Weather and Climate Extremes 37 (2022) 100491

Contents lists available at ScienceDirect

Weather and Climate Extremes

journal homepage: www.elsevier.com/locate/wace

Recent droughts in the United States are among the fastest-developing of the last seven decades

Virginia Iglesias [a,*], William R. Travis [a,b], Jennifer K. Balch [a,b]

[a] Earth Lab, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, United States
[b] Department of Geography, University of Colorado, Boulder, CO, United States

ABSTRACT

Drought has traditionally been characterized as a slow process that requires seasons or even years to fully develop. Recent fast-evolving drying events, however, have challenged our forecasting and response capabilities. A fundamental question emerges: are droughts setting in more quickly? We address this question by evaluating drought intensification rates for the contiguous United States and find that median drought onset rates did not change significantly in 1951–2021. Conversely, development of fast onset droughts (i.e., the 95th percentile of the drought intensification rates per drought region in a given month of the time series) has been speeding up in recent years across most of the country. As a result, intensification rates of the quickest-onset droughts in 2011–2021 are among the fastest of the last seven decades.

1. Introduction

Droughts are the largest driver of relative and absolute crop yield declines on several continents (Gaupp et al., 2020). Annually, they damage agricultural products that could feed over 81 million people for a year, and their global incidence is expected to increase as the climate warms (Cook et al., 2018; Samaniego et al., 2018). In the North American Great Plains, for example, the likelihood and intensity of droughts are already higher than during the 1930's Dust Bowl (Cowan et al., 2020), and projected soil water deficits during the second half of this century will exceed even the driest decades of the last millennium (Cook et al., 2015). Intense droughts may stress urban water supplies (Dilling et al., 2019) and cause a wide range of cascading environmental impacts (Crausbay et al., 2017; Cravens et al., 2021), including soil erosion (García-Ruiz et al., 2017), altered nutrient cycling (Evans and Burke, 2013), increased probability of fire (Moritz et al., 2005), air quality deterioration (Schubert et al., 2004), and acceleration of land degradation (Vicente-Serrano et al., 2012).

Recent studies suggest that global expansion of drying areas is primarily driven by pronounced rises in evaporative demand, often overcoming simultaneous increases in precipitation (Cook et al., 2014). Accordingly, droughts are progressively more likely to be concurrent with (Feng et al., 2020; Hao et al., 2013; Ribeiro et al., 2020; Yu and Zhai, 2020), or followed by (Mueller and Seneviratne, 2012), extremely high temperatures. In the United States, droughts are warming faster than the average climate, especially in southern reaches (Chiang et al., 2018). As a result, droughts may set in more quickly in years to come (Trenberth et al., 2014), challenging the traditional view of drought as a creeping phenomenon that unfolds over seasons or even years (Wilhite and Glantz, 1985).

Recent rapid-onset droughts, highlighted by the acute drying of the Great Plains in 2012–2013 (Hoerling et al., 2014) have been labeled 'flash droughts' and received substantial media and research attention. These rapid drying episodes may or may not be more intense than their conventional counterparts, but are defined as equivalent to flash floods in that their onset and/or rate of intensification is exceptionally quick (Otkin et al., 2018). While the scientific community grapples with how to characterize flash droughts and whether to adopt the label in the U.S. weather, climate and water information enterprise (NOAA, 2021), there is consensus that rapid drying, especially loss of soil moisture, represents serious challenges for drought monitoring, forecasting and impact mitigation (Pendergrass et al., 2020). This raises the question: are droughts speeding up? To address this, we estimate and assess drought intensification rates for the conterminous United States over the last 70 years.

2. Materials and methods

In this study, we do not attempt to propose a definition of 'flash droughts', nor assess their behavior. Instead, we quantify changes in intensification rates of all droughts regardless of their potential classification as 'flash' or conventional. Various indices have been used to

* Corresponding author.
E-mail address: virginia.iglesias@colorado.edu (V. Iglesias).

https://doi.org/10.1016/j.wace.2022.100491
Received 12 May 2021; Received in revised form 9 July 2022; Accepted 7 August 2022
Available online 12 August 2022

track drought intensification rates and to project drought risk (Otkin et al., 2018). We employed the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) to test whether drought onset is speeding up. SPEI is a member of a family of multi-scalar, standardized indices of meteorological drought, including the widely-used Standardized Precipitation Index (SPI). These indices reflect standardized departures from mean conditions frequently estimated over windows of one to 48 months, thus allowing the specification of the temporal scale over which water deficit accumulation is significant for the system and process of interest (Guttman, 1999). SPEI extends SPI by incorporating evaporative demand to account for water loss from evapotranspiration (Vicente-Serrano et al., 2010), an important feature in a warming climate.

We defined drought intensification as the absolute value of the decrease from non-drought (SPEI>=-0.5) (Paulo et al., 2012) to drought conditions (local negative minimum). The first derivative of the drought intensification time series (hereafter 'drought intensification rate') constitutes an approximation of moisture loss per unit of time, and is used in this study as an estimate of the speed of drought evolution. To calculate these rates, we obtained SPEI estimates from the Parameter-elevation Relationships on Independent Slopes Model (PRISM), a validated dataset of gridded surface meteorological variables (spatial resolution = 800 m; temporal resolution = one-month; 1895-present) (PRISM Climate Group, 2004). We start our analyses in 1951 because these data are susceptible to meteorological station openings and closings and technological advances (Daly et al., 2021). We expect that, by constraining our study to the post-World War II, recent past, we will account for some of the effects of changes in technology and operations.

We focused on SPEI-1, i.e., standardized departures from mean conditions calculated over one-month windows, because this window would allow the detection of fast-onset droughts regardless of their duration. To assess this assumption and its influence on our results, we also analyzed SPEI-3, SPEI-6, SPEI-9, and SPEI-12 (i.e., standardized departures from mean conditions calculated over three-, six-, nine-, and 12-month windows). For each cell in the contiguous United States (CONUS), we identified periods with SPEI values smaller than −0.5 (hereafter 'drought') and calculated drought intensification rates as the decline in SPEI per unit of time [1]:

$$I_{(s,t)} = SPEI_{(s,t)} - SPEI_{(s,t0)}, \text{ and}$$

$$IR_{(s,t)} = I_{(s,t)} * (t - t0)^{-1}, \quad [1]$$

where $I_{(s,t)}$ is drought intensification in cell *s* at time *t*; $SPEI_{(s,t)}$ is the SPEI value in cell *s* at time *t*; $SPEI_{(s,t0)}$ is the SPEI value in cell *s* at the onset of the drought (*t0*); and $IR_{(s,t)}$ is the drought intensification rate in cell *s* at time *t*.

Drought intensification rates at each point in time were converted to positive values so that larger values would correspond with more rapid drought onset, aggregated at the Hydrologic Unit Code level 12 (HUC-12) (Steeves and Douglas, 1994), and summarized by their median and 95th percentiles. As a result, we produced 86,798 time series of summary statistics for SPEI-1, -3, -6, -9, and -12, at one-month resolution for 1951–2021. Hereafter, we refer to droughts whose intensification rates in a given month of the time series correspond to the 95th percentile as 'fast droughts'.

Then, for each month in the record, we estimated the median values of these summary statistics in eight CONUS drought regions, namely Pacific northwest, Southwest, Northern plains, Southern plains, Intermountain west, Midwest, Northeast, and Southeast (Fig. S1). These regions are based on Warrick's drought regions (Warrick, 1975), with slight modification to match the Drought Early Warning System (DEWS) (NIDIS, 2021). Specifically, we subdivided the Southwest region into 'Southwest' and 'Intermountain west', and the Great plains into 'Northern plains' and 'Southern plains'. We thus obtained time series of median and fast drought intensification rates for each of these regions at a monthly resolution (1951–2021).

We visually compared the trends derived from SPEI-1, SPEI-3, SPEI-6, SPEI-9, and SPEI-12 in each region and estimated the cross-correlations between the series derived from SPEI-1 and the other time series to assess the sensitivity of our analyses to the time window used in the calculation of SPEI. Additionally, we estimated dynamic cross-correlations at overlapping 10-year windows to evaluate whether the associations had been stable over time.

To better quantify how fast droughts in recent years compare to the past, we created a dataset with drought intensification rates corresponding to the 95th percentile of the drought intensification rates per drought region at a given month in the time series. We then estimated the median onset speed of these droughts in 1951–2010 and 2011–2021 and their respective 95% confidence intervals through bootstrapping (1000 bootstrap replicates per region and period). Lastly, grouping these estimates by season (spring: March, April, May; summer: June, July, August; fall: September, October, November; and winter: December, January, February) allowed us to assess the seasonality of the observed changes in fast drought onset speed. All analyses and figures were performed with R 3.6.2 (R Core Team, 2019), packages boot (Canty and Ripley, 2019), doParallel 1.0.16 (Microsoft Corporation and Weston, 2020a), foreach 1.5.1 (Microsoft Corporation and Weston, 2020b), ncdf4 1.17 (Pierce, 2019), raster 3.3–13 (Hijmans, 2020), rgdal 1.5–17 (Bivand et al., 2020), sf 0.9–7 (Pebesma, 2018), tidyverse 1.3.0 (Wickham et al., 2019), TTR 0.24.2 (Ulrich, 2020), viridis 0.5.1 (Garnier, 2018), and corresponding dependencies.

3. Results and discussion

3.1. Fast droughts are speeding up

Between 1951 and 2021, median drought intensification rates derived from SPEI-1 ranged between 0.46 and 0.72*month^{-1} across the CONUS. Regional analysis performed for the Pacific northwest, Southwest, Northern plains, Southern plains, Intermountain west, Midwest, Northeast, and Southeast reveals an absence of statistically significant trends in these estimates over this period ($p < 0.05$; Fig. 1. See Fig. S1 for information on the location of these regions).

Unlike median drought intensification rates, fast droughts (i.e., the 95th percentile of the drought intensification rates per drought region in a given month of the time series) show a trend of increasing onset speeds beginning in ~1985 in most regions (Fig. 1). This finding is consistent with those of (Qing et al., 2022), who reported more rapid drought development across much of the globe as a result of the co-occurrence of soil moisture depletion and atmospheric aridity (i.e., high vapor pressure deficit, high temperature, and low precipitation). Diverging trends in drought intensification rates near the upper tail and at the center of the distribution (i.e., 'fast' and 'median' droughts) are indicative of increasing variability in speed of drying. A potential mechanism for this divergence centers on thermodynamic land-atmosphere interactions (Cook et al., 2013). Heat enhances evaporative demand and tilts drought events toward greater intensity (Seager et al., 2014). Reduced evapotranspiration during drought, in turn, amplifies the sensible heat flux and ultimately promotes warming on land as near surface moisture is depleted (Betts et al., 1996). These self-reinforcing events are referred to as global change droughts (Breshears et al., 2005), and their increasing concurrence is coming to be recognized as part of a pattern of 'climate whiplash' (Mazdiyasni and AghaKouchak, 2015; Trenberth et al., 2014).

3.2. Long term trends in drought intensification rates are robust to the window size used to calculate SPEI

Intensification rates of median and fast droughts (i.e., the 95th percentile of the drought intensification rates per drought region in a given month of the time series) derived from SPEI-1 (Fig. 1) and SPEI-3 (Fig. S2), SPEI-6 (Fig. S3), SPEI-9 (Fig. S4), and SPEI-12 (Fig. S5) yield

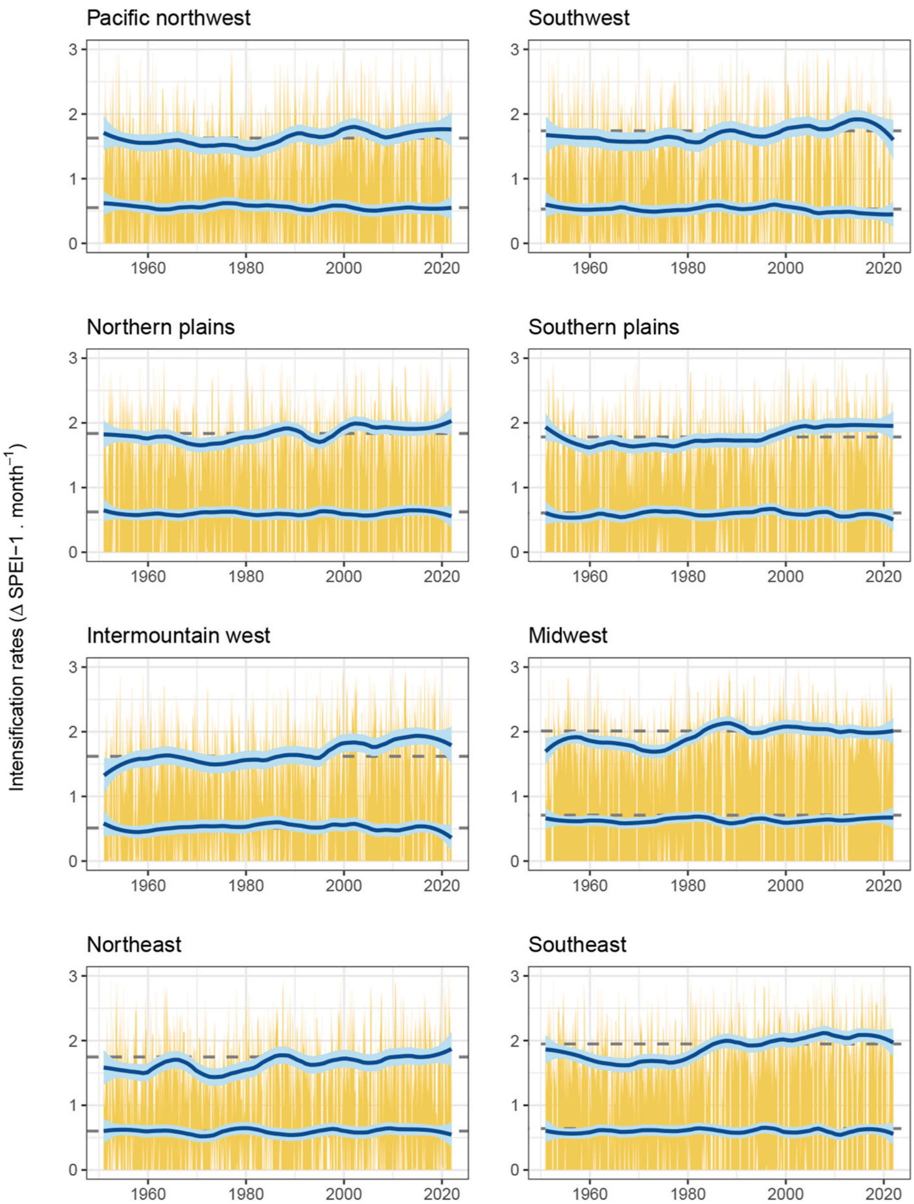

Fig. 1. Drought intensification rates based on changes in SPEI-1 for the regions defined in this study (Fig. S1). The blue lines show trends in the median (bottom line) and 95th percentile (top line) of drought intensification rates smoothed with Locally Weighted Scatterplot Smoothing (LOWESS, smoothing parameter = 0.25). The light blue shading represents the 95% confidence intervals for the smoothers. The dashed lines depict the median and 95th quantiles drought intensification rates for 1951–2021. Departures from these baselines are statistically significant (0.05 alpha-level). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

similar temporal dynamics despite differences in their formulation, suggesting that long-term, low-frequency, trends in onset speeds are robust to the window used to calculate SPEI. Not surprisingly, high-resolution trends derived from SPEI-3 are the best match to those based on SPEI-1, and the cross-correlation between SPEI-1-derived-onset speeds and those obtained from SPEI-3, -6, -9, and -12 decreases

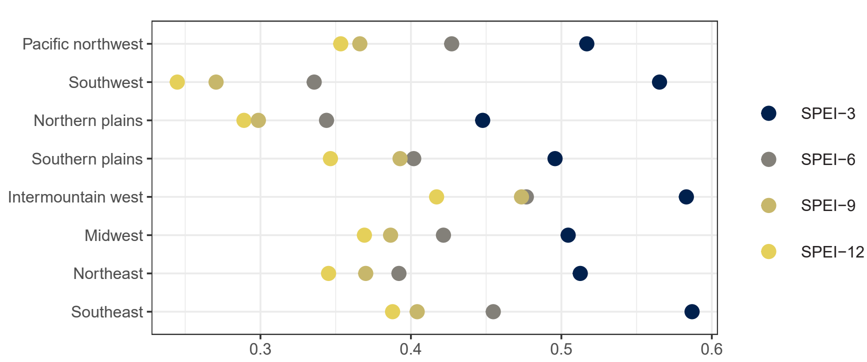

Fig. 2. Cross-correlation between drought intensification rates derived from SPEI-1 and SPEI-3, SPEI-6, SPEI-9, and SPEI-12 for the regions defined in this study (Fig. S1).

as the window size increases (Fig. 2, S6). This observation warrants a word of caution against extrapolating conclusions pertaining to the high-frequency temporal dynamics of drought intensification rates derived from SPEI-1 to time series obtained from other temporal windows. Analysis of dynamic cross-correlations reveals multidecadal-scale oscillations in the strength of these associations, but no long-term trends that could indicate a persistent decoupling of indices (Fig. S6). Taken together, these results suggest that, despite a certain dependence on window size at high temporal resolutions, low-frequency, long-term trends in the onset speed of droughts as estimated with equation [1] are robust to the window used to calculate SPEI.

3.3. The intensification rates of recent fast droughts are comparable to or higher than those observed in the last 70 years

Higher climate/weather variability is conducive to extreme events and an expected feature of a warmer world (IPCC, 2021). More rapid onset of fast droughts (i.e., the 95th percentile of the drought intensification rates per HUC-12 at a given time), in particular, is foreseeable given widespread warming and reduced precipitation observed across much of the United States (Zhang et al., 2021), and may even hold for areas where precipitation is increasing but temperature is also rising apace (e.g., Northern plains and Northeast). Our results show that the onset speeds of recent fast droughts are comparable to or faster than the most rapidly-evolving droughts of the last 70 years (Table 1; Fig. 3).

Although much of the CONUS has experienced quick onset droughts in recent years, changes in intensification rates exhibited significant among- and within-region variability. Median fast drought intensification rates in the Midwest were lower in 2011–2021 than in the reference period of 1951–2010. In the Northern plains, median onset speeds were statistically faster than in the past, but the difference was not pronounced. In contrast, all the other regions showed statistically-significant and large increases in median fast drought intensification rates of up to 113% (Table 1). In all cases, changes in median fast drought behavior were associated with larger standard errors (Fig. 3), suggesting that in all but one region onset speeds became faster but also more spatially variable. These within-region differences are reflected in the number of HUC-12's experiencing unprecedented conditions. A large proportion of HUC-12's in the Pacific northwest (73%), Southwest (52%), Northern plains (53%), and Southeast (56%) were affected by droughts whose onset speeds were unprecedented for the season when they occurred (Fig. 4), representing a 2.91- to 3.89-fold increase in the intensification rate of the fastest drought registered in a HUC-12 in the last decade with respect to the fastest drought in the same HUC in 1951–2010 (Table 1).

In addition to spatial variability, changes in fast drought intensification rates also exhibited seasonal differences among regions, as more rapid fast drought onsets resulted from increased rates in several months of the year (Figs. S7–S14) but displayed region-specific seasonal patterns. In the Intermountain west, temporal trends are largely explained by increases in intensification rates in the spring, while distinctly higher summer intensification rates characterize all regions except the Northeast and Southeast. Conversely, changes in the cooler fall and winter months dominate the signal in the Northeast and across the southern tier (i.e., Southwest, Southern plains, and Southeast; Fig. 5). These patterns closely resemble spatial-temporal trends in vapor pressure deficit (VPD, i.e., the capacity of air to extract moisture from the land surface) observed across the CONUS attributed to larger rises in the water-holding capacity of saturated air than in actual water vapor (Ficklin and Novick, 2017). It is thus possible that these parameters (or their drivers) play a major role in determining the onset speed of droughts. However, a mismatch between large increases in winter drought intensification rates in the southern CONUS (Fig. 5) and negligible changes in VPD across the same area (Ficklin and Novick, 2017) suggest that other factors modulate drought development speeds and their relative importance changes as certain thresholds are reached.

Table 1
Changes in fast drought intensification rates derived from SPEI-1 (FDIR). 'CI' stands for confidence interval, and 'maximum change' refers to the largest change observed within a single HUC-12 in a drought region.

Area	Median FDIR in 1951–2010 (95% CI)	Median FDIR in 2011–2021 (95% CI)	Maximum change in 2011–2021 relative to 1951–2010
Pacific northwest	1.118–1.119	1.160–1.163	3.89
Southwest	1.149–1.150	1.269–1.272	3.45
Northern plains	1.116–1.118	1.120–1.123	3.38
Southern plains	1.114–1.115	1.158–1.162	3.74
Intermountain west	1.144–1.146	1.294–1.299	2.08
Midwest	1.124–1.125	1.075–1.078	1.74
Northeast	1.143–1.146	1.187–1.196	2.75
Southeast	1.121–1.123	1.160–1.164	2.91

Feedback-mediated processes are not rare in the climate system and explain the multiple scenarios that could lead to anomalous drying. For example, severe drought in the southwestern CONUS persisting for over a decade has been mainly attributed to reduced precipitation associated with low sea-surface temperatures in the eastern Pacific (Delworth et al., 2015; Seager et al., 2014). Conversely, a strong signal of anthropogenic warming has been identified in other regions, mainly through the direct impacts of warming temperatures on snow cover and evaporative demand (Cook et al., 2018). In 2015, 80% of meteorological stations in the Pacific northwest registered record low snowpack despite normal precipitation (Mote et al., 2016). Decreases in streamflow in the Colorado basin in 2000–2014 also occurred under conditions of normal precipitation (McCabe et al., 2017; Udall and Overpeck, 2017). In both cases, rising temperatures affecting the type of precipitation (snow vs. rain), snowmelt, and evapotranspiration were identified as significant contributors to drought development. Further, anthropogenic forcing accounts for 47% of the 2000–2018 drought severity in the western United States, turning an otherwise typical drought into a megadrought (Williams et al., 2020). Similarly, anthropogenic warming superimposed on natural variability and mediated by regional-scale mechanisms may explain the increases in drought intensification rates observed across the country.

4. Conclusions

Our analyses document drought onset rates across the contiguous United States (CONUS) using the Standardized Precipitation Evapotranspiration Index (SPEI). We find that median drought intensification rates did not change significantly during 1951–2021. Conversely, intensification rates of the fastest droughts (i.e., the 95th percentile of the drought intensification rates per drought region in a given month of the time series) have sped up in recent decades across most of the CONUS. Faster drought intensification rates are not necessarily a new phenomenon but may be a recurrent feature of the Earth system. Previous studies have shown that changes in temperature and precipitation patterns associated with coupled atmosphere-ocean interactions such as El Niño-Southern Oscillation (ENSO) constitute major drivers of soil moisture (Dai, 2013). In addition, the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) explain over half of the variance in multidecadal drought frequency (Goodrich, 2007; McCabe et al., 2017). These modes of variability may modulate the speed of drought development.

Regardless of their long-term characteristics (persistent trend vs. multidecadal oscillation), our results show that fast droughts have been speeding up in the last few decades and now set in faster than the most rapidly-developing droughts of the last 70 years. Faster-onset droughts could have unanticipated impacts, as drying affects multiple social-environmental processes, and the propagation from meteorological to hydrological, agricultural, socioeconomic, and ecological drought is

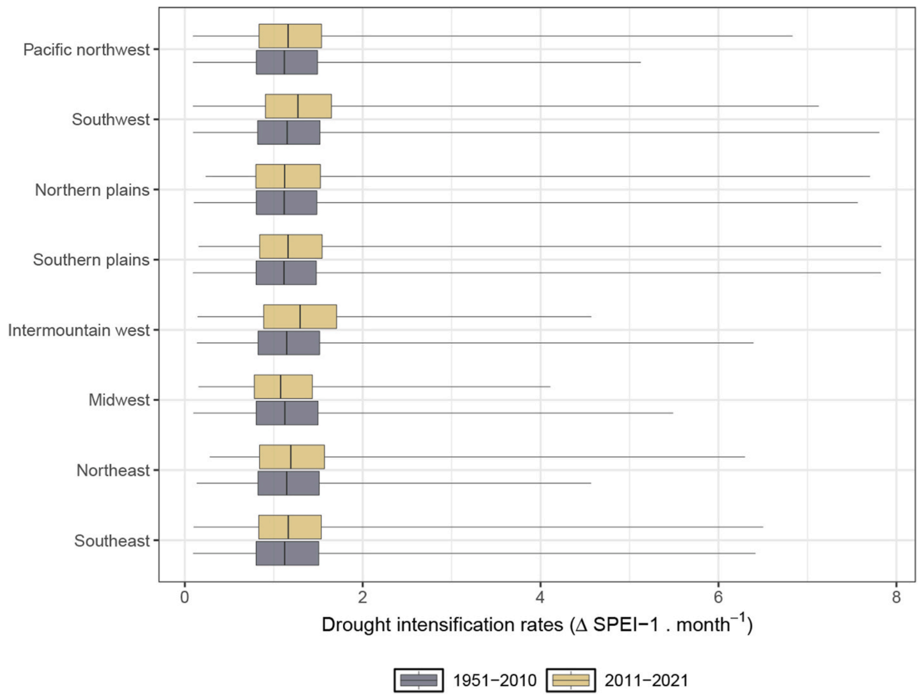

Fig. 3. Boxplots of fast drought intensification rates in 1951–2010 and 2011–2021 in the regions considered in this study (Fig. S1). Fast droughts correspond to the 95th percentile of the SPEI-1 derived drought intensification rates in a given month of the time series. For all regions except the Midwest, median fast drought onset speeds in the last decade were faster than in the past ($p < 0.05$; Table 1).

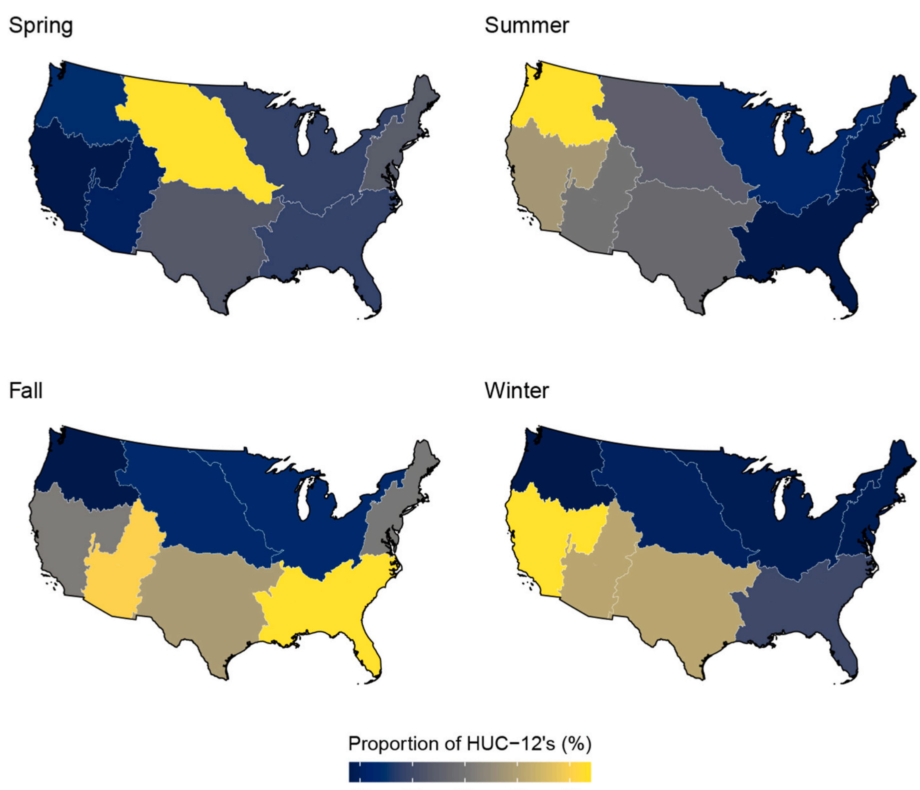

Fig. 4. Proportion of Hydrologic Unit Code level 12 (HUC-12) in each drought region that experienced unprecedented fast drought intensification rates in 2011–2021.

complex (Vicente-Serrano et al., 2020). Although the effects of quicker drying are yet to be assessed, we do know that agricultural and water resource systems are particularly vulnerable to droughts that develop rapidly and with few early warnings (Shrum et al., 2018; Yung et al., 2015).

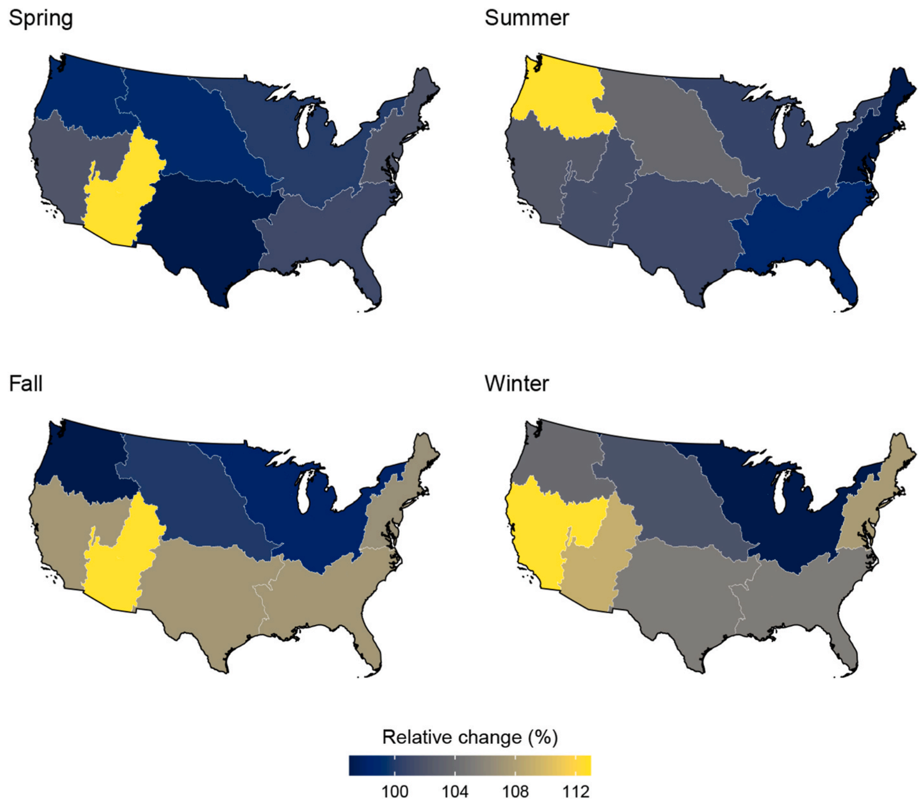

Fig. 5. Changes in the median intensification rate of fast droughts in 2011–2021 relative to 1951–2010 derived from SPEI-1 and aggregated to the drought-region scale (Fig. S1).

Author statement

Virginia Iglesias: Conceptualization, methodology, data curation, formal analysis, visualization, programming, and writing (original draft preparation, reviewing, and editing).

William R. Travis: Conceptualization, methodology, writing (original draft preparation, reviewing, and editing), and supervision.

Jennifer K. Balch: Funding acquisition and supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Funding for this work was provided by Earth Lab through CU Boulder's Grand Challenge Initiative and the Cooperative Institute for Research in Environmental Sciences (CIRES) at CU Boulder.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wace.2022.100491.

References

Betts, A.K., Ball, J.H., Beljaars, A.C.M., Miller, M.J., Viterbo, P.A., 1996. The land surface-atmosphere interaction: a review based on observational and global modeling perspectives. J. Geophys. Res. Atmos. 101 (D3), 7209–7225. https://doi.org/10.1029/95JD02135.

Bivand, R., Keith, T., Rowlingson, B., 2020. Rgdal: Bindings for the "Geospatial" Data Abstraction Library. R Package Version 1.5-17. Retrieved from, Version 1.5-17. https://CRAN.R-project.org/package=rgdal.

Breshears, D.D., Cobb, N.S., Rich, P.M., Price, K.P., Allen, C.D., Balice, R.G., et al., 2005. Regional vegetation die-off in response to global-change-type drought. Proc. Natl. Acad. Sci. USA 102 (42), 15144–15148. https://doi.org/10.1073/pnas.0505734102.

Canty, A., Ripley, B., 2019. Boot: Bootstrap R (S-Plus) Functions, Version 1.3-23.

Chiang, F., Mazdiyasni, O., AghaKouchak, A., 2018. Amplified warming of droughts in southern United States in observations and model simulations. Sci. Adv. 4 (8), eaat2380 https://doi.org/10.1126/sciadv.aat2380.

Cook, B.I., Seager, R., Miller, R.L., Mason, J.A., 2013. Intensification of North American megadroughts through surface and dust aerosol forcing. J. Clim. 26 (13), 4414–4430. https://doi.org/10.1175/JCLI-D-12-00022.1.

Cook, B.I., Smerdon, J.E., Seager, R., Coats, S., 2014. Global warming and 21st century drying. Clim. Dynam. 43 (9–10), 2607–2627. https://doi.org/10.1007/s00382-014-2075-y.

Cook, B.I., Ault, T.R., Smerdon, J.E., 2015. Unprecedented 21st century drought risk in the American southwest and central plains. Sci. Adv. 1 (1), e1400082 https://doi.org/10.1126/sciadv.1400082.

Cook, B.I., Mankin, J.S., Anchukaitis, K.J., 2018. Climate change and drought: from past to future. Curr. Clim. Change Rep. 4 (2), 164–179. https://doi.org/10.1007/s40641-018-0093-2.

Corporation, Microsoft, Weston, S., 2020a. doParallel: Foreach Parallel Adaptor for the "Parallel" Package. R Package Version 1.0.16. Retrieved from, Version 1.0.16. https://CRAN.R-project.org/package=doParallel.

Corporation, Microsoft, Weston, S., 2020b. Foreach: Provides Foreach Looping Construct. R Package Version 1.5.1. Retrieved from, Version 1.5.1. https://CRAN.R-project.org/package=foreach.

Cowan, T., Undorf, S., Hegerl, G.C., Harrington, L.J., Otto, F.E.L., 2020. Present-day greenhouse gases could cause more frequent and longer Dust Bowl heatwaves. Nat. Clim. Change 10 (6), 505–510. https://doi.org/10.1038/s41558-020-0771-7.

Crausbay, S.D., Ramirez, A.R., Carter, S.L., Cross, M.S., Hall, K.R., Bathke, D.J., et al., 2017. Defining ecological drought for the twenty-first century. Bull. Am. Meteorol. Soc. 98 (12), 2543–2550. https://doi.org/10.1175/BAMS-D-16-0292.1.

Cravens, A.E., McEvoy, J., Zoanni, D., Crausbay, S., Ramirez, A., Cooper, A.E., 2021. Integrating ecological impacts: perspectives on drought in the upper Missouri headwaters, Montana, United States. Weather, Climate, and Society 13 (2), 363–376. https://doi.org/10.1175/WCAS-D-19-0111.1.

Dai, A., 2013. Increasing drought under global warming in observations and models. Nat. Clim. Change 3 (1), 52–58. https://doi.org/10.1038/nclimate1633.

Daly, C., Doggett, M., Smith, J., Olson, K., Halbleib, M., Dimcovic, Z., et al., 2021. Challenges in observation-based mapping of daily precipitation across the conterminous United States. J. Atmos. Ocean. Technol. 38 (11), 1979–1992. https://doi.org/10.1175/JTECH-D-21-0054.1.

Delworth, T.L., Zeng, F., Rosati, A., Vecchi, G.A., Wittenberg, A.T., 2015. A link between the hiatus in global warming and North American Drought. J. Clim. 28 (9), 3834–3845. https://doi.org/10.1175/JCLI-D-14-00616.1.

Dilling, L., Daly, M.E., Kenney, D.A., Klein, R., Miller, K., Ray, A.J., et al., 2019. Drought in urban water systems: learning lessons for climate adaptive capacity. Climate Risk Mange. 23, 32–42. https://doi.org/10.1016/j.crm.2018.11.001.

Evans, S.E., Burke, I.C., 2013. Carbon and Nitrogen decoupling under an 11-year drought in the shortgrass steppe. Ecosystems 16 (1), 20–33. https://doi.org/10.1007/s10021-012-9593-4.

Feng, S., Wu, X., Hao, Z., Hao, Y., Zhang, X., Hao, F., 2020. A database for characteristics and variations of global compound dry and hot events. Weather Clim. Extrem. 30, 100299 https://doi.org/10.1016/j.wace.2020.100299.

Ficklin, D.L., Novick, K.A., 2017. Historic and projected changes in vapor pressure deficit suggest a continental-scale drying of the United States atmosphere. J. Geophys. Res. Atmos. 122 (4), 2061–2079. https://doi.org/10.1002/2016JD025855.

García-Ruiz, J.M., Beguería, S., Lana-Renault, N., Nadal-Romero, E., Cerdà, A., 2017. Ongoing and emerging questions in water erosion studies. Land Degrad. Dev. 28 (1), 5–21. https://doi.org/10.1002/ldr.2641.

Garnier, S., 2018. Viridis: Default Color Maps from "Matplotlib". R Package Version 0.5.1. Retrieved from, Version 0.5.1. https://CRAN.R-project.org/package=viridis.

Gaupp, F., Hall, J., Hochrainer-Stigler, S., Dadson, S., 2020. Changing risks of simultaneous global breadbasket failure. Nat. Clim. Change 10 (1), 54–57. https://doi.org/10.1038/s41558-019-0600-z.

Goodrich, G.B., 2007. Influence of the Pacific Decadal Oscillation on winter precipitation and drought during years of neutral ENSO in the Western United States. Weather Forecast. 22 (1), 116–124. https://doi.org/10.1175/WAF983.1.

Guttman, N., 1999. Accepting the Standardized Precipitation Index: A calculation algorithm. J. Am. Water Resour. Assoc. 35 (2), 311–322. https://doi.org/10.1111/j.1752-1688.1999.tb03592.x.

Hao, Z., AghaKouchak, A., Phillips, T.J., 2013. Changes in concurrent monthly precipitation and temperature extremes. Environ. Res. Lett. 8 (3), 034014 https://doi.org/10.1088/1748-9326/8/3/034014.

Hijmans, R., 2020. raster: geographic data analysis and modeling. R package version 3.3-13 (Version 3.3-13). Retrieved from. https://CRAN.R-project.org/package=raster.

Hoerling, M., Eischeid, J., Kumar, A., Leung, R., Mariotti, A., Mo, K., et al., 2014. Causes and predictability of the 2012 Great plains drought. Bull. Am. Meteorol. Soc. 95 (2), 269–282. https://doi.org/10.1175/BAMS-D-13-00055.1.

IPCC, 2021. Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Mazdiyasni, O., AghaKouchak, A., 2015. Substantial increase in concurrent droughts and heatwaves in the United States. Proc. Natl. Acad. Sci. USA 112 (37), 11484–11489. https://doi.org/10.1073/pnas.1422945112.

McCabe, G., Wolock, D., Pederson, G., Woodhouse, C., McAfee, S., 2017. Evidence that recent warming is reducing upper Colorado river flows. Earth Interact. 21 (10), 1–14. https://doi.org/10.1175/EI-D-17-0007.1.

Moritz, M.A., Morais, M.E., Summerell, L.A., Carlson, J.M., Doyle, J., 2005. Wildfires, complexity, and highly optimized tolerance. Proc. Natl. Acad. Sci. USA 102 (50), 17912–17917. https://doi.org/10.1073/pnas.0508985102.

Mote, P.W., Rupp, D.E., Li, S., Sharp, D.J., Otto, F., Uhe, P.F., et al., 2016. Perspectives on the causes of exceptionally low 2015 snowpack in the western United States. Geophys. Res. Lett. 43 (20) https://doi.org/10.1002/2016GL069965.

Mueller, B., Seneviratne, S.I., 2012. Hot days induced by precipitation deficits at the global scale. Proc. Natl. Acad. Sci. USA 109 (31), 12398–12403. https://doi.org/10.1073/pnas.1204330109.

NIDIS, 2021. Drought Early Warning Systems (DEWS) Regions. Retrieved January 20, 2021, from. https://www.drought.gov/drought/regions/dews.

NOAA, 2021. February 2). What is flash drought? What can we do about it? Retrieved February 6, 2021, from. https://www.drought.gov/news/what-flash-drought-what-can-we-do-about-it.

Otkin, J.A., Svoboda, M., Hunt, E.D., Ford, T.W., Anderson, M.C., Hain, C., Basara, J.B., 2018. Flash droughts: a review and assessment of the challenges Imposed by rapid-onset droughts in the United States. Bull. Am. Meteorol. Soc. 99 (5), 911–919. https://doi.org/10.1175/BAMS-D-17-0149.1.

Paulo, A.A., Rosa, R.D., Pereira, L.S., 2012. Climate trends and behaviour of drought indices based on precipitation and evapotranspiration in Portugal. Nat. Hazards Earth Syst. Sci. 12 (5), 1481–1491. https://doi.org/10.5194/nhess-12-1481-2012.

Pebesma, E., 2018. Simple Features for R: standardized support for spatial vector data. Rice J. 10 (1), 439. https://doi.org/10.32614/RJ-2018-009.

Pendergrass, A.G., Meehl, G.A., Pulwarty, R., Hobbins, M., Hoell, A., AghaKouchak, A., et al., 2020. Flash droughts present a new challenge for subseasonal-to-seasonal prediction. Nat. Clim. Change 10 (3), 191–199. https://doi.org/10.1038/s41558-020-0709-0.

Pierce, D., 2019. ncdf4: Interface to Unidata netCDF Format Data Files. R Package Version 1.17. Retrieved from, Version 1.17. https://CRAN.R-project.org/package=ncdf4.

PRISM Climate Group, 2004. PRISM Gridded Climate Data. Oregon State University. Retrieved from. http://prism.oregonstate.edu.

Qing, Y., Wang, S., Ancell, B.C., Yang, Z.-L., 2022. Accelerating flash droughts induced by the joint influence of soil moisture depletion and atmospheric aridity. Nat. Commun. 13 (1), 1139. https://doi.org/10.1038/s41467-022-28752-4.

R Core Team, 2019. R: a language and environment for statistical computing. Version 3.6.2). Vienna. Retrieved from. https://www.R-project.org/.

Ribeiro, A.F.S., Russo, A., Gouveia, C.M., Pires, C.A.L., 2020. Drought-related hot summers: a joint probability analysis in the Iberian Peninsula. Weather Clim. Extrem. 30, 100279 https://doi.org/10.1016/j.wace.2020.100279.

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., et al., 2018. Anthropogenic warming exacerbates European soil moisture droughts. Nat. Clim. Change 8 (5), 421–426. https://doi.org/10.1038/s41558-018-0138-5.

Schubert, S.D., Suarez, M.J., Pegion, P.J., Koster, R.D., Bacmeister, J.T., 2004. On the cause of the 1930s dust Bowl. Science 303 (5665), 1855–1859. https://doi.org/10.1126/science.1095048.

Seager, R., Neelin, D., Simpson, I., Liu, H., Henderson, N., Shaw, T., et al., 2014. Dynamical and thermodynamical causes of large-scale changes in the hydrological cycle over North America in response to global warming. J. Clim. 27 (20), 7921–7948. https://doi.org/10.1175/JCLI-D-14-00153.1.

Shrum, T.R., Travis, W.R., Williams, T.M., Lih, E., 2018. Managing climate risks on the ranch with limited drought information. Climate Risk Mange. 20, 11–26. https://doi.org/10.1016/j.crm.2018.01.002.

Steeves, P., Douglas, N., 1994. 1:250,000-scale Hydrologic Units of the United States. U. S. Geological Survey, Reston. Retrieved from. https://water.usgs.gov/GIS/huc.html.

Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2014. Global warming and changes in drought. Nat. Clim. Change 4 (1), 17–22. https://doi.org/10.1038/nclimate2067.

Udall, B., Overpeck, J., 2017. The twenty-first century Colorado River hot drought and implications for the future. Water Resour. Res. 53 (3), 2404–2418. https://doi.org/10.1002/2016WR019638.

Ulrich, J., 2020. TTR: technical trading rules. R package version 0.24.2 (Version 0.24.2). Retrieved from. https://CRAN.R-project.org/package=TTR.

Vicente-Serrano, S., Beguería, S., López-Moreno, J., 2010. A multiscalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. J. Clim. 23 (7), 1696–1718. https://doi.org/10.1175/2009JCLI2909.1.

Vicente-Serrano, S., Beguería, S., Lorenzo-Lacruz, J., Camarero, J., López-Moreno, J., Azorin-Molina, C., et al., 2012. Performance of drought indices for ecological, agricultural, and hydrological applications. Earth Interact. 16 (10), 1–27. https://doi.org/10.1175/2012EI000434.1.

Vicente-Serrano, S., Quiring, S., Peña-Gallardo, M., Yuan, S., Domínguez-Castro, F., 2020. A review of environmental droughts: increased risk under global warming? Earth Sci. Rev. 201, 102953 https://doi.org/10.1016/j.earscirev.2019.102953.

Warrick, R.A., 1975. Drought Hazard in the U.S.; A Research Assessment. University of Colorado, Boulder.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L.D., François, R., et al., 2019. Welcome to the tidyverse. J. Open Source Software 4 (43), 1686. https://doi.org/10.21105/joss.01686.

Wilhite, D.A., Glantz, M.H., 1985. Understanding the drought phenomenon: the role of definitions. Water Int. 10 (3), 111–120. https://doi.org/10.1080/02508068508686328.

Williams, A.P., Cook, E.R., Smerdon, J.E., Cook, B.I., Abatzoglou, J.T., Bolles, K., et al., 2020. Large contribution from anthropogenic warming to an emerging North American megadrought. Science 368 (6488), 314–318. https://doi.org/10.1126/science.aaz9600.

Yu, R., Zhai, P., 2020. Changes in compound drought and hot extreme events in summer over populated eastern China. Weather Clim. Extrem. 30, 100295 https://doi.org/10.1016/j.wace.2020.100295.

Yung, L., Phear, N., DuPont, A., Montag, J., Murphy, D., 2015. Drought adaptation and climate change beliefs among working ranchers in Montana. Weather, Climate, and Society 7 (4), 281–293. https://doi.org/10.1175/WCAS-D-14-00039.1.

Zhang, F., Biederman, J.A., Dannenberg, M.P., Yan, D., Reed, S.C., Smith, W.K., 2021. Five decades of observed daily precipitation reveal longer and more variable drought events across much of the western United States. Geophys. Res. Lett. 48 (7) https://doi.org/10.1029/2020GL092293.