgin Islands and U.S. Affiliated Pacific Islands were excluded from this analysis since they lacked the 20-year record of weekly drought maps; however, the documentation of historical drought events are available in these areas.

Evaluations of precipitation conditions from nClimGrid-d during phases of intensification and amelioration were based on calculations of percent of normal precipitation (Equation 1).

$$\text{Percent of normal} = \frac{\text{eventPrecip}}{\text{historicalPrecip}} \times 100\% \qquad (1)$$

For drought intensification, eventPrecip was the accumulated precipitation from onset to onset peak and historicalPrecip was the average accumulated precipitation over the same calendar period from 1981 to 2010. Percent of normal precipitation over the amelioration phase was similarly calculated between termination peak and the

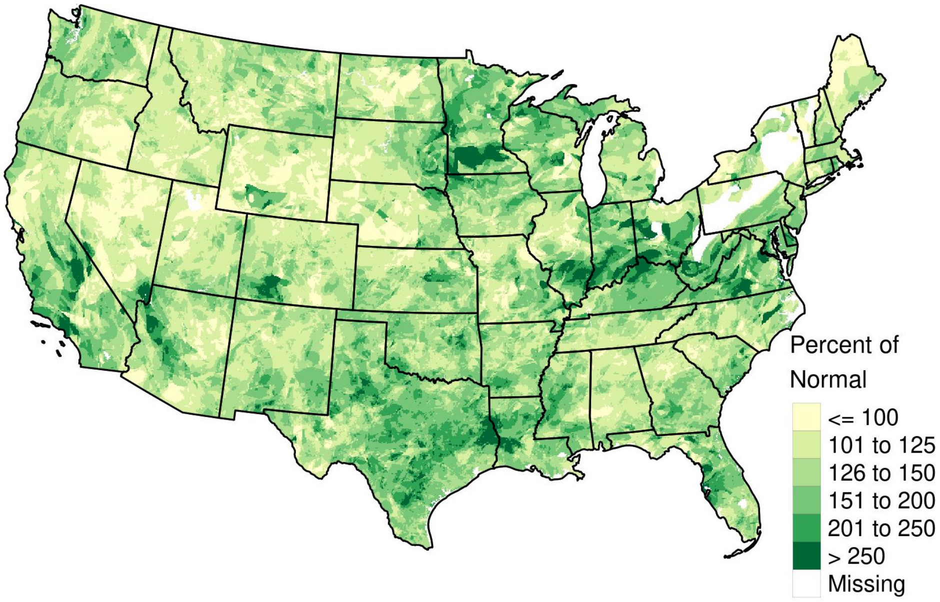


FIGURE 7 Median percent of normal precipitation from termination peak to drought termination. This analysis excluded drought events that had peak status conditions less than D2 with areas having no drought events greater than D2 identified as missing [Colour figure can be viewed at wileyonlinelibrary.com]

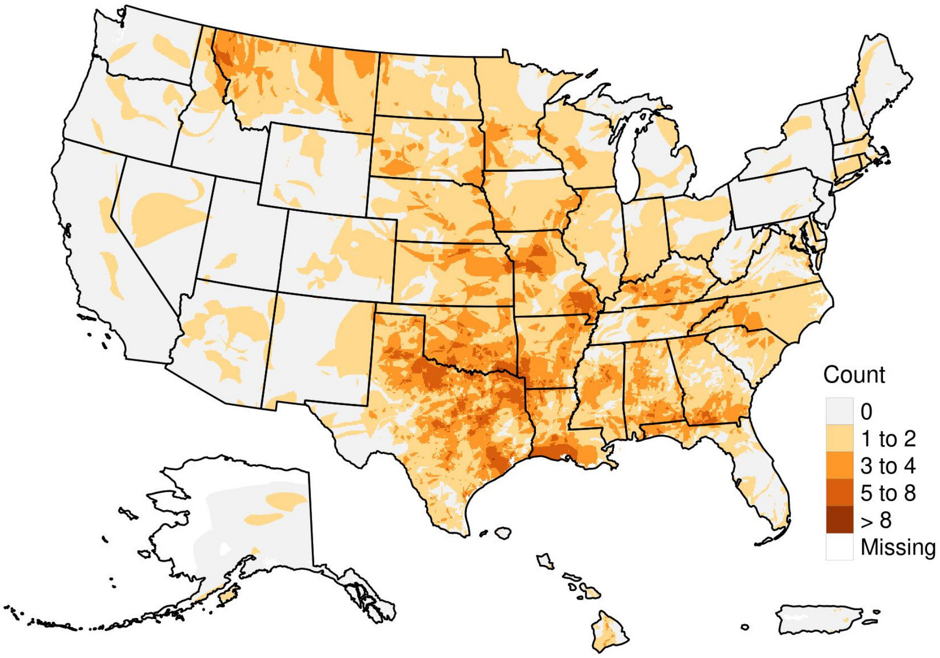


FIGURE 8 The count of flash drought events where increases of three or more USDM statuses occurred within a 5-week period from 2000 through 2019. Areas never experiencing a drought event were set to missing [Colour figure can be viewed at wileyonlinelibrary.com]

week following termination to capture the final reduction in USDM drought status to abnormally dry (D0) conditions. From percent of normal, it is possible to assess if precipitation conditions were drier (<100%) or wetter (>100%) than usual for that location and time of year.

4 | RESULTS

During the 20-year period, drought events identified by the USDM were more frequent across the eastern half of the U.S. than the western half, with some of the highest event counts (+15) in the Southeast and southern Plains (Figure 2). In addition to a west-to-east gradient in drought event frequency, there were also fewer drought events north of Kentucky and Virginia (i.e., portions of Indiana, Ohio, Pennsylvania, New Jersey, Rhode Island, New York, Vermont, Connecticut, New Hampshire, and Maine), which suggest these areas have been largely spared from drought events over the past 20 years. In Hawaii, topographical factors seem to have favoured drought formation on the windward side of the island. A strong spatial gradient of the time spent in drought (D1 or greater conditions; Figure 3) was also captured,

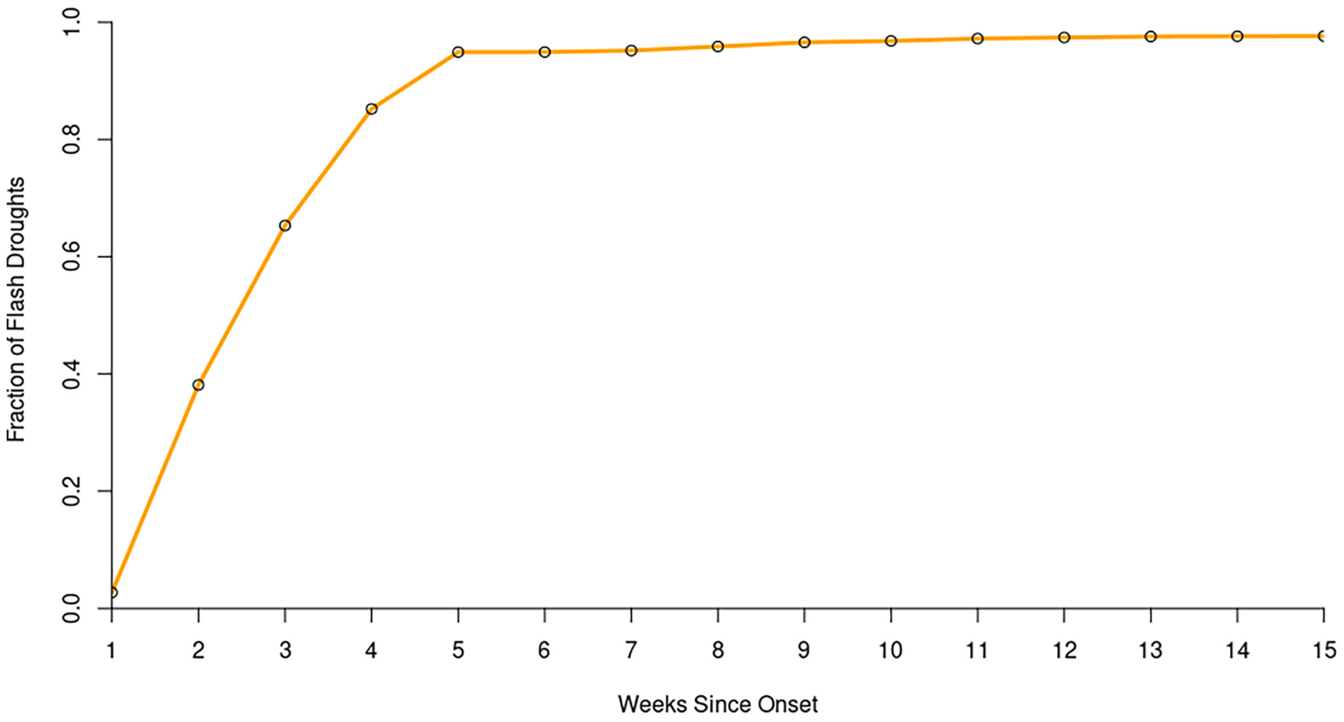
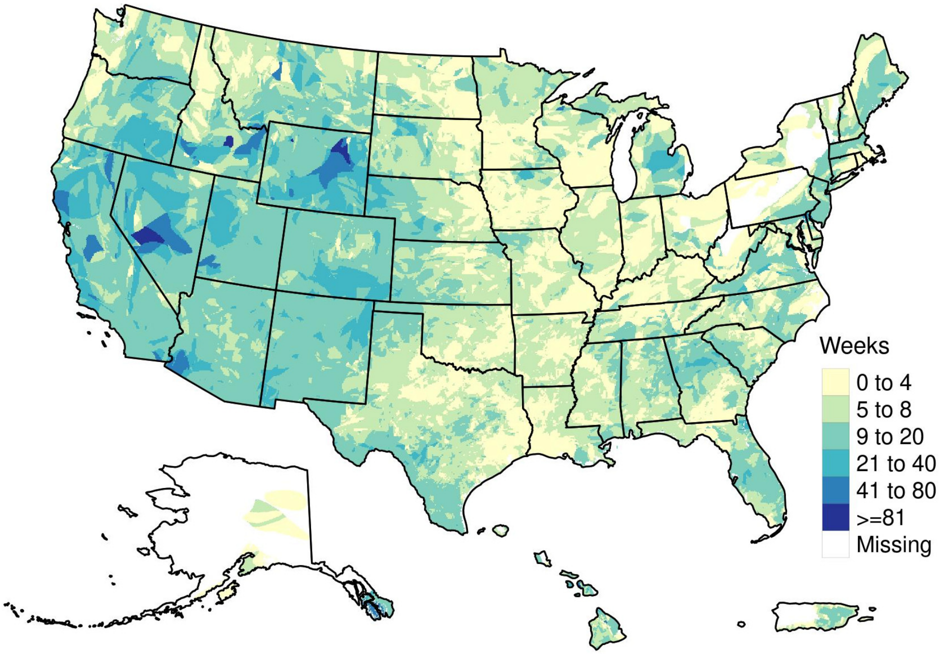


FIGURE 9 The fraction of flash droughts with the period of rapid intensification occurring by weeks since drought onset [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 10 The median number of weeks from drought onset to onset peak of all drought events from 2000 to 2019. This analysis excluded drought events that had peak status conditions less than D2 with areas having no D2 or greater USDM status set to missing [Colour figure can be viewed at wileyonlinelibrary.com]



with the western half of the CONUS and Hawaii experiencing drought conditions for more than 40% of the time between 2000 and 2019. The USDM analysis indicates that drought has occurred infrequently in Alaska. However, this is believed to be the result of an evolving understanding of how drought indicators should be applied in higher-latitude environments when monitoring drought severity and its impacts (Bathke *et al.*, 2019) rather than a lack of drought conditions.

The seasonality of drought onset and termination revealed drought across the U.S. was more spatially variable for drought onset than termination (Figures 4 and 5). Over much of the interior United States and Alaska, drought events typically began over the

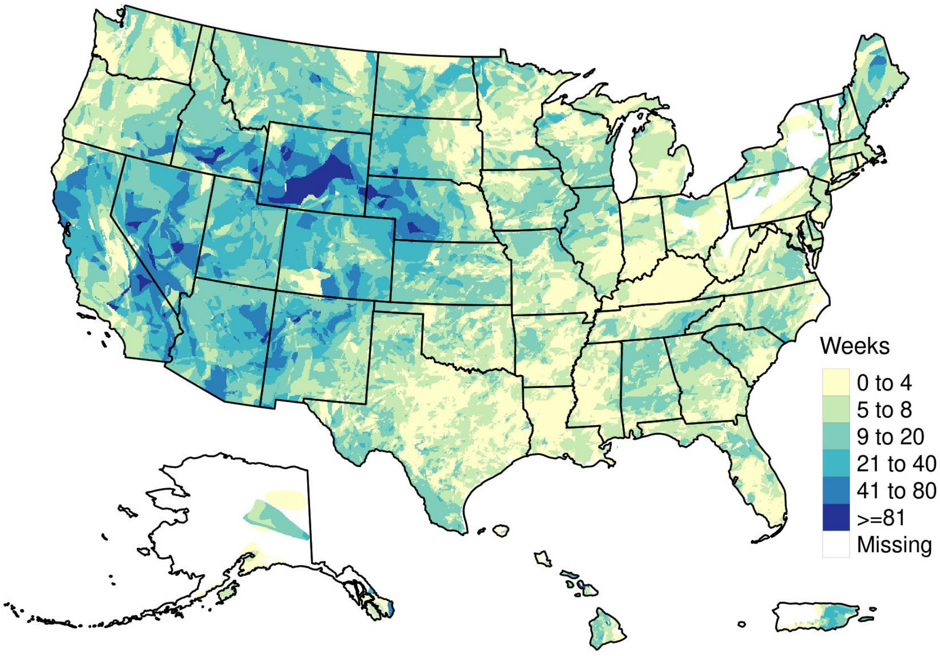


FIGURE 11 The median number of weeks from peak termination to drought termination of all drought events from 2000 to 2019. This analysis excluded drought events that had peak status conditions less than D2 with areas having no D2 or greater USDM status set to missing [Colour figure can be viewed at wileyonlinelibrary.com]

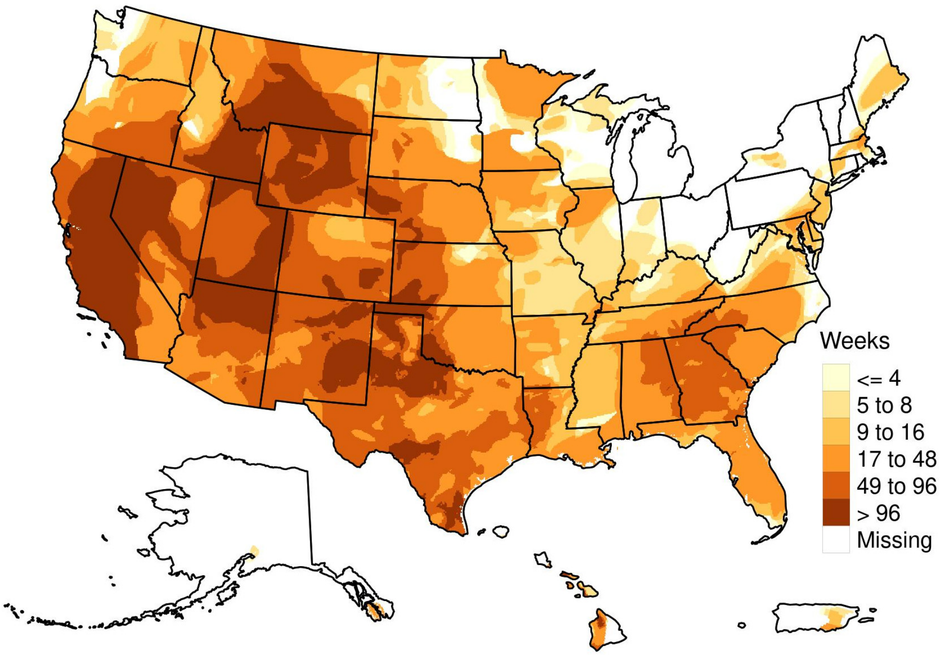


FIGURE 12 Total number of drought weeks at or greater than extreme drought (D3) status from 2000 to 2019. Areas having no drought weeks exceeding D3 status were set to missing [Colour figure can be viewed at wileyonlinelibrary.com]

summer (June, July, and August) and fall (September, October, and November) seasons. In the Alaska panhandle, drought onset primarily occurred over spring months, with winter being the most likely season for much of Washington and Oregon. Over the desert Southwest and the islands of Puerto Rico and Hawaii, seasonal onset was particularly variable. However, the seasonality of drought termination had less spatial variability where drought events typically ended in either the winter or fall seasons over much of the coastal western states and the summer months in the Southwest. Spring termination was mostly confined to the interior portions of the United States with the exception of the Northeast, which tended to have fewer drought events over the past 20 years compared to the rest of the United States. In Alaska, there were sharp contrasts between the temperate rainforest of the panhandle and the rest of Alaska in the seasonality of termination. Similar to the season of onset, the tropical locations of Hawaii and Puerto Rico had a wide range of preferred drought termination, with nearly all four seasons represented.

Evaluations of median precipitation conditions during the identified drought events revealed much of the

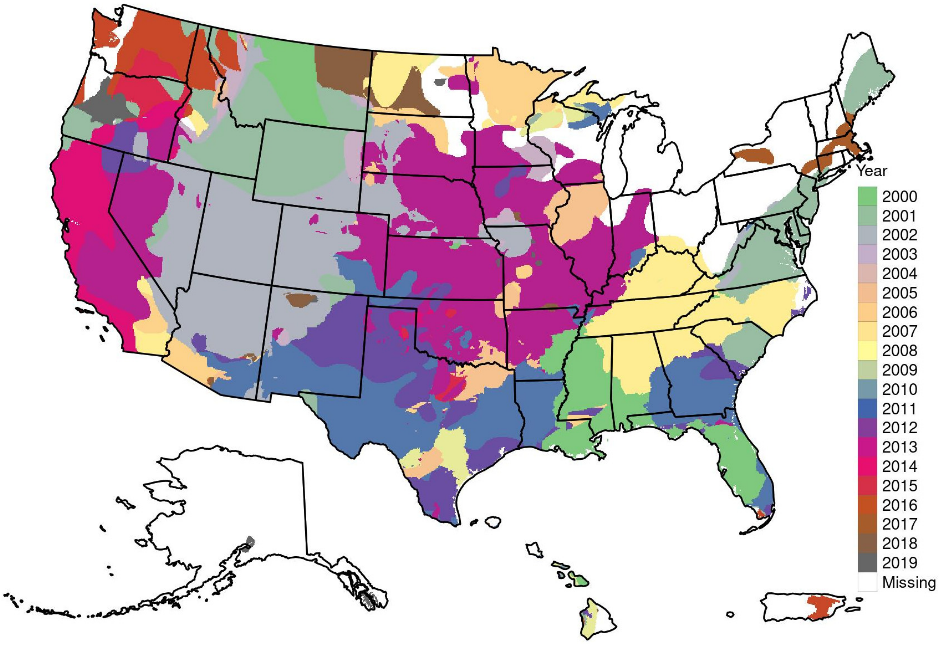


FIGURE 13 Starting year of the most severe (greatest number of weeks in D3 or greater status) drought event over the USDM period of record. Areas having no drought weeks exceeding D3 status were set to missing [Colour figure can be viewed at wileyonlinelibrary.com]

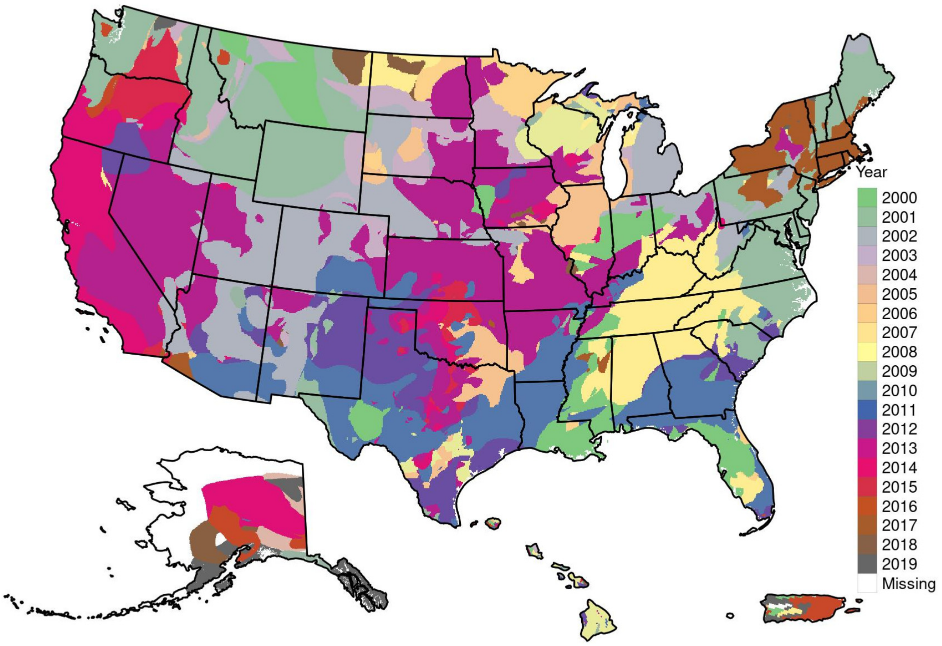


FIGURE 14 Starting year of the longest-duration drought event over the USDM period of record. Areas having no drought events were set to missing [Colour figure can be viewed at wileyonlinelibrary.com]

CONUS had drier than normal precipitation (less than 100%) as drought conditions intensified from onset to onset peak (Figure 6). This was particularly true for much of Texas and Oklahoma, southern California, and the coastal areas of Oregon and Washington, where median precipitation conditions were less than 30% of normal. However, over elevated areas of the central West, conditions during the intensification phase were not as dry, with near-normal (70%–100%) precipitation conditions. During the amelioration phase of drought from termination peak to termination, above-normal precipitation was predominant across the U.S., with some regions receiving up to six times (600%) normal precipitation (Figure 7). Median precipitation conditions exceeding two times the normal precipitation (≥200%) were found over the Ohio Valley, parts of the Midwest, Texas, and California, with near-normal precipitation conditions during drought amelioration over much of the northeastern U.S. The spatial variability of precipitation conditions during these critical phases of drought formation and

TABLE 2 The top five drought events having the most weeks at D3 or greater drought status over the U.S. and Puerto Rico

Start year	Percent of area
2012	21.21
2002	14.81
2001	11.19
2010	11.09
2007	8.41

TABLE 3 The top five longest-lasting droughts over the U.S. and Puerto Rico

Start year	Percent of area
2012	18.72
2001	12.58
2002	11.38
2010	9.99
2013	7.98

termination was very regionalized and likely associated with the timing of drought onset and amelioration in relation to seasonal precipitation patterns, number of drought events, and rates of intensification and improvement.

Flash droughts are a special type of drought event characterized by rapid intensification (Otkin *et al.*, 2018). While the exact definition of a flash drought is still being debated in the literature (Otkin *et al.*, 2018; Chen *et al.*, 2019), in this analysis flash drought was defined as degradations in USDM status of three or more categories over a five-week moving window, which allows for the maximum-possible rate of change (five categorical changes from None to D4 over a 5-week period) to be reported. In addition, there was no requirement for the rapid intensification to occur during drought onset; however, the likelihood of meeting the three-status change requirement is thought be higher during the earlier stages of drought formation. In this analysis, flash droughts represented 9.8% of all droughts and were more likely to occur east of the Rockies, with a greater frequency over southern U.S. States, excluding Florida (Figure 8). Of the flash droughts, 94.9% experienced rapid intensification within 5-weeks of drought onset (Figure 9). This percentage drops to 85.2% and 65.3% of flash droughts when rapid intensification occurs within 4- and 3-weeks of onset respectively.

To further evaluate rates of intensification and abatement, the number of median weeks from drought onset (D1) to peak onset (Figure 10) and termination peak to termination (Figure 11) were analysed. These results illustrate that rates of drought intensification and abatement were much slower over the western third of the U.S. compared to the eastern two-thirds. The slower rates of drought change across the U.S. explain why flash droughts were rare across western portions of the U.S.

Assessments of drought severity revealed that western states have not only spent more time in drought than eastern states (Figure 3), but also have spent more time in Extreme Drought (D3) or greater (Figure 12) conditions. Portions of the U.S. that have spent up to 2 years in D3 or greater drought extend from parts of California over the Rockies and into New Mexico, Texas, and the Oklahoma panhandle. This diminishes to less than a year for most of the eastern U.S., with an exception of Georgia and portions of Alabama and the Carolinas, which had up to a year in D3 or greater conditions from 2000 to 2019. In comparison, D3 or greater status was rare over parts of the Great Lakes, Ohio Valley, and Northeast, which suggests these regions have been largely spared from extreme drought conditions over the past 20 years.

To explore some of the more noteworthy drought events to have impacted the U.S. over the past 20 years, plots of the starting year for the most intense (most weeks at D3 or greater; Figure 13) and longest-lasting (Figure 14) events were generated. Figure 13 illustrates the footprint of the most severe drought events for every region of the U.S., including the 2012 drought over the central U.S.; the 2010–2011 event across parts of Arizona, New Mexico and Texas; and the 2012–2013 California drought. Over the Northeast, the most severe drought event was almost 20 years ago, in 2001. The western half of the main island of Hawaii had its most severe drought event in 2009. Of these severe drought events, the 2012 drought event stands out as representing the greatest area (number of grid cells) of the U.S. and Puerto Rico at 21.21%, followed by 2002 (14.81%), and 2001 (11.19%) rounding out the top three (Table 2). Assessments of the longest-lasting drought events (Figure 14) show some differences over eastern Nevada and the central U.S. compared to the number of weeks greater than D3. However, there was little change in the area ranking among drought event start years (Table 3), apart from 2013 replacing 2007 in the top five. The spatial contrasts between these two measures suggests that the longest-lasting drought event may not always align with the event having the greatest number of weeks at D3 or greater conditions.

5 | DISCUSSION AND CONCLUSIONS

There were strong spatial contrasts in drought frequency, duration, and intensity across the CONUS, Alaska, Hawaii, and to a lesser extent Puerto Rico. These spatial patterns in drought formation and evolution were aligned with seasonal to interannual (i.e., ENSO—Ropelewski and Halpert, 1987, NAO—Hurrell and Van Loon, 1997), topographic, and tropical cyclone influeces on precipitation. The latter two are generalized in monthly Climate Normals of precipitation available from the National Centers for Environmental Information https://www.ncei.noaa.gov/products/land-based-station/us-climate-normals. For instance, in semiarid to arid regions of the U.S. (i.e., Interior West, Southwest), precipitation is characterized by pronounced wet and dry seasons, such as the summer monsoon rains over the Southwest U.S. and the wet winters across the West Coast. Since it is not uncommon to have long periods (i.e., months) with little to no precipitation during the dry season, it can be challenging to identify emerging or improving drought conditions during these seasons. The lack of precipitation would also lead to drought persistence over the dry season, impacting both the longevity and intensity of drought since a previous week's drought status would likely persist into the following week.

Within the more humid climates east of the Rockies and in northeastern Hawaii, year-round precipitation reduces the opportunity for drought persistence since there is no dry season. However, when precipitation is suppressed, especially when combined with above normal temperatures, moisture deficits (i.e., precipitation and soil moisture) can quickly accumulate with respect to normal conditions, leading to rapid drought intensification and potential for flash droughts when combined with high rates of evaporative demand (Hobbins *et al.*, 2016; Otkin *et al.*, 2018; Basara *et al.*, 2019 and Otkin *et al.*, 2019). While there are subdued wet and dry seasonal cycles east of the Plains, there are important variations in the organization of (scattered versus widespread) precipitation events. For instance, convectively driven events such as sea breezes or pop-up showers that are most predominant during the warmth of summer and early fall can lead to localized precipitation that is still outpaced by evaporative demand from warmer temperatures and an active vegetation layer. In contrast, the more organized (usually spring and fall) precipitation events along frontal boundaries and tropical cyclones for much of the Southeast and Puerto Rico can bring about widespread drought-relieving precipitation. It should be noted here that Puerto Rico and coastal areas of the U.S. that are dependent on tropical moisture may see drought formation in years when tropical activity is suppressed (i.e., La Niña events) or if the placement of the subtropical high limits landfalling tropical cyclones. Overall, the combination of year-round precipitation leads to more frequent, shorter-lived drought events that can develop rapidly.

In Alaska, the climate varies from a temperate rainforest in the panhandle (Bathke *et al.*, 2019) to an arctic tundra in the northern and interior regions (mean annual precipitation between 115 and 270 mm; Arguez *et al.*, 2010). The contrast between the panhandle and arctic tundra is particularly evident in drought onset and termination, where droughts in the Alaska panhandle typically begin and end in the spring, prior to the summer dry season. In northern and interior regions, moisture conditions (i.e., deficits) over the summer wet season get frozen in place during the long, cold, dry winter season, so summer and fall are typically the seasons when drought both begins and ends. Despite these contrasts, it should be noted here that assessments of drought severity over Alaska, particularly in polar regions, are challenged by two factors. The first is associated with the difficulty of monitoring drought impacts over areas with low population density, little agriculture, and poor communication networks (i.e., no internet, lack of power), which has limited access to updated information regarding drought conditions on the ground in the past. The second involves the use of drought indices that were developed and verified primarily for use over mid-latitudes. In many ways, our understanding of how drought manifests and how to monitor evolving conditions in near-real-time over northern-latitude regions is still developing and will require extensive outreach to local communities, which is currently ongoing. In a similar way, the USDM dataset has shifted over time. The introduction of new drought indicators (i.e., Evaporative Stress Index [ESI]; Anderson *et al.*, 2011), Evaporative Demand Drought Index (EDDI; Hobbins *et al.*, 2016, etc.) and higher (spatial and temporal) resolution datasets, replacement of drought authors, and the addition of more impact reports and local expert inputs have led to USDM maps with more granular detail.

The USDM-based drought event climatology over the contiguous U.S. was found to both align and contrast with other historical drought analysis. The persistence of drought conditions over the Rocky Mountain States (i.e., Colorado, Wyoming, Utah, and Idaho) is similar to analyses of historical PDSI drought conditions noted in Diaz (1983), Heim (2017), Karl and Koscielny (1982) and Karl (1983); however, the USDM climatology also had areas of higher drought persistence extending further south and west of the Rockies, including New Mexico, Arizona, California, Nevada, and southern Oregon. There were also differences in the frequency of drought with the USDM climatology showing more frequent drought events over the eastern half of the U.S. in contrast to McCabe *et al.* (2017) who found less frequent droughts in this area. This was particularly noteworthy in the Southeast. These contrasts are likely associated with the inputs used to define and characterize U.S. droughts and how these were evaluated. For instance, a drought climatology based on modelled runoff variations was found to have a strong dependence on precipitation events. Even short-lived precipitation can temporarily increase runoff percentiles substantially, breaking drought conditions more often than would be assessed using other measures that change more slowly (Andreadis *et al.*, 2005).

The contrasts in spatial and temporal resolution and thresholds used to define drought events between the USDM (1 week less than −0.7 standard deviations) and other measures (PDSI-1 standard deviation, streamflow and runoff less than the 20th percentiles) are not insignificant, nor are the differences in the period of records these studies were based upon. For instance, the more recent USDM drought analysis includes the 19-year period from 2000 to 2018, which was found to be one of the most significant drought periods in the western U.S. over the last 1200 years (Williams *et al.*, 2020) due in part to anthropogenic climate change. These factors combined likely explain differences in drought climatologies between the more recent contiguous U.S. USDM results presented here and those evaluated previously. The contribution of climatic change to variations in precipitation, temperature, and evaporative demand among others highlight the importance of more recent drought climatologies and provides an impetus for continuously updating these statistics in support of planning and mitigation efforts. An additional factor influencing USDM results are drought impacts, based on discussions and feedback from hundreds of local experts, that cannot be captured by physically based indices. While it is challenging to determine how these impact reports may result in differences between the USDM and other drought climatologies, their inclusion results in one of the most comprehensive perspectives of drought conditions.

While the USDM period of record precludes some of the most severe drought episodes (based on measures of PDSI) over the early to mid-1900s (i.e., 1930s Dust Bowl and 1950s droughts; Heim, 2017), it does capture more recent severe drought episodes such as the 2010–2011 Southwest/Texas drought (Nielsen-Gammon, 2011), the 2012 drought over the central U.S. (Hoerling *et al.*, 2014), and the long-lived 2013–2015 California drought (Mann and Gleick, 2015). These more recent events may provide more relevant insight to drought mitigation and planning efforts than historical "droughts of record" that occurred in a different era of land-use management and other policies and regulations that alters a society's vulnerability to drought. Referring to more recent droughts, particularly ones that were characterized by a more comprehensive index such as the USDM, to develop mitigation and resilience strategies would better inform the planning process (Wilhite, 2000). Improved understanding of the spatial and temporal aspects of drought, as well as how drought severity evolves during an event, can inform how drought is monitored and who needs to be alerted in the drought response process (and at what stage). Furthermore, documenting the frequency and severity of recent drought events may help planners justify the need for funding to develop, update, and evaluate current mitigation and resilience strategies and plans going forward.

The impact of drought on society is a growing area of research that also stands to benefit from a historical documentation of the frequency, timing, and intensity of recent drought events from a common framework (Liu *et al.*, 2020). For instance, linking the USDM-based drought events with reported drought outcomes (i.e., drought impact reporter and others) similar to methods applied in Europe (Stagge *et al.*, 2015; Bachmair *et al.*, 2016) would allow for direct comparisons of drought events that were more impactful for a specific outcome (i.e., hospitalization, agricultural yields, wildfires) and location. This permits decision makers and researchers to explore the relative importance of timing, severity, duration, rates of intensification, and potentially other factors that distinguish impactful drought events from others. This is particularly true if USDM events are combined with other indicators of drought (i.e., SPI, SPEI, PDSI, and others) that can provide additional insight on how moisture deficits propagate differently across the hydrological cycle between separate drought events.

In this study, the USDM 20-year record was used to evaluate one of the first composite based drought climatologies that combines drought indicators and regional impact assessments across the U.S., including Alaska, Hawaii, and Puerto Rico. The climatology, as presented in this paper, illustrates important regional differences in drought frequency, duration, intensity, timing, and rapidity of status changes that are informative to academic, decision makers (disaster declarations), and governmental assistance programs (i.e., Livestock Forage Disaster Program, Noninsured Crop Disaster Assistance Program, and other emergency related loan programs) that rely upon the weekly USDM maps. The authors intend for this climatological assessment of the historical USDM record to provide additional insight on drought evolution (i.e., timing, rate of intensification and amelioration) to inform evaluations of current drought mitigation strategies and federal aid programs as well as the development of future strategies for drought resilience.

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AUTHOR CONTRIBUTIONS

Ronald Leeper: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; supervision; validation; visualization; writing – original draft; writing – review & editing. **Rocky Bilotta:** Data curation; software; visualization. **Bryan Petersen:** Formal analysis; investigation. **Crystal J. Stiles:** Writing – original draft; writing – review and editing. **Richard Heim:** Methodology; validation; writing – original draft; writing – review and editing. **Brian Fuchs:** Methodology; validation; writing – original draft; writing – review and editing. **Olivier P. Prat:** Writing – original draft. **Michael Palecki:** Validation; writing – original draft; writing – review and editing. **Steve Ansari:** Writing – original draft.

DATA AVAILABILITY STATEMENT

The drought status conditions that were gridded and used to define drought events were obtained from the National Drought Mitigation Center at the University of Nebraska, Lincoln, NE, (https://droughtmonitor.unl.edu/Data/GISData.aspx) as described by Svoboda *et al.* (2002). The gridded precipitation dataset from nClimGrid is publicly available at https://www.ncei.noaa.gov/pub/data/daily-grids/with more information regarding the dataset available from Vose *et al.* (2014).

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REFERENCES

Anderson, M.C., Hain, C.R., Wardlow, B., Mecikalski, J.R. and Kustas, W.P. (2011) Evaluation of drought indices based on thermal remote sensing of evapotranspiration over the continental U.S. *Journal of Climate*, 24, 2025–2044. https://doi.org/10.1175/2010JCLI3812.1.

Andreadis, K.M., Clark, E.A., Wood, A.W., Hamlet, A.F. and Lettenmaier, D.P. (2005) Twentieth-century drought in the conterminous United States. *Journal of Hydrometeorology*, 6, 985–1001. https://doi.org/10.1175/JHM450.1.

Arguez, A., I. Durre, S. Applequist, M. Squires, R. Vose, X. Yin, and R. Bilotta, 2010: NOAA's U.S. Climate Normals (1981-2010). Global Historical Climatology Network. NOAA National Centers for Environmental Information. https://doi.org/10.7289/V5PN93JP, January 2021.

Askarimarnani, S.S., Kiem, A.S. and Twomey, C.R. (2020) Comparing the performance of drought indicators in Australia from 1900 to 2018. *International Journal of Climatology*, 41, E912–E934. https://doi.org/10.1002/joc.6737.

Asong, Z.E., Wheater, H.S., Bonsal, B., Razavi, S. and Kurkute, S. (2018) Historical drought patterns over Canada and their teleconnections with large-scale climate signals. *Hydrology and Earth System Sciences*, 22, 3105–3124. https://doi.org/10.5194/hess-22-3105-2018.

Bachmair, S., Svensson, C., Hannaford, J., Barker, L.J. and Stahl, K. (2016) A quantitative analysis to objectively appraise drought indicators and model drought impacts. *Hydrology and Earth System Sciences*, 20, 2589–2609. https://doi.org/10.5194/hess-20-2589-2016.

Barker, L.J., Hannaford, J., Parry, S., Smith, K.A., Tanguy, M. and Prudhomme, C. (2019) Historic hydrological droughts 1891–2015: systematic characterisation for a diverse set of catchments across the UK. *Hydrology and Earth System Sciences*, 23, 4583–4602. https://doi.org/10.5194/hess-23-4583-2019.

Basara, J.B., Christian, J.I., Wakefield, R.A., Otkin, J.A., Hunt, E.H. and Brown, D.P. (2019) The evolution, propagation, and spread of flash drought in the Central United States during 2012. *Environmental Research Letters*, 14, 1–9. https://doi.org/10.1088/1748-9326/ab2cc0.

Bathke, D.J., Prendeville, H.R., Jacobs, A., Heim, R., Thoman, R. and Fuchs, B. (2019) Defining drought in a temperate rainforest. *Bulletin of the American Meteorological Society*, 100, 2665–2668. https://doi.org/10.1175/BAMS-D-19-0223.1.

Caillouet, L., Vidal, J.-P., Sauquet, E., Devers, A. and Graff, B. (2017) Ensemble reconstruction of spatio-temporal extreme low-flow events in France since 1871. *Hydrology and Earth System Sciences*, 21, 2923–2951. https://doi.org/10.5194/hess-21-2923-2017.

Chen, L.G., Gottschalck, J., Hartman, A., Miskus, D., Tinker, R. and Artusa, A. (2019) Flash drought characteristics based on U.S. drought monitor. *Atmosphere*, 10, 1–15. https://doi.org/10.3390/atmos10090498.

Diaz, H.F. (1983) Some aspects of major dry and wet periods in the contiguous United States, 1895-1981. *Journal of Climate and Applied Meteorology*, 22, 3–16.

Heim, R.R. (2002) A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society*, 83, 1149–1166. https://doi.org/10.1175/1520-0477-83.8.1149.

Heim, R.R., Jr. (2017) A comparison of the early twenty-first century drought in the United States to the 1930s and 1950s drought episodes. *Bulletin of the American Meteorological Society*, 98, 2579–2592. https://doi.org/10.1175/BAMS-D-16-0080.1.

Hobbins, M.T., Wood, A., McVoy, D.J., Hurtington, J.L., Morton, C., Anderson, M. and Hain, C. (2016) The evaporative demand drought index. Part I: linking drought evolution to variations in evaporative demand. *Journal of Hydrometeorology*, 17, 1745–1761. https://doi.org/10.1175/JHM-D-15-0121.1.

Hoerling, M., Eischeid, J., Kumar, A., Leung, R., Mariotti, A., Mo, K., Schubert, S. and Seager, R. (2014) Causes and predictability of the 2012 Great Plains drought. *Bulletin of the American Meteorological Society*, 95, 269–282. https://doi.org/10.1175/BAMS-D-13-00055.1.

Hurrell, J.W. and Van Loon, H. (1997) Decadal variations in climate associated with the North Atlantic oscillation. *Climate Change*, 36, 301–326. https://doi.org/10.1023/A:1005314315270.

Karl, T.R. and Koscielny, A.J. (1982) Drought in the United States: 1895–1981. *Journal of Climatology*, 2, 313–329. https://doi.org/10.1002/joc.3370020402.

Karl, T. R. (1983) Some spatial characteristics of drought duration in the United States. *Journal of Applied Meteorology and Climatology*, 22, 1356–1366.

Leeper, R.D., Petersen, B., Palecki, M.A. and Diamond, H. (2021) Exploring the use of standardized soil moisture as a drought indicator. *Journal of Applied Meteorology and Climatology*, 60, 1021–1033. https://doi.org/10.1175/JAMC-D-20-0275.1.

Littell, J.S., Peterson, D.L., Riley, K.L., Lui, Y. and Luce, C.H. (2016) A review of the relationships between drought and forest fire in the United States. *Global Change Biology*, 22, 2353–2369. https://doi.org/10.1111/gcb.13275.

Liu, T., Helm Smith, K., Krop, R., Haigh, T. and Svoboda, M. (2020) Critical analysis of the value of drought information and impacts on land management and public health. *Water*, 12, 1064. https://doi.org/10.3390/w12041064.

Mann, M.E. and Gleick, p.H. (2015) Climate change and California drought in the 21st century. *Proceedings of the National Academy of Sciences of the United States of America*, 112, 3858–3859. https://doi.org/10.1073/pnas.1503667112.

McCabe, G. I., D. M. Wolock, and S. H. Austin, 2017: Variability of runoff-based drought conditions in the conterminous United States. *International Journal of Climatology*, 37, 1014–1021.

McKee, T.R., Doesken, N.J. and Kleist, J. (1993) The relationship of drought frequency and duration to time scales. Preprints, Eighth Conference on applied climatology, Anaheim, California. *American Meteorological Society*, 179–184.

Menne, M.J., Durre, I., Vose, R.S., Gleason, B.E. and Houston, T.G. (2012) An overview of the global historical climatology network-daily database. *Journal of Atmospheric and Oceanic Technology*, 29, 897–910. https://doi.org/10.1175/JTECH-D-11-00103.1.

Mishra, A.K. and Singh, V.P. (2010) A review of drought concepts. *Journal of Hydrology*, 391, 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012.

Nielsen-Gammon, J. W., 2011: The 2011 Texas Drought: a Briefing Packet for the Texas Legislature. Office of the Texas State Climatologist, College of Geosciences, Texas A&M University Report, 43 pp, http://oaktrust.library.tamu.edu/handle/1969.1/158245

NOAA National Centers for Environmental Information (NCEI), 2021: U.S. Billion-Dollar Weather and Climate Disasters. https://www.ncdc.noaa.gov/billions/ https://doi.org/10.25921/stkw-7w73

Noone, S., Broderick, C., Duffy, C., Matthews, T., Wilby, R. and Murphy, C. (2017) A 250-year drought catalogue for the island of Ireland (1765–2015). *Int. J. Climatol*, 37, 239–254. https://doi.org/10.1002/joc.4999

Otkin, J.A., Svoboda, M., Hunt, E.D., Ford, T.W., Anderson, M.C., Hain, C. and Basara, J.B. (2018) Flash droughts: a review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bulletin of the American Meteorological Society*, 99, 911–919. https://doi.org/10.1175/BAMS-D-17-0149.1.

Otkin, J.A., Zhong, Y., Hunt, E.D., Basara, J., Svoboda, M., Anderson, M. C. and Hain, C. (2019) Assessing the evolution of soil moisture and vegetation conditions during a flash drought–flash recovery sequence over the south-Central United States. *Journal of Hydrometeorology*, 20, 549–562. https://doi.org/10.1175/JHM-D-18-0171.1.

Palmer, W. C., 1965: Meteorological drought. U.S. Weather Bureau Research Paper 45, 58 pp.

Ropelewski, C.F. and Halpert, M.S. (1987) Global and regional scale precipitation patterns associated with El Niño/southern oscillation. *Monthly Weather Review*, 115, 1606–1626. https://doi.org/10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2.

Riebsame, W.E., Changnon, S.A. and Karl, T.R. (1991) *Drought and natural resource management in the United States: impacts and implications of the 1987–1989 Drought*. Boulder, CO: Westview Press.

Smith, K.H., Stiles, C.J., Hayes, M.J. and Carparelli, C.J. (2016) Support for drought response and community preparedness: filling the gaps between plans and action. In: Miller, K.A., Hamlet, F. A., Kenney, D. S., Redmond, K. T. (Eds.) *Water Policy and Planning in a Variable and Changing Climate*. Boca Raton, FL: CRC Press, pp. 123–139.

Spinoni, J., Naumann, G., Vogt, J.V. and Barbosa, P. (2015) The biggest drought events in Europe from 1950 to 2012. *Journal of Hydrology*, 3, 509–524. https://doi.org/10.1016/j.ejrh.2015.01.001.

Stagge, J.H., Kohn, I., Tallaksen, L.M. and Stahl, K. (2015) Modeling drought impact occurrence based on meteorological drought indices in Europe. *Journal of Hydrology*, 530, 37–50. https://doi.org/10.1016/j.jhydrol.2015.09.039.

Steinemann, A.C. and Cavalcanti, F.N. (2006) Developing multiple indicators and triggers and drought plans. *Journal of Water Resources Planning and Management*, 132, 164–174. doi:10.1061/(ASCE)0733-9496

Sugg, M., Runkle, J., Leeper, R., Bagli, H., Golden, A., Handwerger, L. H., Magee, T., Moreno, C., Reed-Kelly, R., Taylor, M. and Woolard, S. (2020) A scoping review of drought impacts on health and society in North America. *Climatic Change*, 162, 1177–1195. https://doi.org/10.1007/s10584-020-02848-6.

Svoboda, M., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., Rippey, B., Tinker, R., Palecki, M., Stooksbury, D., Miskus, D. and Stephens, S. (2002) The drought monitor. *Bulletin of the American Meteorological Society*, 83, 1181–1190. https://doi.org/10.1175/1520-0477-83.8.1181.

Tsakiris, G. and Vangelis, H. (2005) Establishing a drought index incorporating evapotranspiration. *European Water*, 9(10), 3–11.

Vicente-Serrano, S.M., Beguería, S. and López-Moreno, J.I. (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *Journal of Climate*, 23, 1696–1718. https://doi.org/10.1175/2009JCLI2909.1.

Vose, R.S., Applequist, S., Squires, M., Durre, I., Menne, M.J., Williams, C.N., Jr., Fenimore, C., Gleason, K. and Arndt, D. (2014) Improved historical temperature and precipitation time series for US climate divisions. *Journal of Applied Meteorology and Climatology*, 53, 1232–1251. https://doi.org/10.1175/JAMC-D-13-0248.1.

Wilhite, D.A. (2000) Drought as a natural hazard. In: Wilhite, D.A. (Ed.) *Drought: a global assessment*, Vol. 1. London, UK: Routledge, pp. 3–18.

Williams, A.P., Cook, E.R., Smerdon, J.E., Cook, B.I., Abatzoglou, J. T., Bolles, K., Baek, S.H., Badger, A.M. and Livneh, B. (2020) Large contribution from anthropogenic warming to an emerging north American megadrought. *Science*, 368, 314–318. https://doi.org/10.1126/science.aaz9600.

Zargar, A., Rehan, S., Bahman, N. and Faisal, I.K. (2011) A review of drought indices. *Environmental Reviews*, 19, 333–349. https://doi.org/10.1139/A11-013.

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