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

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9 February 2021Manuela I Brunner¹ , Daniel L Swain^{2,3,4} , Eric Gilleland¹ and Andrew W Wood^{1,5} ¹ Research Applications Laboratory, National Center for Atmospheric Research, Boulder, CO, United States of America² Institute of the Environment and Sustainability, University of California, Los Angeles, CA, United States of America³ Capacity Center for Climate and Weather Extremes, National Center for Atmospheric Research, Boulder, CO, United States of America⁴ The Nature Conservancy of California, San Francisco, CA, United States of America⁵ Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO, United States of AmericaE-mail: manuela.i.brunner@gmail.com

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**Keywords:** drought, spatial extent, drivers, climate change, United States, precipitation, extremesSupplementary material for this article is available [online](#)**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 varies 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.

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, hydro-power 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, and (3) 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 1(A)). Second, we determine drought spatial extent at a monthly scale as the percentage of catchments affected by drought during a certain month (figure 1(B)). 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 1(C)). 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.

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 1(A)). The use of a variable instead of a fixed threshold leads to the identification of droughts defined as streamflow

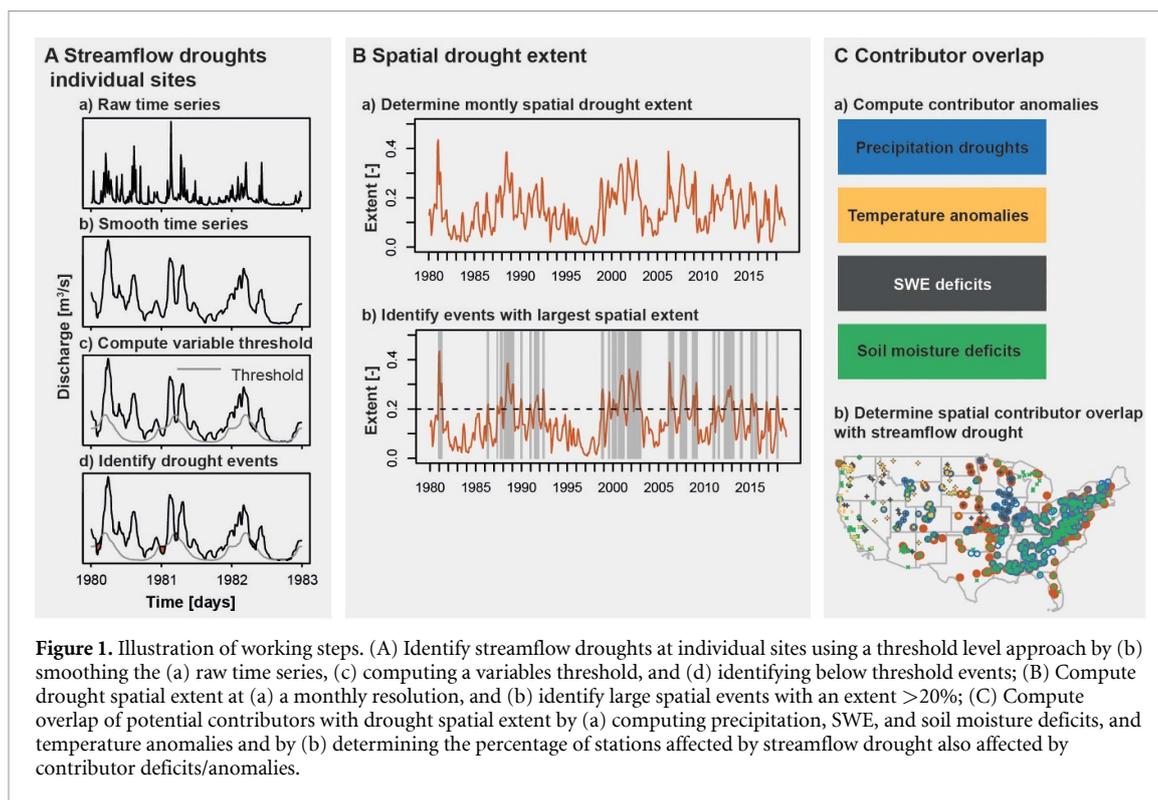


Figure 1. Illustration of working steps. (A) Identify streamflow droughts at individual sites using a threshold level approach by (b) smoothing the (a) raw time series, (c) computing a variable threshold, and (d) identifying below threshold events; (B) Compute drought spatial extent at (a) a monthly 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.

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 1(B)). 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 , $0.1\text{--}0.2$ 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 (figure S1, stacks.iop.org/ERL/16/024038/mmedia). 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

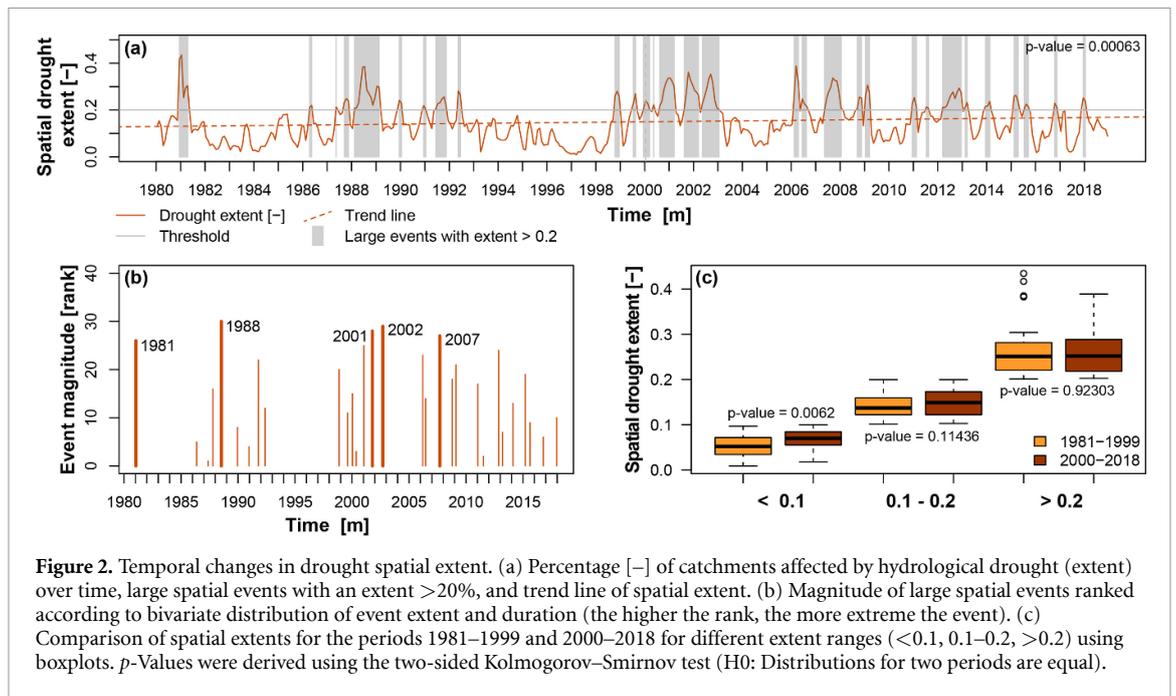
3.1. Temporal changes in drought spatial extent

At the monthly scale, drought spatial extent varies considerably over time ranging from near zero to a maximum of $\sim 40\%$, and shows a modest ($\sim 1\%/decade$) but statistically significant (p -value = 0.00063) increasing trend (figure 2(A)). 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 2(b)). 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 2(b)). 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



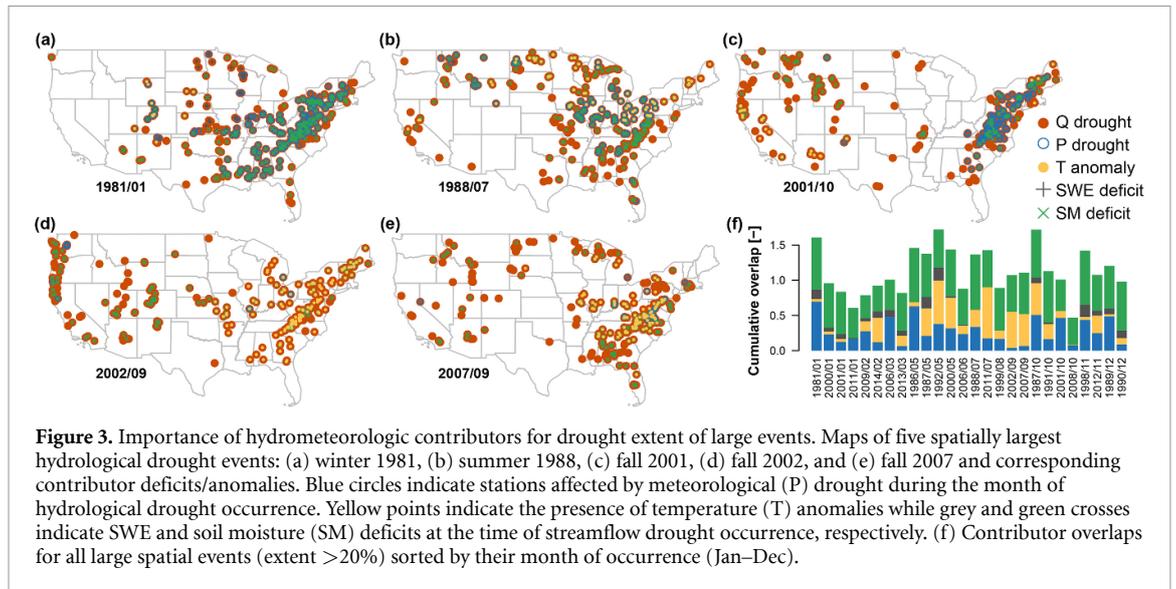
in P and T in advance of their impact on streamflow. We look at the covariation of each potential contributor with monthly spatial streamflow drought extent to assign temporally proximal driving roles to all four variables. If streamflow drought extent shows a high overlap within a specific month with 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 3(a)). The 1988 event affected a similar region but warm temperature anomalies are more prominent than precipitation deficits (especially in the north; figure 3(b)). 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 3(c)). 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 3(d)). Temperature anomalies were also

important during the 2007 event, which affected mainly the eastern and southern portions of the US (figure 3(e)).

Across all events, the importance of different hydro-meteorological variables as contributors to drought spatial extent varies substantially (figure 3(f)). 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.

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 S2). 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

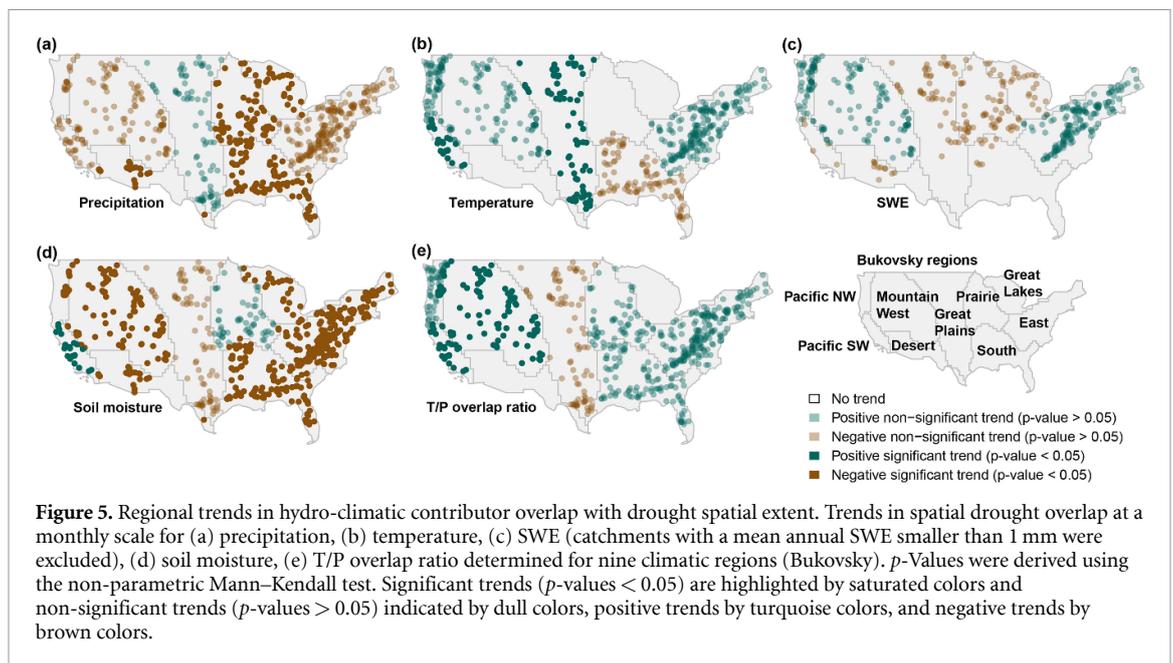
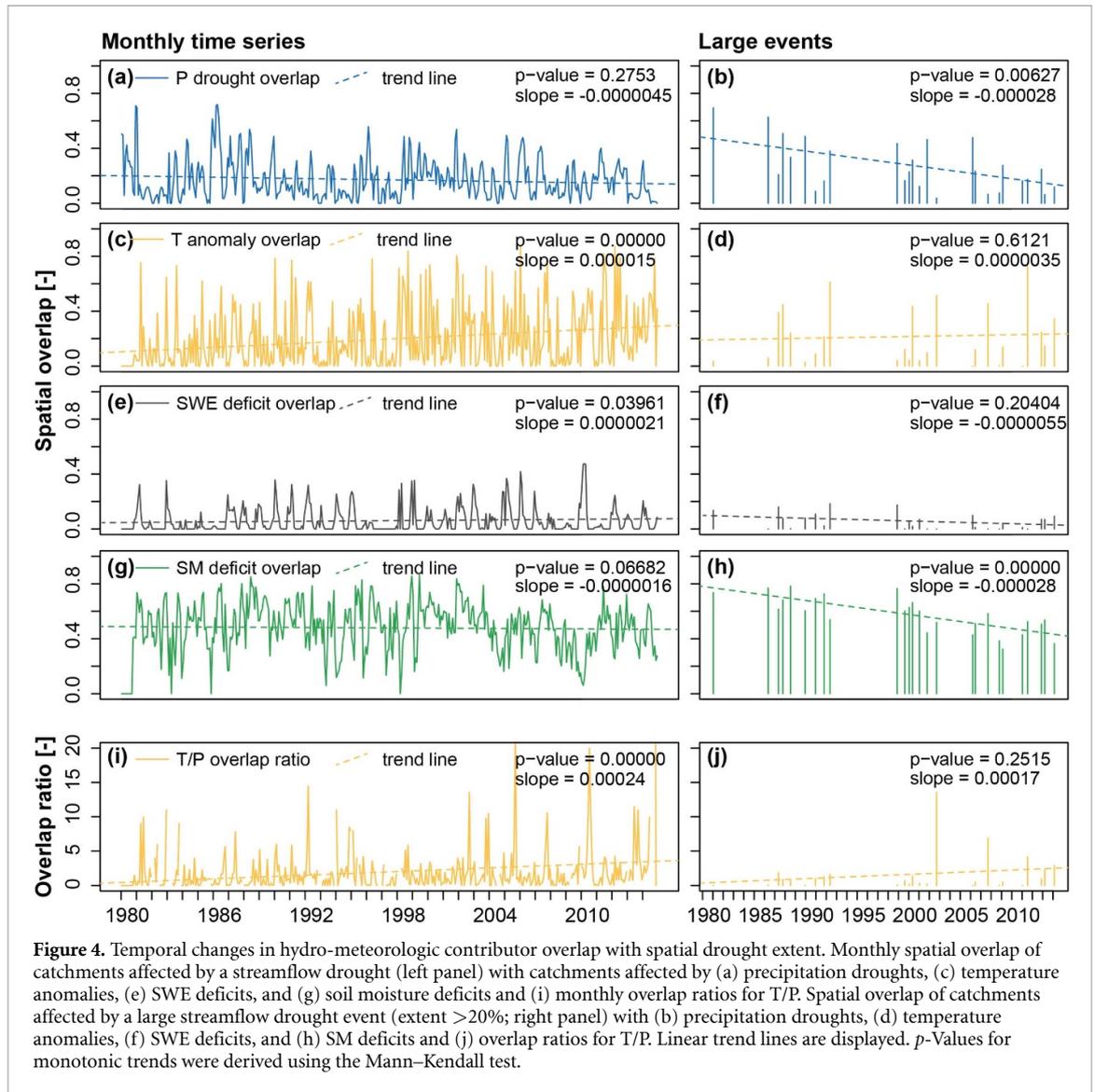
Over the full CONUS, the importance of precipitation as a contributor to drought spatial extent remains relatively stable over time for all events (figure 4(a), p -value = 0.2753) but decreases for the large events (figure 4(b), p -value: 0.00627). In contrast, temperature becomes more important across all events as a contributor to spatial extent (figure 4(c), 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 4(d), 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 4(i) and (j); p -values: 0.00000,

and 0.2515). The importance of both SWE and soil moisture remains relatively stable across all events (figures 4(e) and (g), p -values: 0.03961 and 0.06682) though it decreases for large events (figures 4(f) and (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-meteorological contributors (figure 5). Precipitation overlap decreases over most regions except the Great Plains (figure 5(a)), while temperature overlap increases in most regions except for portions of the southeast (figure 5(b))—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 5(e)). 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 5(c)). 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 5(d)).

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 (Luo *et al* 2017, Dai *et al* 2018).

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, Dai 2013, Lu *et al* 2019) 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.

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Data availability statement

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.

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.

ORCID iDs

Manuela I Brunner  <https://orcid.org/0000-0001-8824-877X>

Daniel L Swain  <https://orcid.org/0000-0003-4276-3092>

Andrew W Wood  <https://orcid.org/0000-0002-6231-0085>

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