ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL092293

Five Decades of Observed Daily Precipitation Reveal Longer and More Variable Drought Events Across Much of the Western United States

Fangyue Zhang[1,2], Joel A. Biederman[1], Matthew P. Dannenberg[3], Dong Yan[2], Sasha C. Reed[4], and William K. Smith[2]

[1]USDA Agricultural Research Service Southwest Watershed Research Center, Tucson, AZ, USA, [2]School of Natural Resources and the Environment, University of Arizona, Tucson, AZ, USA, [3]Department of Geographical and Sustainability Sciences, University of Iowa, Iowa City, IA, USA, [4]Southwest Biological Science Center, U.S. Geological Survey, Moab, UT, USA

Key Points:

- Daily station data reveal longer and more variable dry intervals between rainfall during the period 1976–2019 across much of the western US
- The longest dry interval per year increased in 75% of ecoclimatic domains of the western US
- In the Desert Southwest and Southwest Rockies/Colorado Plateau, increasing temporal variability of rainfall compounded with reduced rainfall

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

F. Zhang,
fangyuezhang@arizona.edu

Citation:

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. *Geophysical Research Letters*, *48*, e2020GL092293. https://doi.org/10.1029/2020GL092293

Received 25 DEC 2020
Accepted 4 MAR 2021

Abstract

Multiple lines of evidence suggest climate change will result in increased precipitation variability and consequently more frequent extreme events. These hydroclimatic changes will likely have significant socioecological impacts, especially across water-limited regions. Here we present an analysis of daily meteorological observations from 1976 to 2019 at 337 long-term weather stations distributed across the western United States (US). In addition to widespread warming (0.2 °C ± 0.01°C/decade, daily maximum temperature), we observed trends of reduced annual precipitation (−2.3 ± 1.5 mm/decade) across most of the region, with increasing interannual variability of precipitation. Critically, daily observations showed that extreme-duration drought became more common, with increases in both the mean and longest dry interval between precipitation events (0.6 ± 0.2, 2.4 ± 0.3 days/decade) and greater interannual variability in these dry intervals. These findings indicate that, against a backdrop of warming and drying, large regions of the western US are experiencing intensification of precipitation variability, with likely detrimental consequences for essential ecosystem services.

Plain Language Summary

Changes in precipitation have far-reaching consequences for socioecological systems, especially in water-limited regions such as those common in the western US. While the total amount of precipitation is important for these systems, key aspects of precipitation timing, such as the length of dry periods between precipitation events, can strongly influence ecosystem services including ecosystem carbon uptake, productivity for grazing and forage, wildfire frequency, and intensity, and water availability for societal use. In this study, we used daily meteorological data from over three hundred long-term weather stations across the western US to understand changes in precipitation amounts and timing during the period 1976–2019. In addition to widespread warming, we found overall lower precipitation combined with increasing variability in the size of precipitation events, indicating the western US is not only getting hotter and drier, but that systems are experiencing more year-to-year variation in precipitation. We also found that the average time without precipitation has increased during the past 45 years across the southwestern US, and we saw increases in year-to-year fluctuations in these dry periods. Together, these changes will likely have large, but still poorly understood, consequences for social and ecological systems of the western US.

1. Introduction

Understanding the impacts of climate change on the hydrologic cycle of the western United States (US) remains an area of critical uncertainty, though emerging evidence suggests precipitation deficits will be amplified by climate warming, with severe consequences for vegetation, water supplies, agriculture, wildlife, and wildfire risk (Cook et al, 2014, 2020; Dai, 2011, 2013; Mankin et al., 2017; Maurer et al., 2020; Milly & Dunne, 2020; Parks et al., 2016). Although the total amount of precipitation is a key commonly reported metric, often the temporal consistency of precipitation is more important than the total amount for maintaining adequate soil moisture supply, forage for livestock and wildlife, the replenishment of human water resources, and the mitigation of wildfire risk (Heisler-White et al., 2008; Littell et al., 2016; Liu et al., 2010). Thus, the timing and duration of dry interval (time between precipitation events) is fundamental to socioecological function, such that a year with above-average total precipitation may not be any better than a below-average year if precipitation events are not consistently distributed in either time or space. Prior studies of daily-scale precipitation observations suggest that the number of dry days per year is increasing across most Southwest US stations, with continued increases projected for the future (McCabe et al., 2010; Polade et al., 2014). Other critical characteristics of precipitation, such as changes in the longest dry interval (including summer dry and winter dry spells), are also expected to change and will likely have dramatic effects on socioecological dynamics (Cable & Huxman, 2004; Huxman et al., 2004; Noy-Meir, 1973; Reed et al., 2012; Tucker et al., 2017). Declines in wetting rain days during fire season was proved to be a driver of increases in western US wildfire area burned (Holden et al., 2018). However, the western US is characterized by precipitation with heterogeneous temporal patterns and high spatial variability due to the hierarchy of climatic controls that operate at different spatial scales, including multiple moisture sources and delivery systems and large mountain ranges (Mock, 1996), and it is unclear how spatial and temporal shifts in the underlying characteristics (e.g., dry interval between events, longest dry interval and frequency) of daily precipitation events will unfold across the region in a changing climate.

Socioecological systems are sensitive not only to the mean state of precipitation (e.g., annual precipitation, mean annual dry interval) but also the intra- and inter-annual variability of precipitation characteristics (e.g., of annual/seasonal precipitation or annual/seasonal dry interval) (Gherardi & Sala, 2015; Pilar Fernandez-Illescas & Rodriguez-Iturbe, 2003; Thomey et al., 2011). Increasing precipitation variability across multiple time scales (daily, annual, or decadal) is a likely consequence of a warmer climate, resulting from both changes in ocean-atmosphere circulation systems like the El Niño–Southern Oscillation and increases in saturation vapor pressure in a warmer atmosphere (Huang & Xie, 2015; Pendergrass et al., 2017; Räisänen, 2002). Since the variability of annual precipitation totals does not fully explain impacts on ecosystems (e.g., a few heavy rainfall events could be less beneficial for ecosystems than many intermediate rainfall events) (Li et al., 2019; Liu et al., 2017), it is necessary to consider the variability of other precipitation variables at the daily scale (such as frequency of wet days, interval between precipitation events). Moreover, the importance and variability of precipitation differs seasonally, and these seasonal changes are important components of the regional precipitation system (McCabe et al., 2010). Increases in intra- and interannual variability and frequency of precipitation extremes could create severe water management problems in most part of western US (Berg & Hall, 2015; Boer, 2009; Fatichi et al., 2012; Swain et al., 2018). Thus, gaining insight into daily, seasonal, and interannual-scale precipitation fluctuations over past decades is a critical gap in our knowledge of annual precipitation and seasonal drought variability in the western US.

To address this knowledge gap in temporal patterns of observed precipitation across the western US, we used daily precipitation records to examine changes in the mean state and interannual variability of key seasonal and annual meteorological attributes including total precipitation, mean and maximum dry interval duration between precipitation events, and wet day frequency. We separately examined changes occurring within the cool and warm seasons, which have important and differing implications for ecosystems and water resources in the western US. In particular, we focus on identifying regions that may be undergoing the greatest pressure from combined changes in temperature, precipitation amount, and the temporal variability of precipitation.

2. Data and Methods

Historical daily precipitation and maximum and minimum temperature across the western US (defined as of 32°N–49°N, 124°W–102°W) during the period 1976–2019 were obtained from the Global Historical Climatology Network (GHCN) (Figure 1a). These data provide the most comprehensive set of historical daily weather station data, which have been compiled from a dozen major meteorological networks in the U.S. and processed using a common set of rigorous quality assurance procedures (Menne et al., 2012; Menne et al., 2012). Here our main focus is on the daily-scale characteristics of total precipitation and how it has changed from 1976 to 2019, during which many stations have nearly complete daily records. We used precipitation records from the 337 stations and temperature from 404 stations with fewer than 5% missing daily records per year (i.e., fewer than 18 days) and with no more than five years of missing data during the study period (Table S1). We additionally evaluated the smaller number of stations available from 1925 to 2019 and from 1955 to 2019 and confirmed the trends in both the mean and the variability of precipitation

10.1029/2020GL092293

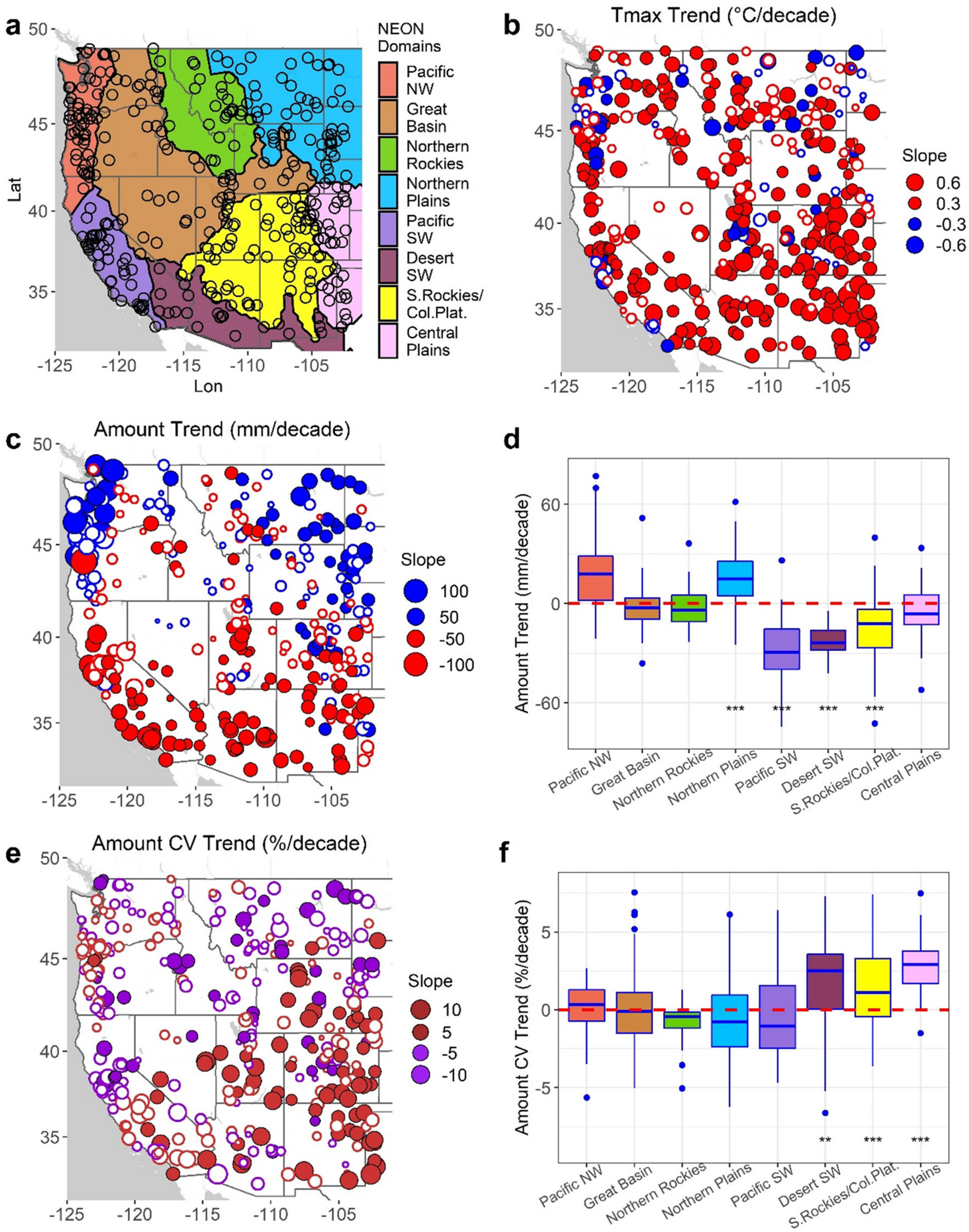


Figure 1. Distribution of meteorological stations and National Ecological Observatory Network domains used in this study (a). Trends of mean maximum temperature (b, °C/decade), precipitation amount (c, mm/decade) and variability (CV, e, %/decade). Filled circles indicate significant trends ($p < 0.05$) while open circles are insignificant ($p > 0.05$), calculated with Mann-Kendall tests. Box plots show the Sen's Slope (mm/decade, %/decade) estimated from Mann-Kendall trend tests of mean (d) and variability (f) of total annual precipitation. Lines inside boxes are medians, while the bottom and top of the box show the first and the third quartiles. Whiskers extend 1.5 times the interquartile range beyond the box or the extreme value, if it is closer. Circles indicate values outside 1.5 times the interquartile range. Asterisks indicate a significant regional trend estimated from the regional Kendall test (*, $p < 0.1$; **, $p < 0.05$; ***, $p < 0.01$).

are similar (Figures S1–S4). We do not explicitly consider changes in the form of precipitation such as the proportion falling as snow, but discuss its importance in the high-elevation portions of the western US, where snowpack acts as a water storage mechanism decoupling the timing of precipitation (i.e., snowfall days) from the moisture inputs to the land surface (snowmelt) (e.g., Harpold et al., 2012; Mote et al., 2018).

Daily precipitation totals outside of three standard deviations from the mean of long-term annual total values were filtered from the analysis of precipitation amount but included in the analysis of interval and frequency (Harpold et al., 2012). Precipitation events smaller than 3 mm result primarily in surface evaporation without wetting the root zone (Huxman et al., 2004), so precipitation events were defined as days with more than 3 mm of precipitation recorded. We selected four variables to assess changes in the mean state and temporal variability of precipitation through time at the 337 climate stations: The total amount of precipitation, frequency of precipitation events, mean dry interval between events (median dry interval duration had little impact on the results), and longest dry interval. Each variable was calculated annually and seasonally for the North American cool season (November to April) and warm season (May to October) (Ralph & Dettinger, 2012; Rutz et al., 2014). We also assessed trends in the interannual variation of these precipitation metrics using the coefficient of variability calculated within five-year moving windows. Trends in the mean and variability of each precipitation metric for each individual station were analyzed using Mann-Kendall (MK) nonparametric trend tests (which does not account for autocorrelation), and regional trends in mean and variability were analyzed using the Regional Kendall test (RKT) (Harpold et al., 2012; Helsel & Frans, 2006) with stations grouped by National Ecological Observatory Network (NEON) domains that represent distinct regions of vegetation, landforms, and ecosystem dynamics (Anderegg & Diffenbaugh, 2015) (Figure 1a). MK and RKT tests were performed using the "modifiedmk" and "rkt" packages, respectively, in R (Marchetto & Marchetto, 2015; Patakamuri & Patakamuri, 2017). The Kendall tests (both MK and RKT) of slopes were estimated using the nonparametric Sen's slope (Sen, 1968) with statistical significance assessed at the 95% level. Since meteorological station networks, including those represented in GHCN, are typically biased toward low elevation sites (Hik & Williamson, 2019) (Figure S5), we also conducted these analyses separately for two subsets of stations: those below 1,000 m elevation, and those above 1,000 m elevation (Figure S6).

3. Results

3.1. Trends in Precipitation Totals and Frequency

Over the past 45 years, most stations in the western US show warming and drying trends. We found an average increase in both daily maximum temperature (0.2°C ± 0.01°C/decade) (Figures 1b, S7a and S7b) and minimum temperature (0.2°C ± 0.01°C/decade) (Figures S7c–S7e). Total annual precipitation decreased with an average trend of −2.3 ± 1.5 mm per year per decade across most of the region, particularly in the Desert Southwest domain, with similar trends in the cool season (Figures 1c, 1d and S8a). The spatial patterns of trends in precipitation amount in the cool and warm seasons were similar to annual trends, but greater in magnitude during the cool season (Figure S8b). However, much of the northern part of the study area, particularly the Northern Plains, experienced a wetting trend in total precipitation at both annual and seasonal time scales (Figure S8). Interannual precipitation variability in the western US also increased over the southern region, especially over the Desert Southwest, Southern Rockies/Colorado Plateau, and Central Plains (Figures 1e and 1f).

Trends in the frequency of precipitation events varied considerably in magnitude and direction over the study domain, with increases in the northern portion and decreases in the southern portion, especially across the Desert Southwest (1.6 days/decade, $p < 0.01$, Figures 2 and S9). Meanwhile, interannual variability of annual wet day frequency generally increased at 60 stations (mostly in the southwestern US) and decreased at 39 stations (mostly in the northern part of the domain) (Figure 2). Overall, precipitation events became more frequent and less variable from year-to-year across most of the northern part of the study area but less frequent and more variable across most of the southwestern US.

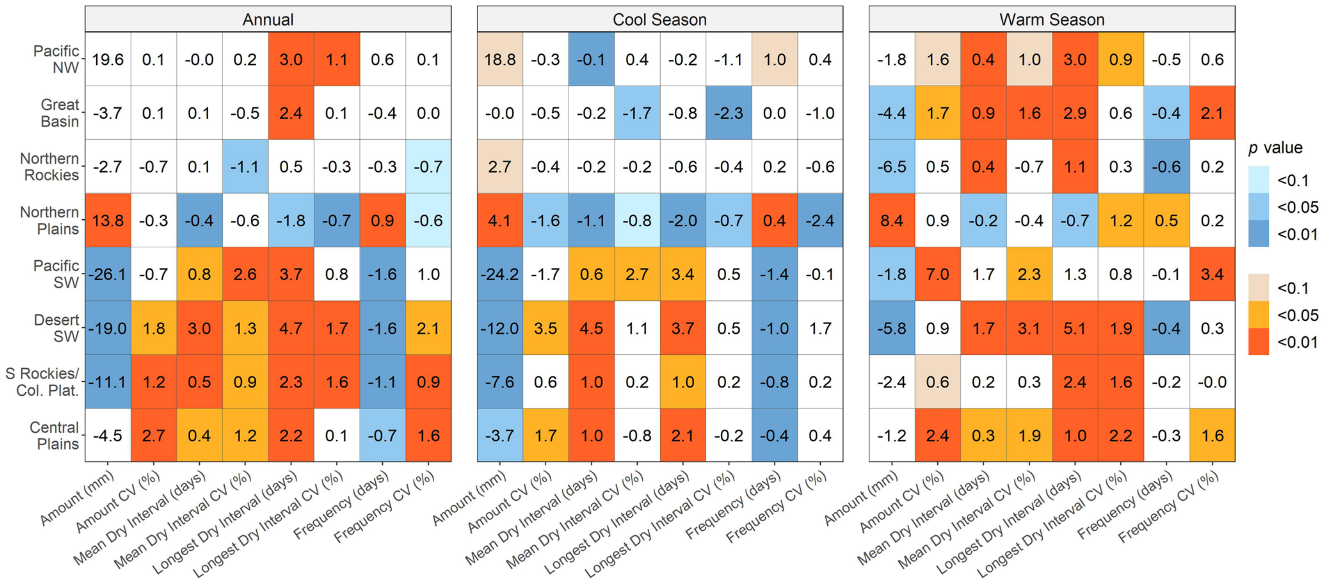


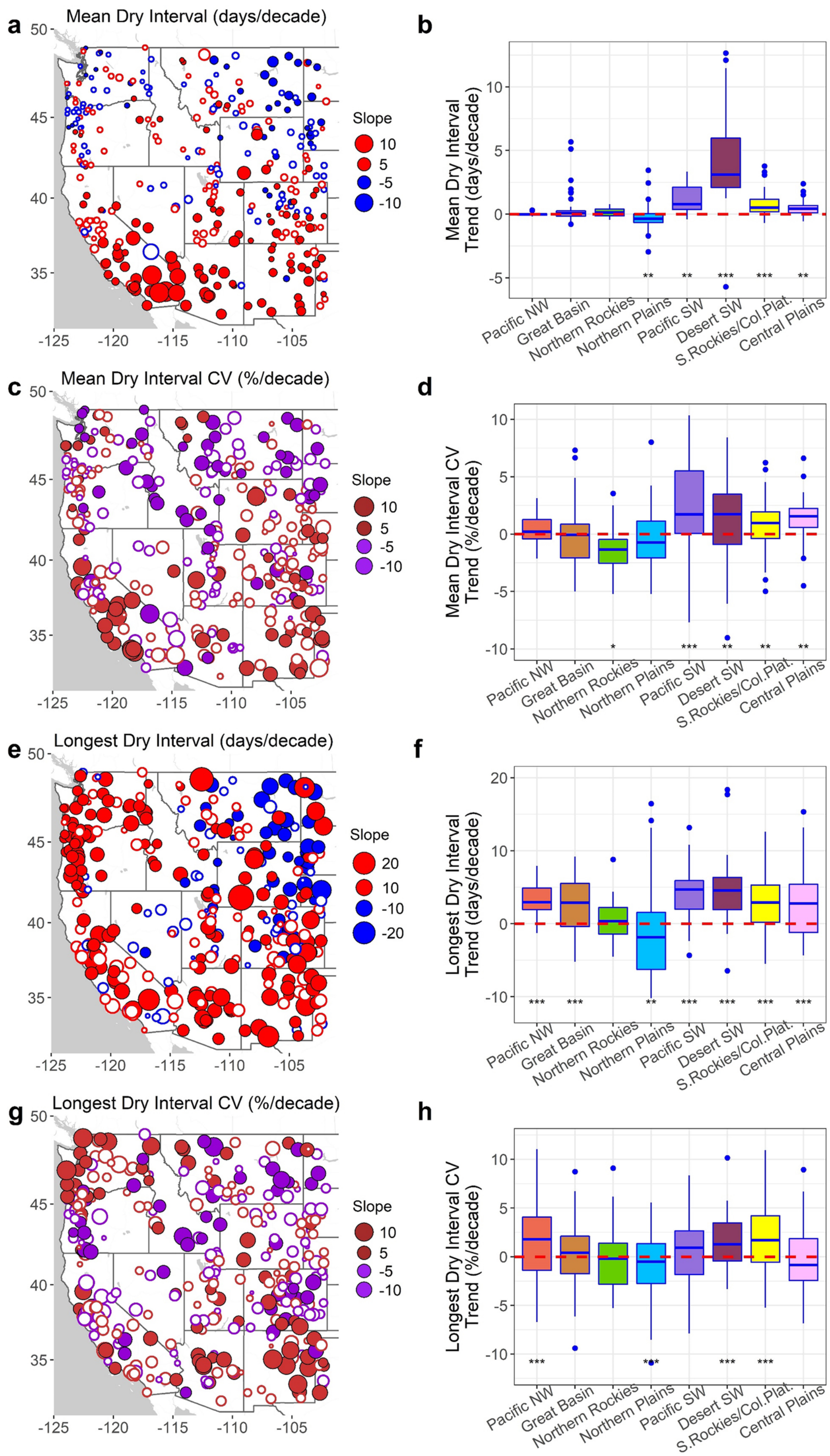
Figure 2. Trends per decade quantified by Sen's Slope estimated from the regional Kendall tests of mean and variability (CV) of precipitation amount, dry interval, longest dry interval, and frequency in annual (November to October), cool (November to April), and warm (May to October) season. Intensity of the color relates to the significance of change through time for each region and precipitation metric. Positive values and orange coloring show a variable increased through time and negative values and blue coloring indicate decreases. White boxes show non-significant trends.

3.2. Trends in Average and Longest Interval Between Precipitation Events

Changes in the mean annual length of dry intervals between precipitation events varied across the western US, with the southwestern US (especially the Desert Southwest and Pacific Southwest) showing large (2.0 ± 0.2 days/decade, $n = 106$) and significant increases ($p < 0.05$) in mean dry interval length, while 40 stations, most in the Northern Plains, showed smaller negative trends ($p < 0.05$, -0.7 ± 0.1 days/decade) (Figures 3a and 3b). In the cool season, four domains exhibited significant increases in mean dry interval length (Pacific Southwest, Desert Southwest, Southern Rockies, and Central Plains, $p < 0.05$), while two domains showed a decrease (Pacific Northwest and Northern Plains, $p < 0.01$) (Figures 2 and S10a). In the warm season, mean dry interval length increased across most NEON domains, except the Northern Plains, Pacific Southwest, and Southern Rockies/Colorado Plateau (Figures 2 and S10b). There was considerable heterogeneity in the trends of the interannual variability of dry interval length across the western US (Figure 3c). Across the NEON domains, the maximum rate of change occurred in the Pacific Southwest, with a regional trend of 2.6% per decade increase in the interannual variability of annual mean dry interval (Figure 2).

The longest annual dry interval increased across the majority of the western US at both annual and seasonal scales (Figures 3e and S11). Six of the eight domains showed significant increases ($p < 0.01$) in longest dry interval duration. Meanwhile, the Northern Plains showed significant decreases ($p < 0.05$), and the Northern Rockies showed no significant change (Figure 2). The increases in longest dry interval duration were largely driven by changes in the latter half of the study period, with more stations showing increasing trends during 2000–2019 than during 1980–1999 (Figure S12). Changes in the interannual variability of annual longest dry interval were generally less significant and more geographically-variable than mean changes in dry interval length (Figure 3g). The interannual variability of annual and warm season longest dry interval increased at more stations (68 in annual, 90 in warm season) than it decreased (44 in annual, 38 in warm season). Overall, the interannual variability of the warm season maximum dry interval increased in most (five out of eight) NEON domains, except the Great Basin, Northern Rockies, and Pacific Southwest (Figure 2).

Against a backdrop of warming across all NEON domains of the western US, the Desert Southwest displayed a critical combination of reduced precipitation totals, increasing interannual variability, and longer-duration dry interval between precipitation events (Figures S13–S19). Precipitation amount and wet


a
Mean Dry Interval (days/decade)
Slope
10
5
-5
-10
b
Mean Dry Interval Trend (days/decade)
c
Mean Dry Interval CV (%/decade)
Slope
10
5
-5
-10
d
Mean Dry Interval CV Trend (%/decade)
e
Longest Dry Interval (days/decade)
Slope
20
10
-10
-20
f
Longest Dry Interval Trend (days/decade)
g
Longest Dry Interval CV (%/decade)
Slope
10
5
-5
-10
h
Longest Dry Interval CV Trend (%/decade)
Pacific NW
Great Basin
Northern Rockies
Northern Plains
Pacific SW
Desert SW
S.Rockies/Col.Plat.
Central Plains

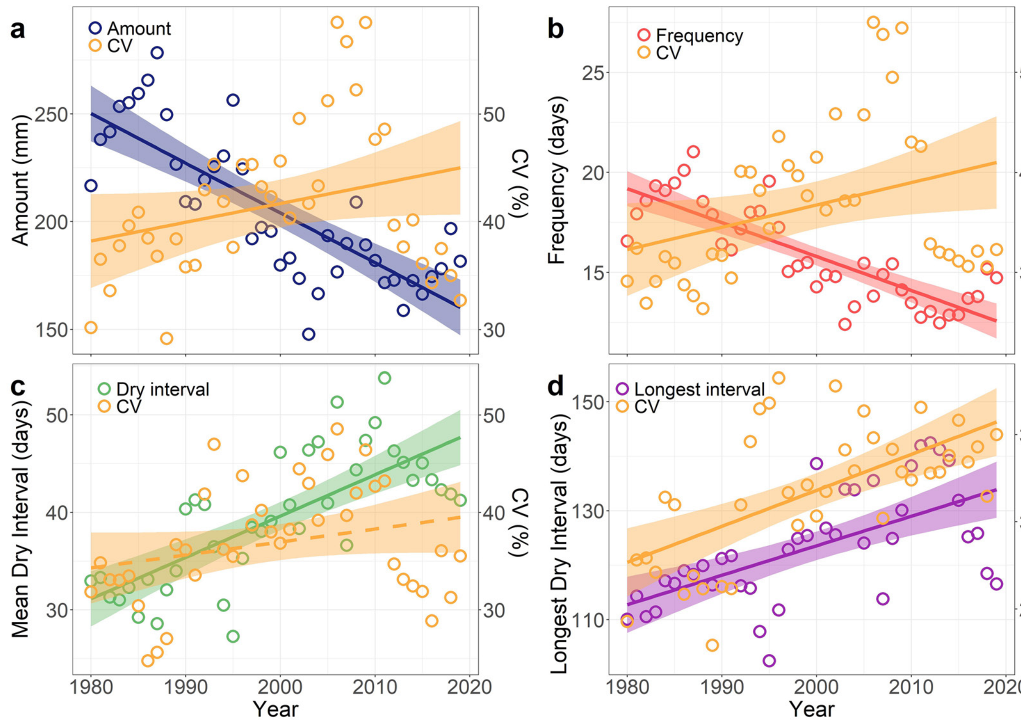


Figure 4. Linear temporal trends with 95% confidence level interval (shaded region) of mean and variability (CV) within 5-year moving windows of precipitation amount (a), frequency (b), dry interval between events (c), and the longest dry interval (d) in the Desert Southwest.

day frequency decreased in the Desert Southwest at both annual and seasonal scales, with increases in interannual variability (Figures 2, 4a and 4b). Mean dry intervals in the Desert Southwest increased by 50% over 45 years, from an estimated regional average of 31.1 ± 1.4 days to 47.7 ± 1.4 days (Figure 4c). The Desert Southwest also experienced an increasing trend in longest dry interval, with regional trend increases of 4.7 days per decade, and increasing interannual variability of annual and warm season longest dry interval (Figures 2 and 4d).

4. Discussion

We found widespread increases in dry interval duration for most of the western US at both annual and seasonal time scales, particularly across the southwestern US (Figure 3). These patterns likely compound the impacts of well-documented warming and decreases in annual precipitation and wet day frequency to suggest strong drying for the region. In particular, our findings quantify where and in what ways the temporal variability of precipitation has already changed in accordance with general expectations of increasing aridity arising from increased moisture divergence and poleward displacement of the mid-latitude jet under warming (Dannenberg & Wise, 2017; Groisman & Knight, 2008; Singh et al., 2013), and/or internal variability in atmospheric circulation (Lehner et al., 2018). This trend toward increasing dry period length is also consistent with a recent increase in frequency and intensity of atmospheric ridging over western North America (Swain et al., 2016; Wise & Dannenberg, 2014) and with higher precipitation variability resulting from increases in saturation vapor pressure in a warming climate (Pendergrass et al., 2017; Yuan et al., 2019). The findings of increased longest dry interval duration are in contrast to a study that reported a

Figure 3. Trends of mean (days/decade) and variability (CV, %/decade) of dry interval (a and c) and longest dry interval (e and g). Filled circles indicate significant trends ($p < 0.05$) while open circles indicate trends that are not significant ($p > 0.05$), calculated with Mann-Kendall tests. Box plots show the Sen's Slope of mean (days/decade) and CV (%/decade) estimated from Mann-Kendall tests of mean dry interval duration (b and d) and longest annual dry interval duration (f and h). Boxes indicate the same statistics as in Figure 1. Asterisks indicate a significant regional trend estimated from the regional Kendall test (*, $p < 0.1$; **, $p < 0.05$; ***, $p < 0.01$).

decreasing trend in the length of longest dry interval during summertime (July to September, 1931–2000) in northern parts of the southwestern US (Anderson et al., 2009), though several stations in that analysis still showed a significant positive trend in the longest dry interval. Differences in seasonal timing (e.g., summertime vs. annual) and study period (e.g., 1931–2000 vs. 1976–2019) could also contribute to this difference in trends (Figure S12), as our results show a significant acceleration of the trend after the year 1999.

We also observed changes in overall precipitation amounts (Figures 1c and 1d) and increases in precipitation variability among years for many regions (Figures 1e and 1f). In terms of precipitation amount, our data support studies showing precipitation is declining for some portions of the western US (e.g., the Desert Southwest; Figure 4), and increasing for others (e.g., Northern Great Plains; Figures 1c and 1d). While historical changes in precipitation variability have received less attention, climate model simulations point to a strongly increasing interannual variability of extreme precipitation events (e.g., Swain et al., 2018). We found overall increases in precipitation variability for multiple regions at annual and seasonal time scales. Interestingly, while some regions showed increased precipitation variability in both the cool and warm seasons (e.g., the Desert Southwest), others showed changes only in particular seasons (e.g., Pacific Southwest).

Our results showed particularly strong patterns for the Desert Southwest (Figure 4), a region that experiences relatively high mean temperatures and lower annual water inputs. We found strong decreases in the amount and frequency of precipitation over the 45 years of our study. We also found that the mean dry interval and the longest dry interval have increased substantially, providing quantitative, multi-decadal evidence that droughts are becoming longer and more frequent. Our findings support previous studies that have found temperatures have increased, total precipitation has decreased, and interannual variability of precipitation has increased across the dry southwestern US (Dannenberg et al., 2019; Fatichi et al., 2012; Sheppard et al., 2002; Sloat et al., 2018). Against this warming and drying backdrop, our daily-scale analysis reveals novel aspects of hydroclimate change including large increases in dry interval and precipitation variability at both annual and season scales (Figures 2 and 3), portending potential large-scale, detrimental socioecological consequences for the Desert Southwest. Changes to the form of precipitation are also likely, such as a transition from snow to rain as the climate warms (Figure 1b), and these changes would also likely have significant effects on the fate of precipitation (Robles et al., 2021).

The timing of precipitation among seasons and years can be critical in determining ecosystem responses. Such changes can have large effects on ecosystem services in the western US, as precipitation variability is strongly correlated to critical ecosystem functions (Fang et al., 2001; Paruelo & Lauenroth, 1998; Vargas et al., 2012). For example, if plant responses to precipitation are "asymmetric"—meaning that ecosystem structure or function responds more strongly to extreme events in one direction (wet or dry) than the other—then an increase in precipitation variability can lead to long-term changes in growth even with no change in mean precipitation inputs (Dannenberg et al., 2019; Knapp et al., 2017). Additionally, precipitation timing could contribute to other more abrupt transitions, such as ecosystem mortality events (Allen & Breshears, 1998; Breshears et al., 2005) and fire activity and severity (Parks & Abatzoglou, 2020). Changes in the amount, frequency, and variability of precipitation could also be exacerbated by other regionally important changes not considered here including soil moisture feedbacks, fuels moisture, runoff, evapotranspiration, snowfall, and snowmelt (Klos et al., 2014; Lynn et al., 2020). For instance, western US ecosystems could experience enhanced drought vulnerability since longer and warmer dry periods could reduce snowpack while simultaneously increasing evapotranspiration, resulting in relatively rapid depletion of plant available water stores (Rungee et al., 2019). Future research aimed at better understanding and projecting the impacts of water resource changes across these various aspects of socioecological drought is urgently needed to mitigate future dryland degradation and loss of the essential ecosystem services they provide, especially in light of evidence of an emerging North American megadrought (Williams et al., 2020).

5. Conclusions

Here, we analyzed the trends and variability of precipitation events using daily records from 337 GHCN-Daily stations across the western US to examine the patterns and magnitude of changes in precipitation characteristics, including the total amount, frequency, dry interval length, and interannual variability of seasonal and annual precipitation. Our findings suggest that dry interval durations are becoming longer

(0.6 ± 0.2 days/decade) and more variable from year-to-year (0.5 ± 0.1%/decade), across many of the West's vulnerable arid and semiarid domains including the Desert Southwest, Southwest Rockies/Colorado Plateau, and Central Plains. Moreover, the longest dry interval per year increased across most NEON domains of the western US, except in the Northern Plains and Northern Rockies, showing that long dry spells are becoming increasingly common. Concurrent with increases in dry interval duration, most parts of the western US became significantly hotter and drier, with lower precipitation totals, decreased frequency of wet days, and greater interannual variability of multiple precipitation characteristics. Each of these changes speaks to increased aridification for the region, and these changes suggest potential amplification of the projected detrimental socioecological impacts of increases in temperature and vapor pressure deficit, including reductions in carbon uptake, increased potential for desertification, intensified wildfire activity, and reduced water availability for human consumption (Williams et al., 2020). Our work highlights the widespread prevalence of changes in the frequency, seasonality, and variability of precipitation across temporal and spatial scales, and it suggests the importance of examining multiple aspects of precipitation change in studies of climate-socioecological system interactions rather than changes in annual mean precipitation alone.

Data Availability Statement

Datasets used in this study were downloaded from https://www.ncdc.noaa.gov/ghcnd-data-access.

Acknowledgments

We greatly appreciate feedback received on an early version of this manuscript from Scott Ferrenberg and Peter Adler. We acknowledge support for this work provided by the Strategic Environmental Research and Development Program (SERDP; project number RC18-1322), the United States Department of Agriculture (USDA; cooperative agreement numbers 58-3050-9-013 and 58-2022-8-010), and the University of Arizona Earth Dynamics Observatory, funded by the office of Research, Innovation & Impact. MPD was also partly supported by the scholar-in-residence program at the University of Iowa's Public Policy Center. Any use of firm, product, or trade names is for descriptive purposes only and does not imply endorsement by the U.S. Government. USDA is an equal opportunity employer.

References

Allen, C. D., & Breshears, D. D. (1998). Drought-induced shift of a forest-woodland ecotone: Rapid landscape response to climate variation. *Proceedings of the National Academy of Sciences*, *95*(25), 14839–14842. https://www.pnas.org/content/95/25/14839

Anderegg, W. R., & Diffenbaugh, N. S. (2015). Observed and projected climate trends and hotspots across the National Ecological Observatory Network regions. *Frontiers in Ecology and the Environment*, *13*(10), 547–552. https://doi.org/10.1890/150159

Anderson, B. T., Wang, J., Salvucci, G., Gopal, S., & Islam, S. (2009). Observed trends in summertime precipitation over the southwestern United States. *Journal of Climate*, *23*(7), 1937–1944. https://doi.org/10.1175/2009JCLI3317.1

Berg, N., & Hall, A. (2015). Increased interannual precipitation extremes over California under climate change. *Journal of Climate*, *28*(16), 6324–6334. https://doi.org/10.1175/JCLI-D-14-00624.1

Boer, G. J. (2009). Changes in interannual variability and decadal potential predictability under global warming. *Journal of Climate*, *22*(11), 3098–3109. https://doi.org/10.1175/2008JCLI2835.1

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. *Proceedings of the National Academy of Sciences*, *102*(42), 15144–15148. https://doi.org/10.1073/pnas.0505734102

Cable, J. M., & Huxman, T. E. (2004). Precipitation pulse size effects on Sonoran Desert soil microbial crusts. *Oecologia*, *141*(2), 317–324. https://doi.org/10.1007/s00442-003-1461-7

Cook, B. I., Mankin, J. S., Marvel, K., Williams, A. P., Smerdon, J. E., & Anchukaitis, K. J. (2020). Twenty-first century drought projections in the CMIP6 forcing scenarios. *Earth's Future*, *8*(6), e2019EF001461. https://doi.org/10.1029/2019EF001461

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

Dai, A. (2011). Drought under global warming: A review. *WIREs Climate Change*, *2*(1), 45–65. https://doi.org/10.1002/wcc.81

Dai, A. (2013). The influence of the inter-decadal Pacific oscillation on U.S. precipitation during 1923–2010. *Climate Dynamics*, *41*(3), 633–646. https://doi.org/10.1007/s00382-012-1446-5

Dannenberg, M. P., & Wise, E. K. (2017). Shifting pacific storm tracks as stressors to ecosystems of western North America. *Global Change Biology*, *23*(11), 4896–4906. https://doi.org/10.1111/gcb.13748

Dannenberg, M. P., Wise, E. K., & Smith, W. K. (2019). Reduced tree growth in the semiarid United States due to asymmetric responses to intensifying precipitation extremes. *Science Advances*, *5*(10), eaaw0667. https://doi.org/10.1126/sciadv.aaw0667

Fang, J., Piao, S., Tang, Z., Peng, C., & Ji, W. (2001). Interannual variability in net primary production and precipitation. *Science*, *293*(5536), 1723a. https://doi.org/10.1126/science.293.5536.1723a

Fatichi, S., Ivanov, V. Y., & Caporali, E. (2012). Investigating interannual variability of precipitation at the global scale: Is there a connection with seasonality?. *Journal of Climate*, *25*(16), 5512–5523. https://doi.org/10.1175/JCLI-D-11-00356.1

Gherardi, L. A., & Sala, O. E. (2015). Enhanced precipitation variability decreases grass- and increases shrub-productivity. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(41), 12735–12740. https://doi.org/10.1073/pnas.1506433112

Groisman, P. Y., & Knight, R. W. (2008). Prolonged dry episodes over the Conterminous United States: New tendencies emerging during the last 40 years. *Journal of Climate*, *21*(9), 1850–1862. https://doi.org/10.1175/2007JCLI2013.1

Harpold, A., Brooks, P., Rajagopal, S., Heidbuchel, I., Jardine, A., & Stielstra, C. (2012). Changes in snowpack accumulation and ablation in the intermountain west. *Water Resources Research*, *48*(11). https://doi.org/10.1029/2012wr011949

Heisler-White, J. L., Knapp, A. K., & Kelly, E. F. (2008). Increasing precipitation event size increases aboveground net primary productivity in a semi-arid grassland. *Oecologia*, *158*(1), 129–140. https://doi.org/10.1007/s00442-008-1116-9

Helsel, D. R., & Frans, L. M. (2006). Regional Kendall test for trend. *Environmental Science Technology*, *40*(13), 4066–4073. https://doi.org/10.1021/es051650b

Hik, D. S., & Williamson, S. N. (2019). Need for mountain weather stations climbs. *Science*, *366*(6469), 1083. https://doi.org/10.1126/science.aaz7450

Holden, Z. A., Swanson, A., Luce, C. H., Jolly, W. M., Maneta, M., Oyler, J. W., et al. (2018). Decreasing fire season precipitation increased recent western US forest wildfire activity. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(36), E8349. https://doi.org/10.1073/pnas.1802316115

Huang, P., & Xie, S.-P. (2015). Mechanisms of change in ENSO-induced tropical Pacific rainfall variability in a warming climate. *Nature Geoscience*, *8*(12), 922–926. https://doi.org/10.1038/ngeo2571

Huxman, T. E., Snyder, K. A., Tissue, D., Leffler, A. J., Ogle, K., Pockman, W. T., et al. (2004). Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. *Oecologia*, *141*(2), 254–268. https://doi.org/10.1007/s00442-004-1682-4

Klos, P. Z., Link, T. E., & Abatzoglou, J. T. (2014). Extent of the rain-snow transition zone in the western US under historic and projected climate. *Geophysical Research Letters*, *41*(13), 4560–4568. https://doi.org/10.1002/2014GL060500

Knapp, A. K., Ciais, P., & Smith, M. D. (2017). Reconciling inconsistencies in precipitation-productivity relationships: Implications for climate change. *New Phytologist*, *214*(1), 41–47. https://doi.org/10.1111/nph.14381

Lehner, F., Deser, C., Simpson, I. R., & Terray, L. (2018). Attributing the U.S. Southwest's recent shift into drier conditions. *Geophysical Research Letters*, *45*(12), 6251–6261. https://doi.org/10.1029/2018gl078312

Li, L., Zheng, Z., Biederman, J. A., Xu, C., Xu, Z., Che, R., et al. (2019). Ecological responses to heavy rainfall depend on seasonal timing and multi-year recurrence. *New Phytologist*, *223*(2), 647–660. https://doi.org/10.1111/nph.15832

Littell, J. S., Peterson, D. L., Riley, K. L., Liu, Y., & Luce, C. H. (2016). A review of the relationships between drought and forest fire in the United States. *Global Change Biology*, *22*(7), 2353–2369. https://doi.org/10.1111/gcb.13275

Liu, W. J., Li, L. F., Biederman, J. A., Hao, Y. B., Zhang, H., Kang, X. M., et al. (2017). Repackaging precipitation into fewer, larger storms reduces ecosystem exchanges of CO_2 and H_2O in a semiarid steppe. *Agricultural and Forest Meteorology*, *247*, 356–364. https://doi.org/10.1016/j.agrformet.2017.08.029

Liu, Y., Stanturf, J., & Goodrick, S. (2010). Trends in global wildfire potential in a changing climate. *Forest Ecology and Management*, *259*(4), 685–697. https://doi.org/10.1016/j.foreco.2009.09.002

Lynn, E., Cuthbertson, A., He, M., Vasquez, J. P., Anderson, M. L., Coombe, P., et al. (2020). Technical note: Precipitation-phase partitioning at landscape scales to regional scales. *Hydrology and Earth System Sciences*, *24*(11), 5317–5328. https://doi.org/10.5194/hess-24-5317-2020

Mankin, J. S., Smerdon, J. E., Cook, B. I., Williams, A. P., & Seager, R. (2017). The curious case of projected twenty-first-century drying but greening in the American West. *Journal Climate*, *30*(21), 8689–8710. https://doi.org/10.1175/JCLI-D-17-0213.1

Marchetto, A., & Marchetto, M. A. (2015). Package 'rkt. *Technology*, *40*, 4066–4073.

Maurer, G. E., Hallmark, A. J., Brown, R. F., Sala, O. E., & Collins, S. L. (2020). Sensitivity of primary production to precipitation across the United States. *Ecology Letters*, *23*(3), 527–536. https://doi.org/10.1111/ele.13455

McCabe, G. J., Legates, D. R., & Lins, H. F. (2010). Variability and trends in dry day frequency and dry event length in the southwestern United States. *Journal of Geophysical Research*, *115*(D7). https://doi.org/10.1029/2009JD012866

Menne, M. J., Durre, I., Korzeniewski, B., McNeal, S., Thomas, K., Yin, X., et al. (2012). *Global historical climatology network-daily (GHCN-Daily), Version 3*. NOAA National Climatic Data Center. https://doi.org/10.7289/V5D21VHZ

Menne, M. J., Durre, I., Vose, R. S., Gleason, B. E., & Houston, T. G. (2012). An overview of the global historical climatology network-daily database. *Journal of Atmospheric and Oceanic Technology*, *29*(7), 897–910. https://doi.org/10.1175/JTECH-D-11-00103.1

Milly, P. C. D., & Dunne, K. A. (2020). Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation. *Science*, *367*(6483), 1252. https://doi.org/10.1126/science.aay9187

Mock, C. J. (1996). Climatic controls and spatial variations of precipitation in the western United States. *Journal of Climate*, *9*(5), 1111–1125. https://doi.org/10.1175/1520-0442(1996)009<1111:CCASVO>2.0.CO;2

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

Noy-Meir, I. (1973). Desert ecosystems: Environment and producers. *Annu. Review Ecology System*, *4*, 25–51. www.jstor.org/stable/2096803

Parks, S. A., & Abatzoglou, J. T. (2020). Warmer and drier fire seasons contribute to increases in area burned at high severity in Western US Forests from 1985 to 2017. *Geophysical Research Letters*, *47*(22), e2020GL089858. https://doi.org/10.1029/2020GL089858

Parks, S. A., Miller, C., Abatzoglou, J. T., Holsinger, L. M., Parisien, M.-A., & Dobrowski, S. Z. (2016). How will climate change affect wildland fire severity in the western US?. *Environmental Research Letters*, *11*(3), 035002. https://doi.org/10.1088/1748-9326/11/3/035002

Paruelo, J. M., & Lauenroth, W. K. (1998). Interannual variability of NDVI and its relationship to climate for North American shrublands and grasslands. *Journal of Biogeography*, *25*(4), 721–733. https://doi.org/10.1046/j.1365-2699.1998.2540721.x

Patakamuri, S. K., & Patakamuri, M. S. K. (2017). *Package 'modifiedmk.'*

Pendergrass, A. G., Knutti, R., Lehner, F., Deser, C., & Sanderson, B. M. (2017). Precipitation variability increases in a warmer climate. *Scientific Reports*, *7*(1), 17966. https://doi.org/10.1038/s41598-017-17966-y

Pilar Fernandez-Illescas, C., & Rodriguez-Iturbe, I. (2003). Hydrologically driven hierarchical competition-colonization models: The impact of Interannual Climate Fluctuations. *Ecological Monographs*, *73*(2), 207–222. https://doi.org/10.1890/0012%2D9615(2003)073[0207:HDHCMT]2.0.CO;2

Polade, S. D., Pierce, D. W., Cayan, D. R., Gershunov, A., & Dettinger, M. D. (2014). The key role of dry days in changing regional climate and precipitation regimes. *Scientific Reports*, *4*(1), 4364. https://doi.org/10.1038/srep04364

Räisänen, J. (2002). CO_2-induced changes in interannual temperature and precipitation variability in 19 CMIP2 experiments. *Journal of Climate*, *15*(17), 2395–2411. https://doi.org/10.1175/1520-0442(2002)015<2395:CICIIT>2.0.CO;2

Ralph, F. M., & Dettinger, M. D. (2012). Historical and national perspectives on extreme West Coast precipitation associated with atmospheric rivers during December 2010. *Bulleting American Meteorological Society*, *93*(6), 783–790. https://doi.org/10.1175/bams-d-11-00188.1

Reed, S. C., Coe, K. K., Sparks, J. P., Housman, D. C., Zelikova, T. J., & Belnap, J. (2012). Changes to dryland rainfall result in rapid moss mortality and altered soil fertility. *Nature Climate Change*, *2*(10), 752–755. https://doi.org/10.1038/nclimate1596

Robles, M. D., Hammond, J. C., Kampf, S. K., Biederman, J. A., & Demaria, E. M. C. (2021). Winter inputs buffer streamflow sensitivity to snowpack losses in the Salt River Watershed in the Lower Colorado River Basin. *Water*, *13*(1). https://doi.org/10.3390/w13010003

Rungee, J., Bales, R., & Goulden, M. (2019). Evapotranspiration response to multiyear dry periods in the semiarid western United States. *Hydrological Processes*, *33*(2), 182–194. https://doi.org/10.1002/hyp.13322

Rutz, J. J., Steenburgh, W. J., & Ralph, F. M. (2014). Climatological characteristics of atmospheric rivers and their inland penetration over the western United States. *Monthly Weather Review*, *142*(2), 905–921. https://doi.org/10.1175/MWR-D-13-00168.1

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's Tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Sheppard, P., Comrie, A., Packin, G., Angersbach, K., & Hughes, M. (2002). The climate of the US Southwest. *Climate Research*, *21*(3), 219–238. https://doi.org/10.3354/cr021219

Singh, D., Tsiang, M., Rajaratnam, B., & Diffenbaugh, N. S. (2013). Precipitation extremes over the continental United States in a transient, high-resolution, ensemble climate model experiment. *Journal of Geophysical Research - D: Atmospheres*, *118*(13), 7063–7086. https://doi.org/10.1002/jgrd.50543

Sloat, L. L., Gerber, J. S., Samberg, L. H., Smith, W. K., Herrero, M., Ferreira, L. G., et al. (2018). Increasing importance of precipitation variability on global livestock grazing lands. *Nature Climate Change*, *8*(3), 214–218. https://doi.org/10.1038/s41558-018-0081-5

Swain, D. L., Horton, D. E., Singh, D., & Diffenbaugh, N. S. (2016). Trends in atmospheric patterns conducive to seasonal precipitation and temperature extremes in California. *Science Advances*, *2*(4). https://doi.org/10.1126/sciadv.1501344

Swain, D. L., Langenbrunner, B., Neelin, J. D., & Hall, A. (2018). Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change*, *8*(5), 427–433. https://doi.org/10.1038/s41558-018-0140-y

Thomey, M. L., Collins, S. L., Vargas, R., Johnson, J. E., Brown, R. F., Natvig, D. O., & Friggens, M. T. (2011). Effect of precipitation variability on net primary production and soil respiration in a Chihuahuan Desert grassland. *Global Change Biology*, *17*(4), 1505–1515. https://doi.org/10.1111/j.1365-2486.2010.02363.x

Tucker, C. L., McHugh, T. A., Howell, A., Gill, R., Weber, B., Belnap, J., et al. (2017). The concurrent use of novel soil surface microclimate measurements to evaluate CO_2 pulses in biocrusted interspaces in a cool desert ecosystem. *Biogeochemistry*, *135*(3), 239–249. https://doi.org/10.1007/s10533-017-0372-3

Vargas, R., Collins, S. L., Thomey, M. L., Johnson, J. E., Brown, R. F., Natvig, D. O., & Friggens, M. T. (2012). Precipitation variability and fire influence the temporal dynamics of soil CO_2 efflux in an arid grassland. *Glob Change Biology*, *18*(4), 1401–1411. https://doi.org/10.1111/j.1365-2486.2011.02628.x

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

Wise, E. K., & Dannenberg, M. P. (2014). Persistence of pressure patterns over North America and the North Pacific since AD 1500. *Nature Communications*, *5*(1), 4912. https://doi.org/10.1038/ncomms5912

Yuan, W., Zheng, Y., Piao, S., Ciais, P., Lombardozzi, D., Wang, Y., et al. (2019). Increased atmospheric vapor pressure deficit reduces global vegetation growth. *Science Advances*, *5*(8). https://doi.org/10.1126/sciadv.aax1396