Increasing importance of temperature as a contributor to the spatial extent of streamflow drought

Article *in* Environmental Research Letters · December 2020

DOI: 10.1088/1748-9326/abd2f0

Manuela Irene Brunner
National Center for Atmospheric Research

Daniel L. Swain
University of California, Los Angeles

A. W. Wood
National Center for Atmospheric Research

Increasing importance of temperature as a contributor to the spatial extent of streamflow drought

Manuela I. Brunner[1], Daniel L. Swain[2,3,4], Eric Gilleland[1], and Andrew W. Wood [1,5]

[1] Research Applications Laboratory, National Center for Atmospheric Research, Boulder CO, USA
[2] Institute of the Environment and Sustainability, University of California, Los Angeles, CA, USA
[3] Capacity Center for Climate and Weather Extremes, National Center for Atmospheric Research, Boulder, CO, USA
[4] The Nature Conservancy of California, San Francisco, CA, USA
[5] Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO, USA

E-mail: manuela.i.brunner@gmail.com

August 2020

Abstract. Widespread streamflow droughts can pose substantially greater societal challenges than spatially less extensive events because of the complex realities of trans-regional water management. In a warming climate, drought spatial extent may change along with changes in underlying hydro-meteorological contributors. Here, we assess changes in streamflow drought spatial extent over the period 1981–2018 across the conterminous United States, and how the importance of potential hydro-meteorological contributors has changed over time. We first derive a monthly time series of drought spatial extent and look at trends in streamflow drought spatial extent. We then determine the spatial percentage 'overlap' of precipitation droughts, temperature anomalies, snow-water-equivalent deficits, and soil moisture deficits with the area under streamflow drought to look at the changing influence of these contributors on spatial extent. Our results show that (1) the spatial extent of droughts has increased, mainly because of increases in the extent of small droughts; (2) streamflow drought extents overall substantially overlap with soil moisture deficits and the relationship of drought to precipitation and temperature anomalies vary seasonally; and (3) the importance of temperature as a contributor to drought extent has increased over time. We therefore conclude that continued global warming may further increase drought extents, requiring adaptation of regional drought management strategies.

Keywords: drought, spatial extent, drivers, climate change, United States, snow-water-equivalent, precipitation, extremes, soil moisture

1. Introduction

Droughts often affect larger geographic regions than do most other types of hydro-meteorological extremes, and subsequently can have potentially severe impacts on water supply, agriculture, hydropower production, and ecosystems (e.g. Seager et al., 2009). Over the last two decades, several notable widespread drought events have occurred in the United States (US) – including the California (2012–2016; Diffenbaugh et al., 2015; Luo et al., 2017), Colorado River basin (2000–2014; Udall and Overpeck, 2017) and Missouri River basin droughts (2000–2010; Martin et al., 2020; Woodhouse and Wise, 2020). While not all of these events were historically unprecedented from a precipitation perspective (Andreadis et al., 2005; Woodhouse et al., 2009; Hanel et al., 2018; Williams et al., 2020a), their co-occurrence with anomalously warm and, in some cases, record-breaking temperatures (Weiss et al., 2009; Luo et al., 2017; Udall and Overpeck, 2017; Hanel et al., 2018; Martin et al., 2020; Woodhouse and Wise, 2020) produced impacts that were indeed extraordinary in a historical context (Diffenbaugh et al., 2015; Martin et al., 2020).

Drought events with large spatial extents particularly challenge existing water management strategies because they can make drought-alleviating, regional water transfers from upstream or adjacent basins impossible (Patterson et al., 2013). Subsequently, the societal impacts of large-scale droughts can be amplified, since many drought mitigation strategies are predicated on some degree of water availability in less severely affected adjacent regions. The importance of spatial extent as a drought characteristic has previously been acknowledged in frequency analysis through regional drought indices (Rossi et al., 1992), severity-area-frequency curves, (Henriques and Santos, 1999; Hisdal and Tallaksen, 2003), severity-area-duration curves (Andreadis et al., 2005; Sheffield et al., 2009), and stochastic models for spatial drought events (max-stable models; Oesting and Stein, 2018) but mostly in a time-stationary setting. Recently, however, changes in drought spatial extents have begun to receive greater attention. Newer studies have shown that drought extents have changed in the past and might further change in the future for a range of drought definitions, including meteorological (Ganguli and Ganguly, 2016; Sharma and Mujumdar, 2017), soil moisture (Sheffield and Wood, 2008; Lu et al., 2019), ecological (Crockett and Leroy Westerling, 2018), and hydrological (Rudd et al., 2019) – all of which may affect the societal and environmental risks associated with drought.

Changes in drought spatial extent may plausibly result from changes in underlying hydro-meteorological contributors, including precipitation and temperature. In addition to precipitation deficits, temperature is increasingly being recognized as an important contributor to soil moisture (Weiss et al., 2009; Diffenbaugh et al., 2015; Hari et al., 2020; Williams et al., 2020a) and streamflow drought severity (Woodhouse et al., 2016; Udall and Overpeck, 2017) because temperature directly influences snow water accumulation, snowmelt seasonality (Luo et al., 2017; Mote et al., 2018; Martin et al., 2020; Williams et al., 2020b), and evaporative demand (Dai et al., 2018). However, it remains largely unknown how these potential contributors besides drought magnitude also influence streamflow drought spatial extent.

The aim of this study is to better understand recent changes in streamflow drought spatial extent and their linkage to changes in hydro-meteorological contributors to drought. We ask (1) how streamflow drought spatial extent has changed over time, (2) which physical contributors govern drought spatial extent, (3) and whether/how the importance of these contributors has changed over time. Improving our understanding of how hydro-meteorological contributors influence streamflow drought extent and whether this influence changes over time is crucial in understanding potential future changes in drought spatial extents and assessing the overall risks associated with widespread drought events.

2. Methods

We analyze temporal changes in streamflow drought extents and their contributors over the period 1981–2018 using a dataset of 671 catchments with nearly natural flow conditions in the conterminous US (CONUS; Catchments Attributes and Meteorology for Large-sample Studies CAMELS; Newman et al., 2015; Addor et al., 2017) with a wide range of streamflow characteristics and regimes (Brunner et al., 2020). It would be desirable to work with a dataset extending further back in time, which would, however, come at the expense of spatial coverage. We first extract streamflow droughts at individual sites using a variable threshold-level approach suitable for regions with a seasonal streamflow regime (Van Loon and Laaha, 2015) (Figure 1A).

Second, we determine drought spatial extent at a monthly scale as the percentage of catchments affected by drought during a certain month (Figure 1B). Based on this drought spatial extent time series, we consider trends in drought spatial extent over time and define spatially large drought events as events affecting at least 20% of the catchments in the dataset. Third, we determine the spatial percentage 'overlap' of precipitation (P) droughts, temperature (T) anomalies, snow-water-equivalent (SWE) deficits, and soil moisture deficits (SM) with the area under streamflow drought for each month to explain important hydro-meteorological contributors to drought spatial extent (Figure 1C). In order to avoid confusing impacts of changes in hydro-meteorological contributors to drought extent with impacts of management changes, we focus the analysis on catchments with nearly natural flow conditions. The overlap time series for the four hydro-meteorological variables are finally used in a trend analysis to determine changes in the importance of different variables as contributors on drought spatial extent.

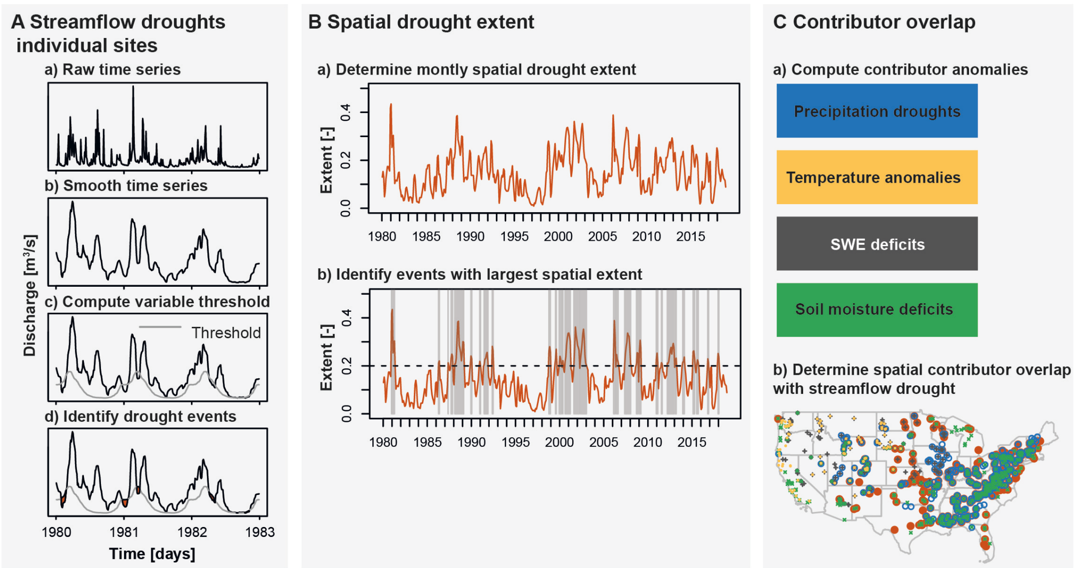

Figure 1. Illustration of working steps. (A) Identify streamflow droughts at individual sites using a threshold level approach by b) smoothing the a) raw time series, c) computing a variables threshold, and d) identifying below threshold events; (B) Compute drought spatial extent at a) a monthly resolution, and b) identify large spatial events with an extent $> 20\%$; (C) Compute overlap of potential contributors with drought spatial extent by a) computing precipitation, SWE, and soil moisture deficits, and temperature anomalies and by b) determining the percentage of stations affected by streamflow drought also affected by contributor deficits/anomalies.

2.1. Data

The daily streamflow time series were downloaded for the period 1981–2018 from the USGS website (`https://waterdata.usgs.gov/nwis`) using the R-package dataRetrieval (De Cicco et al., 2018). Areal precipitation (mm) and mean daily temperature (°C) for the same period were computed using the Daymet dataset which provides gridded, observation-based estimates of daily precipitation and temperature at a 1-km spatial resolution (Thornton et al., 2012). Snow-water-equivalents (SWE; mm) and soil moisture values (mm) for the period 1981–2014 were derived from a modeled data set by Newman et al. (2015) who used calibrated lumped implementations of the Snow–17 snow accumulation and ablation model and the Sacramento Soil Moisture Accounting model (SacSMA; Burnash et al., 1973) to derive a consistent set of hydro-meteorological variables.

2.2. Droughts at individual sites

Streamflow droughts at individual sites are extracted using a variable threshold-level approach suitable for regions with a seasonal streamflow regime (Van Loon and Laaha, 2015; Heudorfer and Stahl, 2017) at the 15th flow percentile (Figure 1A). The use of a variable instead of a fixed threshold leads to the identification of droughts defined as streamflow anomalies rather than low flows. Please note that such anomalies can also be detected in winter when streamflow anomalies may not have direct societal impacts. The daily time series is smoothed over a moving window of 30 days prior to event extraction to avoid identifying dependent events (Tallaksen and Hisdal, 1997; Van Loon and Laaha, 2015). The variable threshold is composed by the 15th flow percentile for each day of the year determined within a moving window of ± 15 days around the day of interest. We only include events with a minimum duration of 30 days to avoid the consideration of minor droughts. The drought extraction procedure results in a first quartile of 18, a median of 20, and a third quartile of 23 events identified per catchment. These events are spread across seasons as a result of using a variable threshold, which depends on flow seasonality.

2.3. Drought spatial extent

Drought spatial extent is determined at a monthly scale as the percentage of catchments affected by drought during a certain month (Figure 1B). Alternatively, spatial extent could be defined by area-weighting the affected catchments, which does, however, not change the main conclusions of this study. Based on this drought spatial extent time series, we define spatially large drought events as events affecting at least 20% of the catchments in the dataset. However, the drought-affected area does not necessarily need to be contiguous. The duration of these large events is determined as the time elapsing between the start of the event defined as the time of the rise of the extent time series above the threshold of 0.2 and the end of the event when the time series falls below that threshold again. The main date of occurrence is determined as the month with the largest drought extent. We rank the large spatial events according to their bivariate, joint probabilities in terms of event duration and extent determined by their empirical copula (the most severe event is assigned the highest rank; Deheuvels, 1979; Genest and Favre, 2007).

To evaluate changes in the monthly time series of drought spatial extent, we apply the non-parametric Mann–Kendall test (Mann, 1945). In addition, we compare the distributions of drought spatial extent for the two periods 1981–1999 and 2000–2018 for the three value ranges < 0.1, $0.1 - 0.2$ and > 0.2 using the two-sided Kolmogorov–Smirnov test (Smirnov, 1939).

2.4. Contributor overlap

To analyze the importance of different hydro-meteorological contributors to drought spatial extent, we introduce a *contributor overlap* measure defined as the percentage of catchments under hydrological drought simultaneously affected by precipitation drought, temperature anomaly, SWE deficit, or soil moisture deficit. The higher the overlap of a hydro-meteorological contributor with the area under hydrological drought, the more important is the contributor to explain drought spatial extent. An overlap of 1 (0) means that 100% (0%) of the stations under hydrological drought are affected by a deficit in the contributor considered. Precipitation (P) droughts are defined in the same way as streamflow droughts, using a variable threshold, and based on daily precipitation time series. Temperature (T) anomalies are determined as above threshold events using monthly temperature time series and a variable threshold at the 85% quantile. SWE and soil moisture (SM) deficits are similarly determined using a below-threshold approach on monthly SWE and soil moisture time series, respectively, with a variable threshold at the 15% quantile. In addition to pure overlap time series, we look at overlap ratios for T/P to assess how the relative importance of these two contributors changes. Denominators of zero were replaced by 0.001.

The contributor overlap measure is computed over the whole study domain (CONUS) to determine the overall importance of different hydro-meteorological contributors on drought spatial extent. In addition, it is computed for nine eco-regions with similar regional climatology (Bukovsky regions; Bukovsky, 2011) to identify regionally important contributors. Furthermore, we perform a correlation analysis of regional contributor overlap with physiographical and climatic catchment characteristics as provided by the CAMELS dataset (Addor et al., 2017) to identify catchment characteristics that might be related to the strength of contributor overlap. The following catchment characteristics are considered: latitude, longitude, catchment area, elevation, mean precipitation, mean potential evapotranspiration, aridity, snow fraction, mean discharge, baseflow index, runoff ratio, soil porosity, soil conductivity, sand fraction, silt fraction, porosity, permeability, and forest cover.

The overlap time series for the four hydro-meteorological variables are used in a trend analysis to determine changes in the importance of different variables as contributors to drought spatial extent. We use the non-parametric Mann–Kendall test (Mann, 1945) to compute p-values and the Sen's slope estimator to determine the direction of change (Sen, 1968). The results of the trend analysis are mapped per Bukovsky region.

2.5. Sensitivity analysis

We vary the drought threshold at individual sites ($t = 0.1, 0.15, 0.2$) and the areal percentage threshold when defining large spatial events ($p = 0.15, 0.2, 0.25, 0.3$) to investigate the sensitivity of threshold choices on the number of spatial events, event duration and spatial extent. The number of large spatial events extracted lies around 25 if a drought threshold at the 15% quantile or higher and an areal percentage threshold lower than 20% is chosen (SM Figure Appendix A.1). An increase in thresholds results in the selection of fewer events. Event duration and extent also depend on the thresholds chosen with extents hardly exceeding 0.5 even for low drought thresholds. A drought threshold at the 15% flow quantile and an areal percentage of 20% were chosen for the final analysis resulting in 30 spatially large drought events.

3. Results

3.1. Temporal changes in drought spatial extent

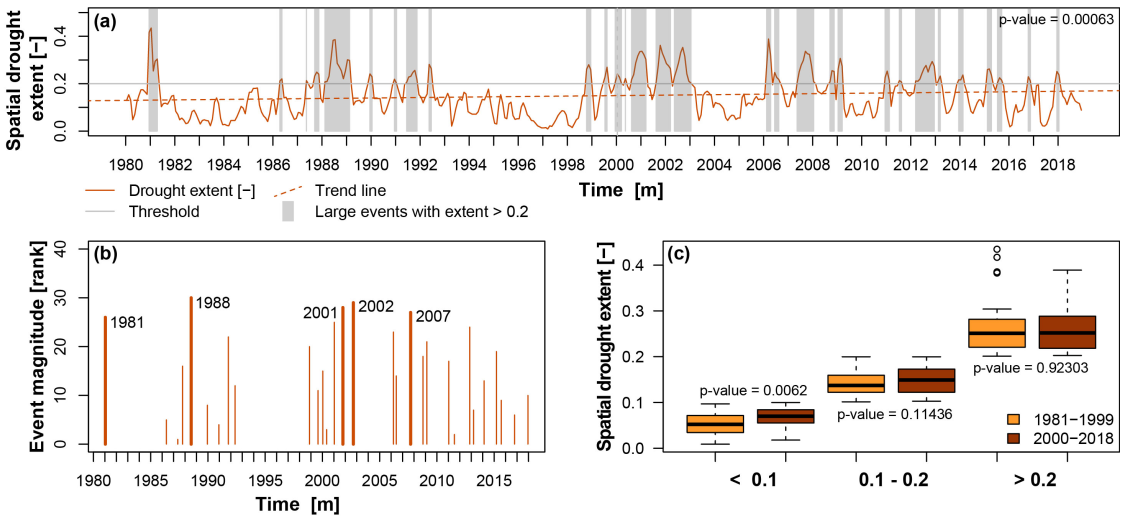

Figure 2. Temporal changes in drought spatial extent. (a) Percentage [-] of catchments affected by hydrological drought (extent) over time, large spatial events with an extent > 20%, and trend line of spatial extent. (b) Magnitude of large spatial events ranked according to bivariate distribution of event extent and duration (the higher the rank, the more extreme the event). (c) Comparison of spatial extents for the periods 1981–1999 and 2000–2018 for different extent ranges (< 0.1, 0.1 − 0.2, > 0.2) using boxplots. p-values were derived using the two-sided Kolmogorov–Smirnov test (H0: Distributions for two periods are equal).

At the monthly scale, drought spatial extent varies considerably over time ranging from near zero to a maximum of ∼40%, and shows a modest (∼1%/decade) but statistically significant (p-value = 0.00063) increasing trend (Figure 2A). This increase in spatial extent with time can mainly be attributed to increases in spatial extents at lower extent ranges (i.e., events with $< 10\%$ coverage; < 0.1; p-value $= 0.0062$), while the distributions at higher ranges do not show statistically significant changes ($0.1 - 0.2$ and > 0.2, p-values: 0.11436 and 0.92303) (Figure 2b). In other words: the extent of small spatial events is increasing, while there is little evidence for an increase in the extent of the most geographically extensive events. These changes were assessed by comparing events during the period 2000–2018 to 1981–1999.

Within the spatial extent time series, we identify 30 spatially large events (extent > 0.2) with durations of 1–13 months occurring throughout the year (Figure 2b). The large events generally appear to cluster in time with several large events occurring in the periods 1986–1992, 1998–2003, 2006–2009, and 2010–2018. We find the most severe of these spatial events in terms of extent and duration were the events in 1988 (start: 1988/02, end: 1989/02, duration: 13 months, max. extent: 0.386); 2002 (start: 2002/05, end: 2003/01, duration: 9 months, max. extent: 0.353), 2001 (start: 2001/08, end: 2002/03, duration: 8 months, max. extent: 0.362), 2007 (start: 2007/05, end: 2008/01, duration: 9 months, max. extent: 0.337), and 1981 (start: 1981/01, end: 1981/04, duration: 4 months, max. extent: 0.435). The 1988 event and the events in the early 2000s were also identified as spatially extensive in a model-based study by Andreadis et al. (2005).

3.2. Contributors of drought spatial extent

We now consider the importance of hydro-meteorological contributors in governing the strength of drought spatial extent. To do so, we introduce *contributor anomaly overlap* as a measure of association, which describes the percentage of catchments in streamflow drought simultaneously affected by a precipitation drought/deficit (P), positive temperature anomaly (T), snow-water-equivalent (SWE) or soil moisture deficit (SM). We define both the meteorological forcings (P and T) and modulating hydrologic storages (SM and SWE) as potential contributors to streamflow drought extent, while recognizing that variability in SM and SWE is driven by variability in P and T in advance of their impact on streamflow. We look at the covariation of each potential contributor with monthly spatial streamflow drought extent to assign temporally proximal driving roles to all four variables. If streamflow drought extent shows a high overlap within a specific month with SWE or SM deficits, we treat these as contributors to streamflow drought. These storage deficits may have been driven in turn by P deficits or above average T, which in our analysis would not be identified as contributors if that influence occurred prior to the month under consideration. By including storages as a distinct driving factor, we are able to highlight their role in modulating the spatial coherence of streamflow drought and to implicitly consider the lagged influence of the climatic contributors precipitation and temperature.

Figure 3 illustrates the overlap measure for the five largest events. The 1981 event mainly affected the eastern part of the US, a large part of which was simultaneously affected by precipitation drought and soil moisture deficit (Figure 3a). The 1988 event affected a similar region but warm temperature anomalies are more prominent than precipitation deficits (especially in the north; Figure 3b). In 2001, basins along the west coast and in the Rocky Mountains were jointly affected by streamflow drought with catchments along the east coast (Figure 3c). Precipitation deficits show high overlap in the east, while soil moisture deficits are more prominent in the Rocky Mountains and temperature anomalies are more prominent in the southwest. Temperature anomalies and soil moisture deficits were also important during the 2002 event, which affected the eastern US simultaneously with the Pacific Northwest and the Rocky Mountains (Figure 3d). Temperature anomalies were also important during the 2007 event, which affected mainly the eastern and southern portions of the US (Figure 3e).

Across all events, the importance of different hydro-meteorological variables as contributors to drought spatial extent varies substantially (Figure 3f). While a subset of events do appear to have one primary hydro-meteorological contributor (e.g. 1981: precipitation deficits), streamflow drought is more often associated with a range of underlying contributors that vary by region (e.g. 2002: warm temperature anomalies in the east and soil moisture deficits in the west). That the relative importance of different hydro-meteorological contributors varies on an event-by-event basis is consistent with earlier studies (e.g., for the Pacific Northwest in Bumbaco and Mote, 2010).

Soil moisture deficits are the single contributor with the highest mean explanatory power for drought extent (mean overlap ca. 50%) meaning that regions affected by streamflow drought are often simultaneously affected by soil moisture deficits. The direct importance of precipitation deficits and temperature anomalies, on the other hand, varies more widely across events with overlaps ranging from near zero to as high as 80%. The importance of temperature as a contributor during the month of streamflow drought occurrence varies on a seasonal basis, and is relatively low during the cool season (late autumn through early spring) but often quite high during the warm season (late spring through early autumn). The seasonal importance of temperature as a contributor to drought spatial extent corroborates earlier findings showing that temperature strongly influences other drought characteristics such as duration (Southwestern US; Woodhouse et al., 2009). SWE deficits have only limited explanatory power for drought spatial extent for the US as a whole but can be important regionally – particularly in the Rocky Mountains where snow water storage represents a large fraction of the water balance.

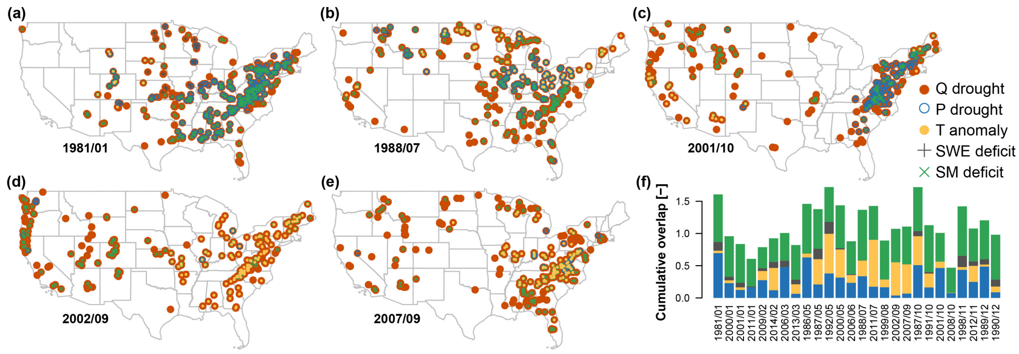

Figure 3. Importance of hydrometeorologic contributors for drought extent of large events. Maps of five spatially largest hydrological drought events: (a) Winter 1981, (b) summer 1988, (c) fall 2001, (d) fall 2002, and (e) fall 2007 and corresponding contributor deficits/anomalies. Blue circles indicate stations affected by meteorological (P) drought during the month of hydrological drought occurrence. Yellow points indicate the presence of temperature (T) anomalies while grey and green crosses indicate SWE and soil moisture (SM) deficits at the time of streamflow drought occurrence, respectively. (f) Contributor overlaps for all large spatial events (extent $> 20\%$) sorted by their month of occurrence (Jan–Dec).

The importance of individual hydro-meteorological variables for drought spatial extent not only varies by event but also by region as shown by our correlation analysis of regional contributor overlap with catchment characteristics (Figure Appendix A.2). Precipitation droughts are generally important contributors to streamflow drought extent in the eastern US, while they are less important in high-elevation regions with strong snow influences. Temperature is an important contributor in arid and non-forest catchments, while SWE is important at higher latitudes and more generally in places with higher snow fraction. Soil moisture deficits are especially important in lower-elevation regions and in the eastern US.

3.3. Changes in the importance of contributors to drought spatial extent

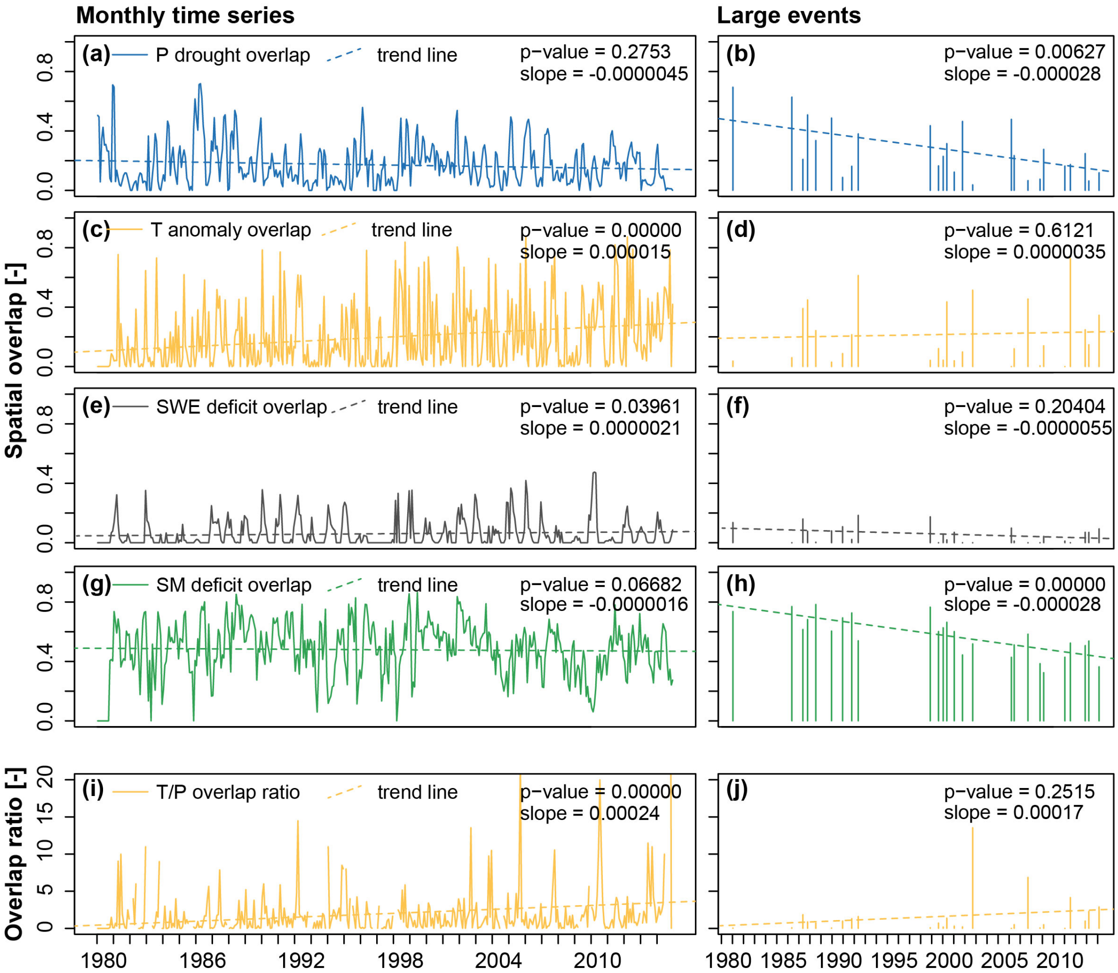

Figure 4. Temporal changes in hydro-meteorologic contributor overlap with spatial drought extent. Monthly spatial overlap of catchments affected by a streamflow drought (left panel) with catchments affected by (a) precipitation droughts, (c) temperature anomalies, (e) SWE deficits, and (g) soil moisture deficits and (i) monthly overlap ratios for T/P. Spatial overlap of catchments affected by a large streamflow drought event (extent $> 20\%$; right panel) with (b) precipitation droughts, (d) temperature anomalies, (f) SWE deficits, and (h) SM deficits and (j) overlap ratios for T/P. Linear trend lines are displayed. p-values for monotonic trends were derived using the Mann–Kendall test.

Over the full CONUS, the importance of precipitation as a contributor to drought spatial extent remains relatively stable over time for all events (Figure 4a, p-value: 0.2753) but decreases for the large events (Figure 4b, p-value: 0.00627). In contrast, temperature becomes more important across all events as a contributor to spatial extent (Figure 4c, p-value: 0.00000). However, this increase is weaker and not statistically significant for the large events alone because the really large events are driven by a combination of precipitation and temperature (Figure 4d, p-value: 0.6121). The strong increase in the relative importance of temperature, combined with the more weakly decreasing relative importance of precipitation, yields a large and statistically robust increase in the ratio of T to P influence (T/P) (Figures 4i, j; p-values: 0.00000, and 0.2515). The importance of both SWE and soil moisture remains relatively stable across all events (Figures 4e, g, p-values: 0.03961 and 0.06682) though it decreases for large events (Figures 4f, h, p-values: 0.0.20404 and 0.00000).

Trend analyses for the nine climatic regions reveal substantial regional differences in the monthly overlap time series for the different hydro-meteorologic contributors (Figure 5). Precipitation overlap decreases over most regions except the Great Plains (Figure 5a), while temperature overlap increases in most regions except for portions of the southeast (Figure 5b) – resulting in an overall increase of the importance of temperature relative to precipitation (increase in T/P overlap ratio in all regions except the Great Plains, Figure 5e). The increase of the importance of temperature relative to precipitation is especially pronounced across the inter-mountain west and Pacific Southwest but is also strong across the eastern US. Changes in SWE deficit overlap are mostly small except in the Pacific Northwest, where we note a substantial increase in SWE deficit overlap with drought spatial extent (Figure 5c). Finally, the importance of soil moisture as an explanatory variable for drought extent decreases in most regions, with the strongest decreases found across the eastern US (Figure 5d).

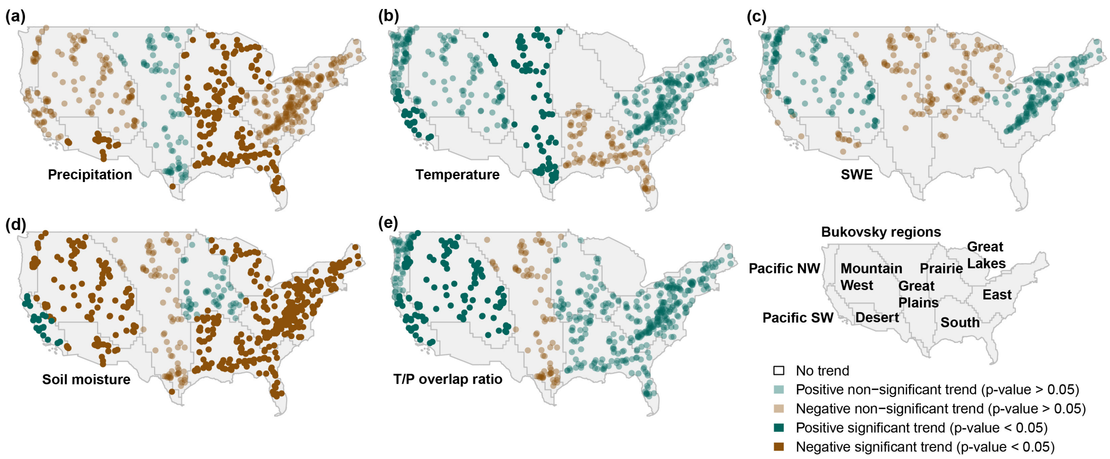

Figure 5. Regional trends in hydro-climatic contributor overlap with drought spatial extent. Trends in spatial drought overlap at a monthly scale for (a) precipitation, (b) temperature, (c) SWE (catchments with a mean annual SWE smaller than 1 mm were excluded), (d) soil moisture, (e) T/P overlap ratio determined for nine climatic regions (Bukovsky). p-values were derived using the non-parametric Mann-Kendall test. Significant trends (p-values < 0.05) are highlighted by saturated colors and non-significant trends (p-values > 0.05) indicated by dull colors, positive trends by turquoise colors, and negative trends by brown colors.

4. Discussion

The overall increase in streamflow drought extent corroborates increases in drought extent found for meteorological drought in India (Sharma and Mujumdar, 2017), although such regional analyses may be strongly affected by spatially heterogeneous trends in regional precipitation. This increase in drought spatial extent is reflected in increasing probabilities of catchments to be jointly affected by drought as determined by Patterson et al. (2013) for the South Atlantic region. Our findings mainly show increases in smaller drought extents and not the large events. However, the extent of these large events may change in future as Rudd et al. (2019) showed that streamflow droughts with the largest spatial extent in Great Britain are projected to further increase in extent towards the middle and end of the century. These findings have potentially major implications for regional water management strategies as well as for future studies on drought in a warming climate.

4.1. Water management implications of increasing drought extent

Increasing spatial extent of streamflow droughts – as we have identified in the present study in the US and has been previously identified in Great Britain (Rudd et al., 2019) – have substantial implications for their associated socioeconomic and environmental impacts. An increase in drought extent, for instance, implies increases in the probability that neighboring or upstream-downstream catchments co-experience drought (Patterson et al., 2013). Such an increase in regional drought hazard makes water management considerably more challenging. Inter-basin transfers (Gupta and van der Zaag, 2008) may no longer be an option, and water contributions from water-abundant upstream regions to dependent downstream regions may be reduced if upstream and downstream regions co-experience drought (Viviroli et al., 2020). For example, Southern California, home to roughly 25 million people, sources water originating in both the north and south Sierra mountain ranges, as well as from the upper Colorado River basin, a strategy which ideally hedges against the risk of co-varying droughts in all source regions (Record et al., 2016). A decrease in the possibility of such transfers and contributions may increase the severity of drought impacts and drought risk as potentially more people, ecosystems, and industries are affected. The simultaneous occurrence of drought in several basins and regions may therefore expose weaknesses in existing water management policies and increase the need for coordination among regions from both water supply and demand perspectives.

4.2. Implications of increasingly temperature-driven drought extent

High temperatures can intensify drought events and support their propagation from one to another region through land-atmospheric feedbacks (e.g. Miralles et al., 2019). Our findings show that the importance of temperature as a contributor to drought is not limited to soil moisture droughts (Ault, 2020; Williams et al., 2020a) but extends to the spatial extent of streamflow droughts particularly during the warm season (late spring through early autumn). The impact of temperature on drought and therefore drought extent is twofold: In winter, increased temperatures decrease snow accumulation, which can lead to time-lagged streamflow deficits later in the year (Bumbaco and Mote, 2010). In summer, high temperatures increase evaporative demand which can reduce streamflow directly through in-channel evaporation and indirectly through reduced soil moisture inputs (Dai et al., 2018; Luo et al., 2017).

The increasing importance of temperature as a contributor to drought spatial extent suggests that future temperature increases might not only lead to increases in soil moisture drought spatial extents (Sheffield and Wood, 2008; Lu et al., 2019; Dai, 2013) and streamflow drought frequencies (Strzepek et al., 2010) but related to these also to spatial streamflow drought extents. In relatively moist and cool regions such as the Pacific Northwest, where a lack of snowpack has historically been an important contributor to hydrological drought (Bumbaco and Mote, 2010), temperature may be especially influential. Indeed, a decrease in Pacific Northwest snowpack has already been observed as temperature has warmed over the past few decades (Mote et al., 2018). In more arid regions, such as the Great Plains and the interior Southwest, temperature affects drought extent primarily through an increase in evaporative demand (Vicente-Serrano et al., 2020). Here, too, a temperature driven climate change signal has already been identified in drought trends during the late 21st century (Cook et al., 2015; Martin et al., 2020). Indeed, temperature changes may be more directly translated into changes in drought spatial extent than precipitation changes as they are more spatially coherent (i.e., virtually the entire Earth is warming, but regional precipitation trends are far more heterogeneous; Wuebbles et al., 2014; Cook et al., 2020).

5. Conclusions

We conclude that: (1) Drought spatial extent over the United States (US) has increased over the period 1981–2018, mainly resulting from increases of events with a small spatial extent; (2) The importance of different hydro-meteorological contributors for drought spatial extent greatly varies across events and is strongest overall for soil moisture; (3) Temperature has become more important as a contributor to drought spatial extent over time, mainly at the expense of precipitation.

How future changes in different hydro-meteorological contributors will impact spatial streamflow drought extent still needs to be formally quantified using directed modeling. Such an approach might leverage the outcomes of widely available studies in which a hydrological model is driven by downscaled climate model output to simulate future streamflow time series. However, the use of such a modeling process is associated with several substantial uncertainties some of which remain difficult to account for using current methods. One key aspect of such modeling work is the need to incorporate not only key geophysical and ecohydrological processes, but also human interventions within watersheds including flood and water management infrastructure, legal and public policy considerations, and land use changes. However, such an assessment would require a modeling framework enabling a realistic representation of human activities and their impact on the water cycle, which remains challenging. Ultimately, it is clear that water management strategies will need to account for the increasingly temperature-driven nature of droughts, as well as their increased spatial extent, in a warming climate.

Acknowledgements

Funding: This work was supported by the Swiss National Science Foundation via a PostDoc.Mobility grant (Number: P400P2_183844, granted to MIB). DLS was supported by a joint collaboration between the Institute of the Environment and Sustainability at the University of California, Los Angeles; the Center for Climate and Weather Extremes at the National Center for Atmospheric Research; and the Nature Conservancy of California as well as NSF PREEVENTS award 1854940. Support for AW was provided by the Bureau of Reclamation (CA R16AC00039), the US Army Corps of Engineers (CSA 1254557), and the NASA Advanced Information Systems Technology program (award ID 80NSSC17K0541).

Author contributions: MIB developed the study concept in discussions with all co-authors. MIB performed the analyses, produced the figures, and wrote the first draft of the manuscript. DLS provided input on data interpretation and the climate context of the results. AW provided input on the framing of the contributor concepts. All co-authors revised and edited the manuscript.

Competing interests: The authors have no competing interests.

Data and materials availability: The daily discharge time series used in this study are available via the USGS website: `https://waterdata.usgs.gov/nwis`. The gridded precipitation and temperature time series can be downloaded via the Daymet website: `http://daymet.ornl.gov/`. The simulated SWE and soil moisture time series and the CAMELS catchment attributes can be downloaded via `https://ral.ucar.edu/solutions/products/camels`. The data that support the findings of this study are available upon reasonable request from the authors.

Appendix A. Supplementary material

Appendix A.1. Sensitivity analysis for large spatial events with respect to threshold choices

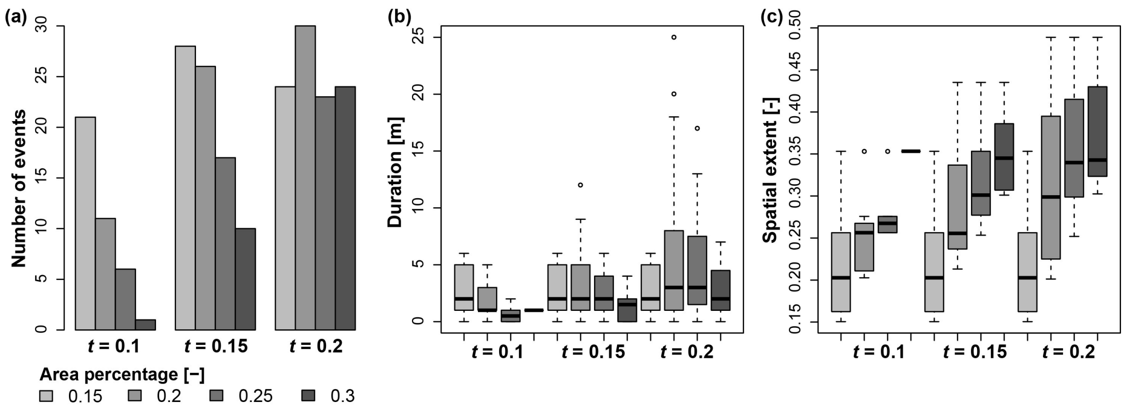

Figure Appendix A.1. Sensitivity analysis for large spatial events with respect to threshold choices. Threshold effect on (A) number of events, (B) event duration, and (C) spatial extent.

Appendix A.2. Correlation of hydro-climatic contributor overlap for the nine climatic regions with catchment characteristics from the CAMELS dataset

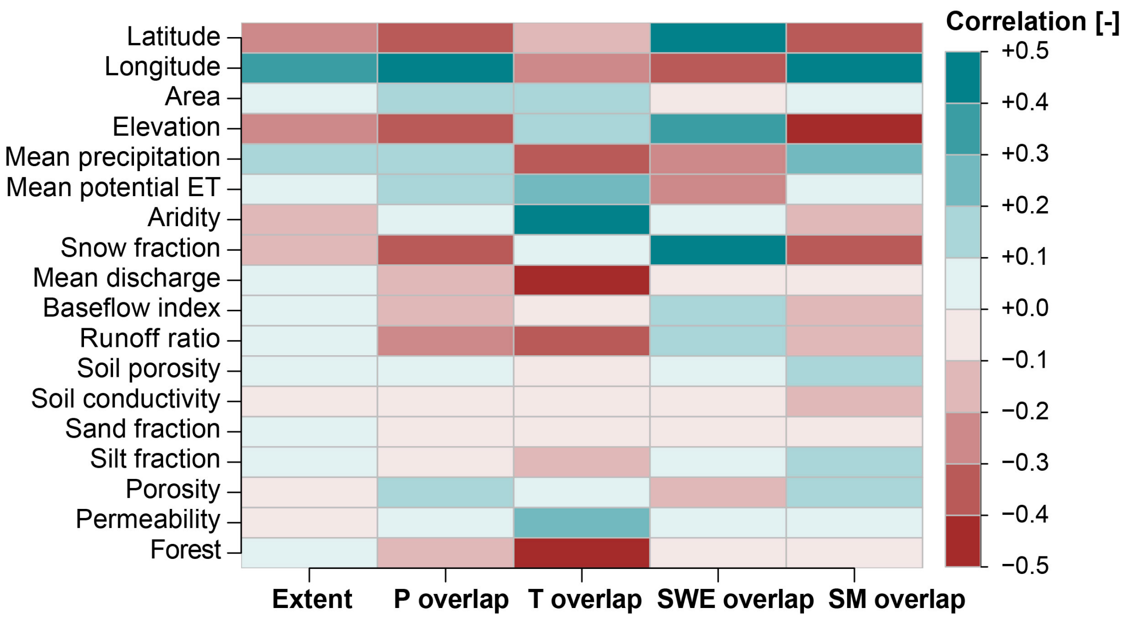

Figure Appendix A.2. Correlation of hydro-climatic contributor overlap for the nine climatic regions with catchment characteristics from the CAMELS dataset. Turquoise and red colors indicate positive and negative correlations, respectively.

References

Addor, N., Newman, A. J., Mizukami, N., and Clark, M. P.: The CAMELS data set: Catchment attributes and meteorology for large-sample studies, Hydrology and Earth System Sciences, 21, 5293–5313, https://doi.org/10.5194/hess-21-5293-2017, 2017.

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

Ault, T. R.: On the essentials of drought in a changing climate, Science, 368, 256–260, https://doi.org/10.1126/science.aaz5492, 2020.

Brunner, M. I., Newman, A., Melsen, L. A., and Wood, A.: Future streamflow regime changes in the United States: assessment using functional classification, Hydrology and Earth System Sciences, 24, 3951–3966, https://doi.org/10.5194/hess-24-3951-2020, 2020.

Bukovsky, M. S.: Masks for the Bukovsky regionalization of North America, URL `http://www.narccap.ucar.edu/contrib/bukovsky/`, 2011.

Bumbaco, K. A. and Mote, P. W.: Three recent flavors of drought in the Pacific Northwest, Journal of Applied Meteorology and Climatology, 49, 2058–2068, https://doi.org/10.1175/2010JAMC2423.1, 2010.

Burnash, R. J. C., Ferral, R. L., and McGuire, R. A.: A generalized streamflow simulation system. Conceptual modeling for digital computers, Tech. rep., Joint Federal-State River Forecast Center, Sacramento, 1973.

Cook, B. I., Ault, T. R., and Smerdon, J. E.: Unprecedented 21st century drought risk in the American Southwest and Central Plains, Science Advances, 1, 1–7, https://doi.org/10.1126/sciadv.1400082, 2015.

Cook, B. I., Mankin, J. S., Marvel, K., Williams, A. P., Smerdon, J. E., and Anchukaitis, K. J.: Twenty-first century drought projections in the CMIP6 forcing scenarios, Earth's Future, 8, 1–18, https://doi.org/10.1029/2019ef001461, 2020.

Crockett, J. L. and Leroy Westerling, A.: Greater temperature and precipitation extremes intensify Western U.S. droughts, wildfire severity, and sierra Nevada tree mortality, Journal of Climate, 31, 341–354, https://doi.org/10.1175/JCLI-D-17-0254.1, 2018.

Dai, A.: Increasing drought under global warming in observations and models, Nature Climate Change, 3, 52–58, https://doi.org/10.1038/nclimate1633, 2013.

Dai, A., Zhao, T., and Chen, J.: Climate change and drought: a precipitation and evaporation perspective, Current Climate Change Reports, 4, 301–312, https://doi.org/10.1007/s40641-018-0101-6, 2018.

De Cicco, L. A., Lorenz, D., Hirsch, R. M., and Watkins, W.: dataRetrieval: R packages for discovering and retrieving water data available from U.S. federal hydrologic web services, https://doi.org/10.5066/P9X4L3GE, URL https://code.usgs.gov/water/dataRetrieval, 2018.

Deheuvels, P.: La fonction de dépendance empirique et ses propriétés. Un test non paramétrique d'indépendance, Bulletin de la Classe des sciences, 65, 274–292, https://doi.org/10.3406/barb.1979.58521, 1979.

Diffenbaugh, N. S., Swain, D. L., Touma, D., and Lubchenco, J.: Anthropogenic warming has increased drought risk in California, Proceedings of the National Academy of Sciences of the United States of America, 112, 3931–3936, https://doi.org/10.1073/pnas.1422385112, 2015.

Ganguli, P. and Ganguly, A. R.: Space-time trends in U.S. meteorological droughts, Journal of Hydrology : Regional Studies, 8, 235–259, https://doi.org/10.1016/j.ejrh.2016.09.004, 2016.

Genest, C. and Favre, A.-C.: Everything you always wanted to know about copula modeling but were afraid to ask, Journal of Hydrologic Engineering, 12, 347–367, https://doi.org/10.1061/(ASCE)1084-0699(2007)12:4(347), 2007.

Gupta, J. and van der Zaag, P.: Interbasin water transfers and integrated water resources management: Where engineering, science and politics interlock, Physics and Chemistry of the Earth, 33, 28–40, https://doi.org/10.1016/j.pce.2007.04.003, 2008.

Hanel, M., Rakovec, O., Markonis, Y., Máca, P., Samaniego, L., Kyselý, J., and Kumar, R.: Revisiting the recent European droughts from a long-term perspective, Scientific Reports, 8, 1–11, https://doi.org/10.1038/s41598-018-27464-4, 2018.

Hari, V., Rakovec, O., Markonis, Y., Hanel, M., and Kumar, R.: Increased future occurrences of the exceptional 2018–2019 Central European drought under global warming, Scientific Reports, 10, 1–10, https://doi.org/10.1038/s41598-020-68872-9, URL https://doi.org/10.1038/s41598-020-68872-9, 2020.

Henriques, A. G. and Santos, M. J. J.: Regional drought distribution model, Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, 24, 19–22, https://doi.org/10.1016/S1464-1909(98)00005-7, 1999.

Heudorfer, B. and Stahl, K.: Comparison of different threshold level methods for drought propagation analysis in Germany, Hydrology Research, 48, 1311–1326, https://doi.org/10.2166/nh.2016.258, 2017.

Hisdal, H. and Tallaksen, L. M.: Estimation of regional meteorological and hydrological drought characteristics: A case study for Denmark, Journal of Hydrology, 281, 230–247, https://doi.org/10.1016/S0022-1694(03)00233-6, 2003.

Lu, J., Carbone, G. J., and Grego, J. M.: Uncertainty and hotspots in 21st century projections of agricultural drought from CMIP5 models, Scientific Reports, 9, 1–12, https://doi.org/10.1038/s41598-019-41196-z, 2019.

Luo, L., Apps, D., Arcand, S., Xu, H., Pan, M., and Hoerling, M.: Contribution of temperature and precipitation anomalies to the California drought during

2012–2015, Geophysical Research Letters, 44, 3184–3192, https://doi.org/10.1002/2016GL072027, 2017.

Mann, H. B.: Nonparametric tests against trend, Econometrica, 13, 245–259, 1945.

Martin, J. T., Pederson, G. T., Woodhouse, C. A., Cook, E. R., McCabe, G. J., Wise, E. K., Erger, P., Dolan, L., McGuire, M., Gangopadhyay, S., Chase, K. J., Littell, J. S., Gray, S. T., St. George, S., Friedman, J. M., Sauchyn, D., Jacques, S., and King, J. C.: Increased drought severity tracks warming in the United States' largest river basin, Proceedings of the National Academy of Sciences, pp. 1–9, https://doi.org/10.1073/pnas.1916208117, 2020.

Miralles, D. G., Gentine, P., Seneviratne, S. I., and Teuling, A. J.: Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges, Annals of the New York Academy of Sciences, 1436, 19–35, https://doi.org/10.1111/nyas.13912, 2019.

Mote, P. W., Li, S., Lettenmaier, D. P., Xiao, M., and Engel, R.: Dramatic declines in snowpack in the western US, npj Climate and Atmospheric Science, 2, 1–6, https://doi.org/10.1038/s41612-018-0012-1, 2018.

Newman, A. J., Clark, M. P., Sampson, K., Wood, A., Hay, L. E., Bock, A., Viger, R. J., Blodgett, D., Brekke, L., Arnold, J. R., Hopson, T., and Duan, Q.: Development of a large-sample watershed-scale hydrometeorological data set for the contiguous USA: Data set characteristics and assessment of regional variability in hydrologic model performance, Hydrology and Earth System Sciences, 19, 209–223, https://doi.org/10.5194/hess-19-209-2015, 2015.

Oesting, M. and Stein, A.: Spatial modeling of drought events using max-stable processes, Stochastic Environmental Research and Risk Assessment, 32, 63–81, https://doi.org/10.1007/s00477-017-1406-z, 2018.

Patterson, L. A., Lutz, B. D., and Doyle, M. W.: Characterization of drought in the South Atlantic, United States, Journal of the American Water Resources Association, 49, 1385–1397, https://doi.org/10.1111/jawr.12090, 2013.

Record, R. A., Kightlinger, J., and Man, D. C.: Integrated water resources plan: 2015 update, Tech. rep., The metropolitan water district of southern California, Los Angeles, 2016.

Rossi, G., Benedini, M., Tsakiris, G., and Giakoumakis, S.: On regional drought estimation and analysis, Water Resources Management, 6, 249–277, https://doi.org/10.1007/BF00872280, 1992.

Rudd, A. C., Kay, A. L., and Bell, V. A.: National-scale analysis of future river flow and soil moisture droughts: potential changes in drought characteristics, Climatic Change, 156, 323–340, https://doi.org/10.1007/s10584-019-02528-0, 2019.

Seager, R., Tzanova, A., and Nakamura, J.: Drought in the Southeastern United States: Causes, variability over the last millennium, and the potential for future hydroclimate change, Journal of Climate, 22, 5021–5045, https://doi.org/10.1175/2009JCLI2683.1, 2009.

Sen, P. K.: Estimates of the regression coefficient based on Kendall's Tau, Journal of the American Statistical Association, 63, 1379–1389, https://doi.org/10.2307/2285891, 1968.

Sharma, S. and Mujumdar, P.: Increasing frequency and spatial extent of concurrent meteorological droughts and heatwaves in India, Scientific Reports, 7, 1–9, https://doi.org/10.1038/s41598-017-15896-3, 2017.

Sheffield, J. and Wood, E. F.: Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations, Climate Dynamics, 31, 79–105, https://doi.org/10.1007/s00382-007-0340-z, 2008.

Sheffield, J., Andreadis, K. M., Wood, E. F., and Lettenmaier, D. P.: Global and continental drought in the second half of the twentieth century: Severity-area-duration analysis and temporal variability of large-scale events, Journal of Climate, 22, 1962–1981, https://doi.org/10.1175/2008JCLI2722.1, 2009.

Smirnov, N. V.: Estimate of deviation between empirical distribution functions in two independent samples., Bull. Moscow Univ., 2, 3–16, 1939.

Strzepek, K., Yohe, G., Neumann, J., and Boehlert, B.: Characterizing changes in drought risk for the United States from climate change, Environmental Research Letters, 5, https://doi.org/10.1088/1748-9326/5/4/044012, 2010.

Tallaksen, L. M. and Hisdal, H.: Regional analysis of extreme streamflow drought duration and deficit volume, Friend'97 - Regional Hydrology: Concepts and Models for Sustainable Water Resource Management, 246, 141–150, https://doi.org/10.1212/WNL.0b013e31823ed0a4, 1997.

Thornton, P., Thornton, M., Mayer, B., Wilhelmi, N., Wei, Y., and Cook, R.: Daymet: daily surface weather on a 1 km grid for North America, 1980-2012, 2012.

Udall, B. and Overpeck, J.: The twenty-first century Colorado River hot drought and implications for the future, Water Resources Research, 53, 2404–2418, https://doi.org/10.1002/2016WR019638, 2017.

Van Loon, A. F. and Laaha, G.: Hydrological drought severity explained by climate and catchment characteristics, Journal of Hydrology, 526, 3–14, https://doi.org/10.1016/j.jhydrol.2014.10.059, 2015.

Vicente-Serrano, S. M., McVicar, T. R., Miralles, D. G., Yang, Y., and Tomas-Burguera, M.: Unraveling the influence of atmospheric evaporative demand on drought and its response to climate change, Wiley Interdisciplinary Reviews: Climate Change, 11, 1–31, https://doi.org/10.1002/wcc.632, 2020.

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., and Wada, Y.: Increasing dependence of lowland populations on mountain water resources, Nature Sustainability, https://doi.org/10.1038/s41893-020-0559-9, 2020.

Weiss, J. L., Castro, C. L., and Overpeck, J. T.: Distinguishing pronounced droughts in the southwestern united states: Seasonality and effects of warmer temperatures, Journal of Climate, 22, 5918–5932, https://doi.org/10.1175/2009JCLI2905.1, 2009.

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.: Large contribution from anthropogenic warming to an emerging North American megadrought, Science, 368, 314–318, https://doi.org/10.1126/science.aaz9600, 2020a.

Williams, E., Funk, C., Shukla, S., and McEvoy, D.: Quantifying human-induced temperature impacts on the 2018 United States Four corners hydrologic and agro-pastoral drought, Bulletin of the American Meteorological Society, 101, S11–S15, https://doi.org/10.1175/BAMS-D-19-0187.1, 2020b.

Woodhouse, C. A. and Wise, E. K.: The changing relationship between the upper and lower Missouri River basins during drought, International Journal of Climatology, pp. 1–18, https://doi.org/10.1002/joc.6502, 2020.

Woodhouse, C. A., Russell, J. L., and Cook, E. R.: Two modes of North American drought from instrumental and paleoclimatic data, Journal of Climate, 22, 4336–4347, https://doi.org/10.1175/2009JCLI2705.1, 2009.

Woodhouse, C. A., Pederson, G. T., Morino, K., McAfee, S. A., and McCabe, G. J.: Increasing influence of air temperature on upper Colorado River streamflow, Geophysical Research Letters, 43, 2174–2181, https://doi.org/10.1002/2015GL067613, 2016.

Wuebbles, D., Meehl, G., Hayhoe, K., Karl, T. R., Kunkel, K., Santer, B., Wehner, M., Colle, B., Fischer, E. M., Fu, R., Goodman, A., Janssen, E., Kharin, V., Lee, H., Li, W., Long, L. N., Olsen, S. C., Pan, Z., Seth, A., Sheffield, J., and Sun, L.: CMIP5 climate model analyses: Climate extremes in the United States, Bulletin of the American Meteorological Society, 95, 571–583, https://doi.org/10.1175/BAMS-D-12-00172.1, 2014.