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How unusual is the 2012–2014 California drought?

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Key Points:

- Tree rings reveal California drought severity is unusual in 1200 years
- 2012–2014 precipitation deficits severe but not exceptional in paleocontext
- Record high temperatures exacerbate moisture deficit for extraordinary drought

Supporting Information:

- Figures S1–S6

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Abstract For the past three years (2012–2014), California has experienced the most severe drought conditions in its last century. But how unusual is this event? Here we use two paleoclimate reconstructions of drought and precipitation for Central and Southern California to place this current event in the context of the last millennium. We demonstrate that while 3 year periods of persistent below-average soil moisture are not uncommon, the current event is the most severe drought in the last 1200 years, with single year (2014) and accumulated moisture deficits worse than any previous continuous span of dry years. Tree ring chronologies extended through the 2014 growing season reveal that precipitation during the drought has been anomalously low but not outside the range of natural variability. The current California drought is exceptionally severe in the context of at least the last millennium and is driven by reduced though not unprecedented precipitation and record high temperatures.

1. Introduction

Drought is a fundamental feature of the climate of western North America. Over the last century, regions of the western United States have experienced protracted decadal-scale dry periods, including those during the Dust Bowl, the 1950s, and now again during the early 21st century [*Seager et al.*, 2005; *Cook et al.*, 2009; *Woodhouse et al.*, 2010; *Cook et al.*, 2014a]. Each of these resulted in substantial economic, agricultural, hydrological, and ecological consequences. The paleoclimate record also provides unequivocal evidence of previous epochs of longer and more severe "megadroughts" [*Woodhouse and Overpeck*, 1998; *Cook et al.*, 2007; *Stahle et al.*, 2007; *Cook et al.*, 2010; *Woodhouse et al.*, 2010] particularly in the Great Plains and semiarid western North America. In Central and Southern California, the instrumental spectrum of drought variability is predominantly interannual [*Ault and St. George*, 2010], reflecting the quasiperiodic influence of the El Niño–Southern Oscillation [*Cayan et al.*, 1999], regional atmospheric pressure anomalies [*Cayan et al.*, 1998], and "drought-busting" atmospheric rivers [*Dettinger*, 2013]. However, even in California paleoclimate records point to transient but important low-frequency hydroclimate variability during the Common Era [*Malamud-Roam et al.*, 2006], with clear evidence of sustained multidecadal megadroughts [*Stine*, 1994].

California is presently in the midst of the worst drought in over a century of instrumental observations (Figure 1a and Figures S1 and S2 in the supporting information), with extreme aridity in 2014 compounding already dry conditions in 2012 and 2013 [*Swain et al.*, 2014]. The 3 year episode now surpasses the historic 1976–1977 and late 1980s droughts. "Exceptional drought" covered most of the state by September 2014, as measured by an integrated assessment of meteorological, agricultural, and hydrological indices that reflects the combined influence of precipitation, evapotranspiration, and soil water storage (Figure S1) [*Svoboda et al.*, 2002]. From autumn 2013 through spring of 2014, Central and Southern California in particular experienced some of the lowest water year precipitation totals in the observational climate record (Figure S4), the effects of which have been amplified by record high temperatures (Figure S3) [*Vose et al.*, 2014; *NOAA*, 2014]. Diminished snowpack, streamflows, and reservoir levels have resulted in a convergence of reduced surface water supply with heightened demand that appears to be unique in modern California history.

How unusual is the current California drought in the context of the last millennium? While drought conditions are expected to be exacerbated as a consequence of anthropogenic warming and increased evaporative demand [*Seager et al.*, 2007; *Cook et al.*, 2014b; *Seager and Hoerling*, 2014], California has suffered severe multiyear droughts during the instrumental era as well as over the last several centuries [*Meko and Woodhouse*, 2005]. Here we use two complementary paleoclimate resources to provide a long-term context for the current drought. We focus on the National Oceanic and Atmospheric Administration (NOAA) California climate divisions 4 through 7 (Figure S1) in Central and Southern California. This region includes

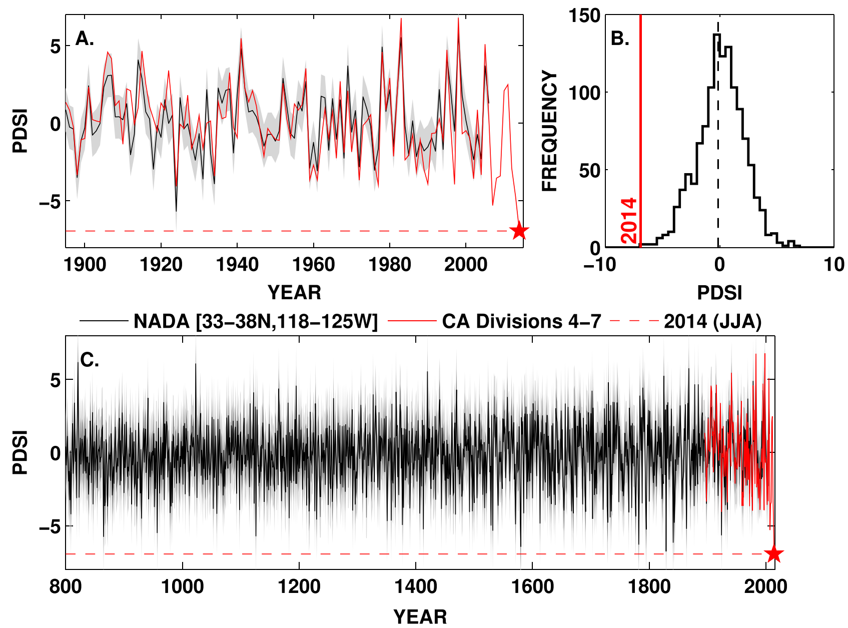

Figure 1. (a) Regional mean North American Drought Atlas (NADA) PDSI for Central and Southern California (33°N to 38°N and 118°W to 125°W; black line) and instrumental June through August NOAA Climate Division 4–7 PDSI (solid red line) for the observational period 1895 to 2014 [*Vose et al.*, 2014]. The JJA season is chosen to match the NADA reconstruction target. Uncertainty (1σ) calculated as the root-mean-squared error from the residual fit of the NADA to the instrumental series shown as the shaded gray region. The red line and star indicate the 2014 value. (b) Distribution of the composite NADA-NOAA JJA PDSI values for the period 800 to 2014. The 2014 value is indicated by the red line and is labeled. (c) Long-term (800 to 2014) composite NADA-NOAA (black line) and instrumental (solid red line) PDSI. The horizontal dashed red line and star indicate the 2014 value. Uncertainty on the composite calculated as the root-mean-squared error from the residual fit of the NADA to the NOAA instrumental series shown as light (2σ) and dark (1σ) shaded gray regions.

most of California below 38°N and south of San Francisco Bay and has experienced the most historically severe drought conditions (Figure S2). The first reconstruction is the North American Drought Atlas (NADA) [*Cook et al.*, 2004, 2010], a 2.5°× 2.5° gridded continental-scale reconstruction of the June through August (JJA) Palmer Drought Severity Index (PDSI) based on an extensive network of nearly 2000 tree ring chronologies. PDSI integrates precipitation and temperature into an estimate of available soil moisture. For the western United States in particular the NADA displays strong calibration and verification statistics and resolves between ~40 and 60% of the variance in the target PDSI series over California [*Cook et al.*, 2010]. We extend the NADA tree ring PDSI reconstructions for Central and Southern California through the present by using the latest NOAA climate division instrumental PDSI [*Vose et al.*, 2014]. We also develop new tree ring estimates of water year (October through June) precipitation in Central and Southern California through the 2014 growing season using updated and existing blue oak (*Quercus douglasii*) tree ring chronologies from four sites. Blue oak tree ring chronologies have one of the strongest moisture signals of all the species used for dendroclimatology [*St. George*, 2014], can resolve more that 80% of the local variability in precipitation [*Meko et al.*, 2011; *Stahle et al.*, 2013], and reflect coherent large-scale rainfall anomalies over hundreds of kilometers [*Meko et al.*, 2011]. The data from the NADA provides a longer-term, highly replicated and integrative moisture perspective on California drought, while the blue oak data are a unique and up-to-date proxy source of local, precise, and highly sensitive precipitation information.

2. Methods

From the North American Drought Atlas [*Cook et al.*, 2004, 2010] we extracted all the terrestrial grid points in the range 33°N to 38°N and 118°W to 125°W for 800 to 2006 [*Cook et al.*, 2004] and calculated the area mean June through August (JJA) PDSI value. In order to maintain consistency with the NADA and make valid seasonal comparisons to the current drought, we averaged California's NOAA Climate Division 4 though 7 PDSI data [*Vose et al.*, 2014] for June through August and scaled the NADA time series by the mean of the observations and verified their standard deviations. Even prior to adjustment, these two time series are

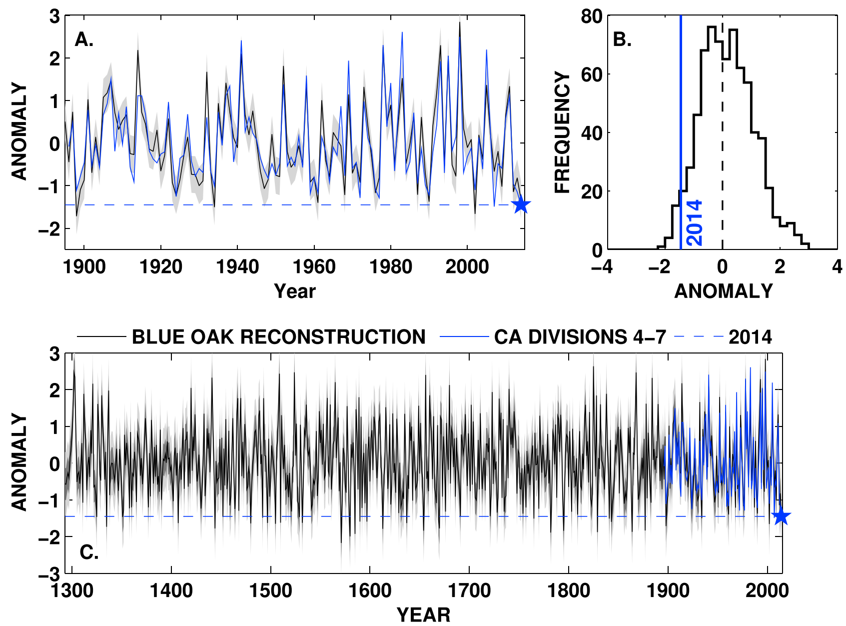

Figure 2. (a) Blue oak reconstructed (black line) and instrumental (blue line) October through June normalized mean precipitation anomalies from California NOAA Climate Divisions 4–7 [*Vose et al.*, 2014]. Uncertainty (1σ) calculated as the root-mean-squared error from the residual fit to the instrumental series shown as the shaded gray region. The dashed blue line and star indicate the 2014 value. (b) Distribution of the reconstructed October through June normalized mean precipitation anomalies for 1293–2014. The 2014 value is indicated by the blue line and labeled. (c) Long-term (1293 to 2014) reconstructed (black line) and instrumental (blue line) normalized precipitation anomalies. The dashed blue line and star indicate the 2014 value. Uncertainty on the reconstruction calculated as the root-mean-squared error from the residual fit to the instrumental series shown as light (2σ) and dark (1σ) shaded gray regions.

highly similar ($r = 0.81, p \ll 0.001$). We estimated the uncertainty in the scaled reconstruction by calculating the root-mean-squared error (1.4 PDSI units) from the residual of the fit between the instrumental and original paleoclimate data. Results are shown in Figure 1.

Our *Quercus douglasii* tree ring data and precipitation reconstruction were developed with methods standard in dendroclimatology [*Cook and Kairiūkštis*, 1990]. The regional blue oak tree ring chronology is composed of 327 radii from 273 individual trees at four sampling sites (Figure S5). Existing ring width data from Rock Springs Ranch, Figueroa Mountain, and Los Lobos sites [*Stahle et al.*, 2013] were augmented with new specimens from 65 trees sampled at Los Lobos and Little Sycamore Canyon sites (Figure S5) after the 2014 growth season was completed. Ring width measurements were detrended and prewhitened and the regional chronology was calculated as the robust biweight mean of all available tree ring indices in a given year. Fifty year running mean correlations ($\bar{r}$) of all tree ring indices averaged 0.55 and the expressed population signal (EPS) averaged 0.98, reaching a minimum value of 0.88 in the year 1363. Comparison of the regional chronology with normalized precipitation and temperature data averaged for California Climate Divisions 4 through 7 revealed a precipitation-dominated climate response with statistically significant correlation coefficients ($p < 0.05$) for individual months from October through June, a season that accounts for 96% of average water year (July–June) precipitation in the average of California Divisions 4 through 7. Bivariate linear regression was used to calibrate the prewhitened tree ring data on the instrumental target for the period 1920–2014. Regression residuals were serially random, normally distributed, heteroscedastic, and without monotonic trend. Calibration results were all positive and statistically significant ($R^2 = 0.82$; $RE = 0.81$; $CE = 0.81$). Verification statistics calculated with the independent data for the 1896–1919 period were also positive and significant ($R^2 = 0.75$, $RE = 0.69$, $CE = 0.68$). Regression results are similar ($R^2 = 0.78 - 0.83$) when the full common period was split into halves for calibration and verification and then switched (i.e., 1896–1955 and 1956–2014). Reconstruction results are shown in Figure 2. We conducted a bivariate runs analysis [*González and Valdés*, 2003] on both the precipitation reconstruction and the composite PDSI series in order to estimate the duration, severity (cumulative deficit), and interarrival interval for droughts.

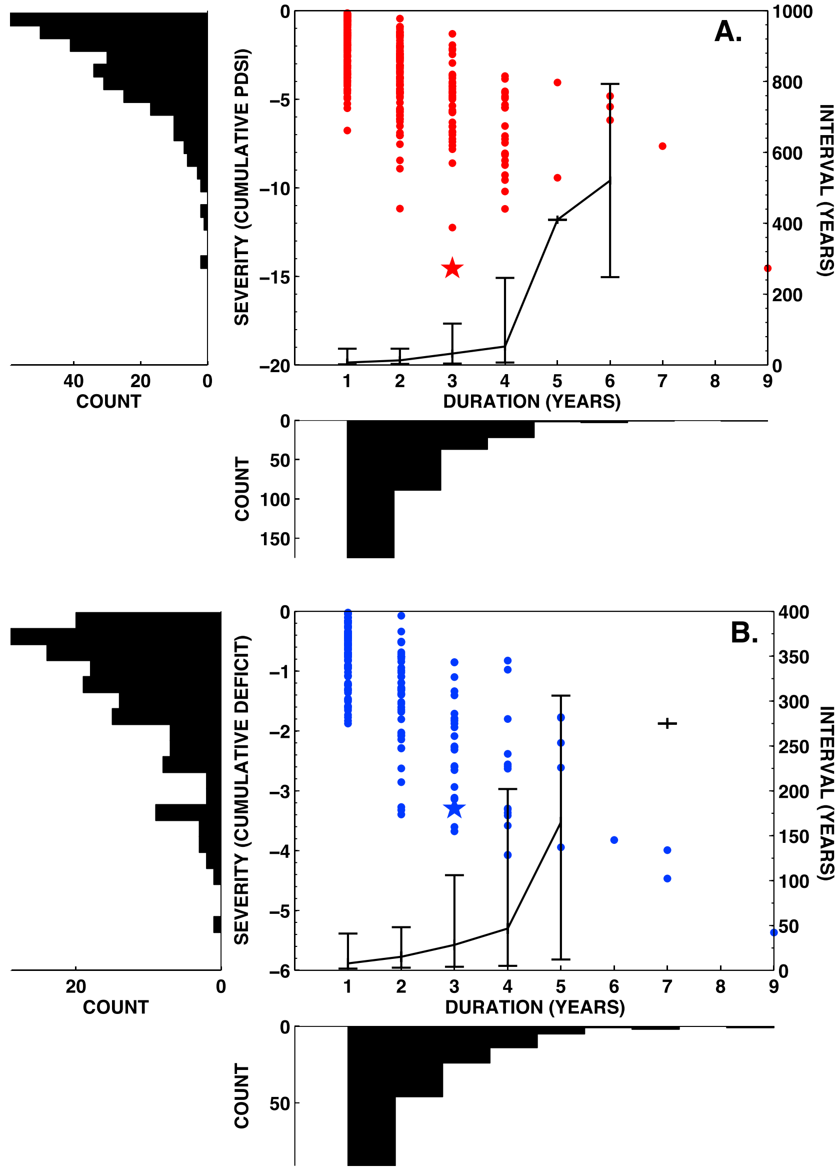

Figure 3. Severity-duration analysis [*González and Valdés*, 2003] for PDSI and precipitation reconstructions. (a) Runs analysis for the JJA PDSI composite for consecutive years below the long-term (800–2014) mean value. Filled circles indicate individual drought events of the duration (defined as consecutive years below the long-term 800–2014 mean) shown on the *x* axis and of a cumulative severity shown on the left-hand *y* axis. Marginal histograms show the distribution of severity (left-hand *y* axis) with the associated duration (*x* axis). The vertical line and whisker plots correspond to the right-hand *y* axis and show the interval between droughts of the duration shown on the *x* axis. These are calculated as the number of years between the end of one and beginning of the next drought of the corresponding duration. Whiskers show the maximum and minimum interval between events. The 2012–2014 drought is indicated by the filled star. (b) As in Figure 3a but for the October–March (1293–2014) blue oak precipitation reconstruction.

3. Results

Based on our NOAA-NADA composite PDSI record, we estimate that 2014 is the worst single drought year of at least the last ~1200 years in California (Figure 1). Taking into account the uncertainties in scaling the NADA tree ring data to the instrumental PDSI, 6 years were possibly similar to or drier than 2014, (including 1580, 1782, 1829, and 1841 CE) at the 1σ level, while 36 years out of the last 1215 years include the 2014 value within 2σ uncertainty. Three year droughts are not unusual over the last millennium in California and they can occur with as little as a single year between negative moisture anomalies (Figure 3a). Over the last 1200 years, we estimate that there are 37 occurrences of 3 year droughts and a total of 66 uninterrupted dry

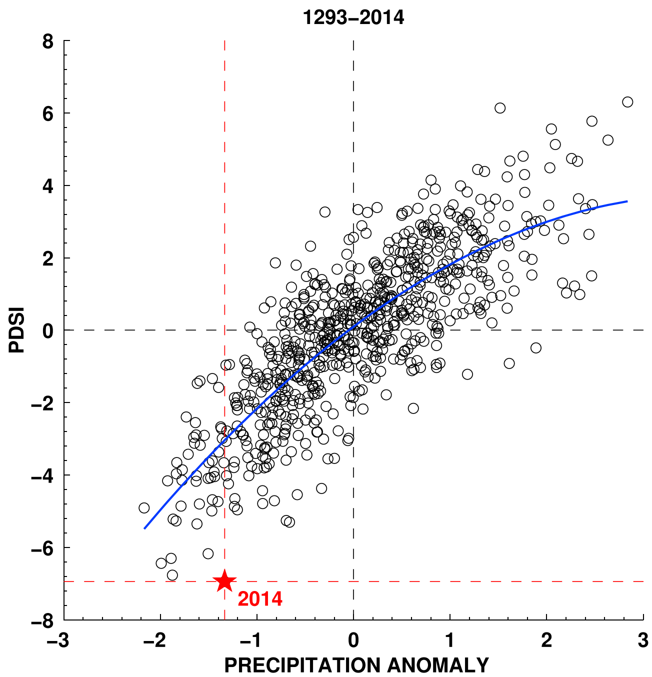

Figure 4. Bivariate distribution of the composite JJA NADA-NOAA PDSI and October–June reconstructed normalized mean precipitation anomalies. The 2014 value is indicated by the red star and dashed red lines and is labeled. The blue curve shows the least squares second-order polynomial fit to the data. Dashed black lines show the zero values for each distribution.

periods (e.g., every year below the 800 to 2014 mean) lasting between 3 and 9 years. We estimate that ~44% of 3 year droughts go on to last 4 years or longer. However, the 2012–2014 drought stands out in the context of the last millennium. In terms of cumulative severity, it is the worst drought on record (−14.55 cumulative PDSI), more extreme than longer (4 to 9 year) droughts. Considering only drought episodes defined by at least three consecutive years all lower than −2 PDSI, only three such events occur in the last 1200 years, and 2012–2014 is the most severe of these.

Our October to June precipitation reconstruction is based on existing blue oak tree ring chronologies [*Stahle et al.*, 2013] augmented with new specimens collected after the completion of the 2014 growth season and therefore spans 1293 to 2014 CE (Figure 2). The bivariate proxy-observation relationship is linear, stable through time, coherent across the frequency domain, and exceptionally robust by dendroclimate standards ($R^2_{calibration} = 0.82$, $R^2_{validation} = 0.75$). The hydroclimate signal in blue oak is dominated by cool season precipitation [*Meko et al.*, 2011], with minimal secondary influence of warm season temperature. Comparison with a high-resolution gridded precipitation data set demonstrates that the reconstruction reflects precipitation variability over a large region and that this coherence reflects the influence of westerly storm tracks on the blue oak tree ring sites in Central and Southern California (Figure S5).

The reconstructed precipitation value for 2014 is extremely low, in the lowest sixth percentile (1293–2014; Figure 2b). However, deficits in 2014 are less severe than those reconstructed during punctuated dry periods in the late sixteenth (1571, 1580, and 1585), eighteenth (1721, 1765, 1782, and 1795), or nineteenth (1829, 1864, 1877, and 1898) centuries (Figure 2c). Moderately greater precipitation deficits were also reconstructed during the instrumental period (1934, 1961, 1990, and 2002). All years during 2012–2014 have below-average precipitation, but their cumulative reconstructed rainfall deficit is not yet unprecedented (Figure 3b). More extreme consecutive year precipitation deficits are evident near the turn of the twentieth century (1898–1900) and in the early sixteenth century (1527–1529). Similar events were reconstructed during the early (1735–1737) and late eighteenth (1794–1796) century. Longer episodes (from four to nine consecutive years) of below-average precipitation are also present in the reconstruction, and many of these had more severe accumulated precipitation deficits than the 2012–2014 event (Figure 3b). Approximately 50% of 3 year periods with below-average precipitation continue on to last for 4 years or longer.

4. Discussion and Conclusions

Evaluated using an integrated soil moisture metric like PDSI, the 2012–2014 drought is the worst in our combined NOAA-NADA estimate and 2014 is the single most arid case in at least the last 1200 years. In contrast, the precipitation deficits of 2014 and the 3 year period are not unique in the paleoclimate record (Figure 4). A simple modeling exercise (Figure S6), calculating the average division 4–7 PDSI with observed [*Vose et al.*, 2014] versus climatological mean temperatures, suggests that temperature could have exacerbated the 2014 drought by approximately 36%. Based on these complementary lines of evidence, we infer that the severity of the 2014 drought is a result of both anomalously low—yet not unprecedented—water year precipitation (Figure S4) and record high temperatures (Figure S3). The 2014 JJA PDSI value is ~3.5 standard deviations below the long-term (800–2014) mean (Figure 1b) and the cumulative 2012–2014 drought is the worst unbroken drought interval of the last millennium (Figures 3a and 4). Precipitation for 2012–2014 was indeed low but is less than 1.5 standard deviations below the reconstructed long-term normalized regional mean and not unprecedented over the last seven centuries, neither on the annual nor 3 year time scale. These observations from the paleoclimate record suggest that high temperatures have combined with the low but not yet exceptional precipitation deficits to create the worst short-term drought of the last millennium for the state of California.

A return to normal rainfall levels may partially relieve some of the immediate water resources pressures imposed by the current drought, perhaps through an El Niño event or a series of landfalling atmospheric rivers [*Dettinger*, 2013]. However, the blue oak precipitation reconstruction reveals that the climate system is capable of natural precipitation deficits of even greater duration and severity than has so far been witnessed during the comparatively brief 2012–2014 drought episode. Attribution of anthropogenic influence on California rainfall and Pacific storm tracks during the current drought is thus far equivocal [*Funk et al.*, 2014; *Swain et al.*, 2014; *Wang and Schubert*, 2014] and future rainfall patterns in California remain unclear, due both to climate model differences and internal climate system variability [*Pierce et al.*, 2012; *Kirtman et al.*, 2013; *Deser et al.*, 2014]. However, projections for a continued trend toward higher mean and extreme temperatures are robust and will play an increasingly important role in 21st century hydroclimate [*Seager and Hoerling*, 2014]. Future "hot" droughts [*Overpeck*, 2013; *Pederson et al.*, 2014], driven by increasing temperatures due to anthropogenic emissions of greenhouse gases and enhanced evaporative demand, are assured and will be a substantial influence on future water resources supply and management in the western United States [*Cook et al.*, 2014b]. Additional uncertainties remain, including the nature of land-surface feedbacks between soil moisture and temperatures [*Yin et al.*, 2014], the sensitivity of drought metrics such as PDSI to data and methodological choices [*Trenberth et al.*, 2014], and the multivariate influence of temperature and precipitation on paleoclimate proxy records. Further insight into California's drought history will come from developing longer tree ring chronologies by updating existing series to the present, expanding the use of subfossil wood to extend further into the past, and exploring the dendrochronological potential of underutilized species.

In California, droughts have and will continue to occur, as evidenced by the paleoclimate and instrumental record and as projected by Earth System Models of the anthropogenic future. While the natural environments of Central and Southern California have been shaped by hydroclimatic extremes, the state's built environment reflects a complex—and at times maladaptive [*Christian-Smith et al.*, 2014]—solution to the spatial and temporal asymmetry between surface water supplies and socioeconomic water resources demand. Future severe droughts are expected to be in part driven by anthropogenic influences and temperatures outside the range of the last millennium. However, understanding past drought and precipitation variability through paleoclimate data may prove useful for adapting to climate change despite continuing uncertainties regarding regional precipitation in a warmer future.

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