Longer and More Variable Drought Events Across Much of the Western United States

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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 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.
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, %/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.
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
day frequency decreased in the Desert Southwest at both annual and seasonal scales, with increases in inter-
annual 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 tem-
poral 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 ($^*$,
$p < 0.1$; $^{**}$, $p < 0.05$; $^{***}$, $p < 0.01$).

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.
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 aridity 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.

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