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2,500 Years of Hydroclimate Variability in New Mexico, USA

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Key Points:
- Over the past 2,500 years, over 50 drought events surpass the severity of the recent 21st century droughts
- 20th to 21st century had more extreme hydroclimate flips than any other period
- Document previously unknown prolonged and severe drought during the second to third century BCE (Pre-Ancestral Puebloan)

Supporting Information:
- Supporting Information S1

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Abstract We provide a 2,508-year reconstruction (492 BCE–2015 CE) of hydroclimate variability for west-central New Mexico using the long-lived conifer Rocky Mountain juniper (*Juniperus scopulorum* Sarg.). The reconstruction model explains 53% of the instrumental soil moisture variance and all validation statistics indicate a skillful record. More hydroclimate flips (extreme wet-dry, vice versa) occur during the 20th–21st century than any other century in the past 2,500 years. Yet, drought and pluvial events captured during the instrumental period (since ca. 1900) do not represent the full range and variability of historical conditions. Since ca. 500 BCE, over 50 drought events have surpassed the severity of recent 21st century conditions, including the first documentation of a prolonged and severe drought during the second to third century BCE (Pre-Ancestral Puebloan). Continued extreme hydroclimate variability (e.g., flips) in the 21st century could create infrastructure challenges for regional water planning authorities in this arid region.

1. Introduction

The emerging reality across the Western United States is that human-induced climate change will continue to exacerbate hydroclimate conditions and extremes. Portions of California have recently experienced unprecedented drought conditions in the last 1,200 years (Griffin & Anchukaitis, 2014), and precipitation volatility is projected to increase during the 21st century (Swain et al., 2018). Over the past millennium, regions across the Great Plains (Woodhouse & Overpeck, 1998), Colorado (Meko et al., 2007; Salzer & Kipfmueller, 2005; Udall & Overpeck, 2017), Utah (Knight et al., 2010), and the broader American Southwest (e.g., Cook et al., 1999, 2004; Woodhouse et al., 2010) have experienced dry conditions that exceed the severity and duration of conditions recorded during the observed period. Tree rings are the most widely used high-resolution hydroclimate proxies in the Southwest, where adverse growing conditions (e.g., Schulman, 1954) yield a region rich with millennial-length paleoclimate records. More records in this region offer the chance to better understand interrecord differences, such as to corroborate records when they agree or identify subregional hydroclimate differences over the past ca. 2,000 years.

In this paper, we provide a 2,508-year record of hydroclimate variability from west-central New Mexico using the long-lived conifer Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) sampled at the Candelaria site (hereafter CAN) near the town of Ramah. Our overarching objective is to provide a better understanding of the frequency, magnitude, and intensity of extreme droughts and pluvials in New Mexico, USA, and how the CAN drought reconstruction compares with other paleorecords across the Southwest over the past 2,500 years. First, we assess how instrumentally measured droughts of the 1950s (e.g., McGregor, 1985; Seager et al., 2005; Stahle et al., 2007) and the turn of the 21st century (e.g., Seager, 2007; Udall & Overpeck, 2017) compare with hydroclimate variability over the past 2,500 years. Routson et al. (2011) suggests the second century contained the driest conditions in the past 2,200 years in Colorado. In Utah, Knight et al. (2010) show the sixth century drought to be the most severe in the past 2,300 years. In New Mexico, Grissino-Mayer (1996) demonstrates the 16th century megadrought ranked as the most severe and prolonged since 136 BCE (2,129 years). The subregional differences between these records demonstrate the need for increased network density of multi-millennial length tree-ring chronologies and subsequent hydroclimate reconstructions (c.f. Maxwell & Harley, 2017). Second, we highlight previously unknown drought and pluvial events suggested by our long-term record. Third, we consider the spatial and temporal variability of droughts and pluvials in the region over the past 2,000+ years.

2. Methods

2.1. Experimental Design

The Zuni-Bandera volcanic field in west-central New Mexico is known to contain some of the longest-lived conifers in the Southwest (Grissino-Mayer, 1996; Lindsey, 1951). Lindsey (1951) states that trees growing on the highly porous and permeable volcanic basalt substrate are likely hypersensitive to changes in moisture availability. We sampled living and remnant Rocky Mountain juniper from the CAN site on the Zuni-Bandera volcanic field. Samples collected in the field (n = 46 radii; 23 trees) were combined with remnant wood collected previously at the site and archived at the Laboratory of Tree-Ring Research at the University of Arizona (n = 30 radii; 15 trees). Cores and cross sections were prepared and measured to the nearest 0.001 mm using standard dendrochronological methods (Speer, 2010). In the detrending process to remove biological growth trends, we maximized low frequency variability by applying a negative exponential function with variance stabilization.

Rocky Mountain juniper is found on drier mountain slopes and foothills from the Canadian Rockies south to New Mexico, USA. Testing the hypothesis of Lindsey (1951), Spond et al. (2014) demonstrate that the radial growth of juniper individuals in New Mexico is highly sensitive to water-year moisture availability. To determine climate-growth relationships and variability through time, we use instrumental self-calibrating Palmer Drought Severity Index (scPDSI; Wells et al., 2004) spanning 1901–2015 CE to test [1] monthly correlations between ring width and hydroclimate and [2] the stability of the climate signal via forward moving correlation analysis in the dplR library in R (R Core Team, 2017).

A reconstruction model was estimated by linear regression of water year (October–September) scPDSI (34.99°N, −108.08°W) on the CAN Rocky Mountain juniper tree-ring chronology (Figure S1). To validate the reconstruction model, we split the instrumental period (1902–2015) into two equal periods for calibration (1902–1957) and verification (1958–2015). Calibration models were validated using two rigorous tests of fit, the reduction of error statistic (RE) and coefficient of efficiency (CE; Fritts, 1976; Cook et al., 1999). Given that RE ranges from $-\infty$ to $+1$, a positive RE denotes that the calibration model is more skillful than the mean of the instrumental data during the calibration period. The CE has the same range and calculation, yet it relies on the verification period mean for a baseline of predictive skill and is thus more difficult to pass (value >0).

Once both RE and CE are calculated, a cross-calibration/verification process is used by switching the calibration and verification periods. The validation statistics produced are VRE (VCE) = verification period reduction of error (coefficient of efficiency). After ensuring cross-validation of the model, we use linear regression to reconstruct scPDSI calibrated over the full instrumental period (1902–2015) with the tree-ring index chronology. We evaluate the model residuals for linear trends and first order autocorrelation (Durbin-Watson statistic). To assess model uncertainty, we use the maximum entropy bootstrapping method (MEBoot; Vinod & Lopez-de-Lacalle, 2009) to produce 300 reconstruction replicates. MEBoot produces an empirical probability distribution for each reconstructed estimate (e.g., each year) on which the estimation of uncertainty is based (see Cook et al., 2013, for details).

2.2. Statistical Analyses

We use runs analysis to suggest the importance of reconstructed drought and pluvial events based on cumulative severity and duration (e.g., Bekker et al., 2014; Gray et al., 2011; Griffin & Anchukaitis, 2014; Hessl et al., 2018). We rank consecutive water-year scPDSI estimates (of at least 2+ years) below and above the reconstruction mean by duration (period of event), magnitude (cumulative values below/above the mean), and intensity (magnitude divided by duration). The total score (combined magnitude rank and duration rank) of events is ranked in determining the most impactful climatic events within the record. We characterize extreme hydroclimate "flips" during consecutive years in the reconstruction. A positive flip (dry-wet) occurs when the value of year t is <25th percentile (P_{25}) and year $t + 1$ is $> P_{75}$, and negative flips (wet-dry) vice versa. We only consider the record from 80 BCE to 2015 CE for this analysis given the effect of low sample depth on increased variability prior to 80 BCE.

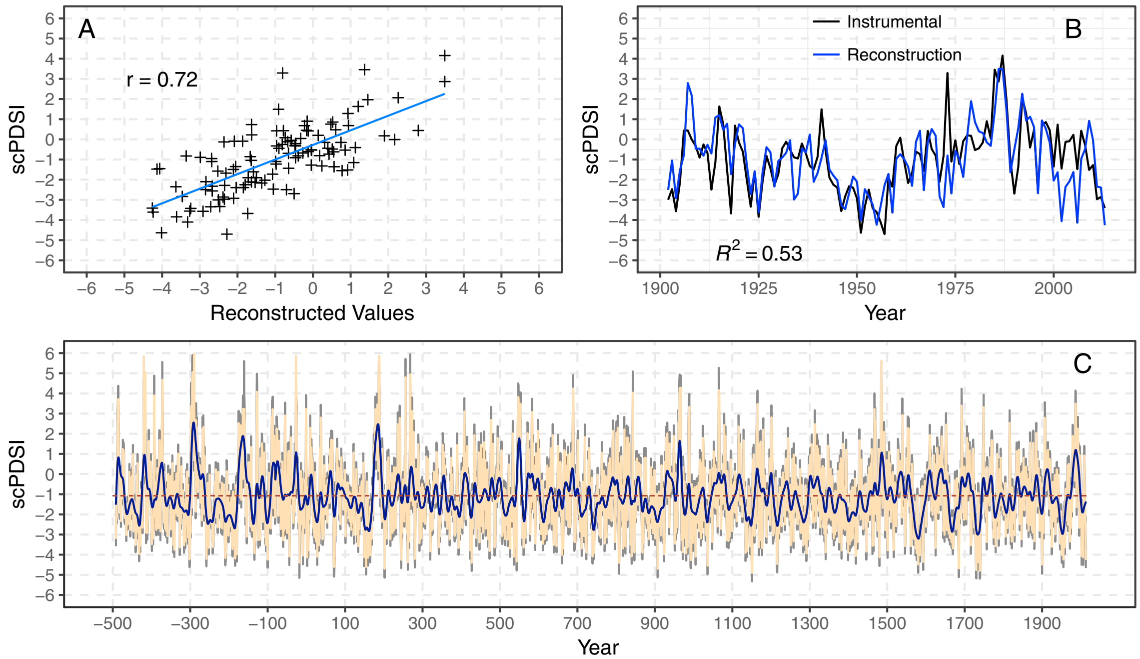

Figure 1. The Candelaria drought reconstruction. (a) Scatter plot of self-calibrating Palmer Drought Severity Index (scPDSI; 27) values and reconstructed values 1902–2015. (b) Instrumental (black) and reconstructed (blue) scPDSI values for the Candelaria drought reconstruction model 1902–2015. (c) Reconstructed scPDSI 492 BCE–2015 CE for west-central New Mexico. Time series shown are annual reconstruction values (yellow) with 5% and 95% MEBoot uncertainties (gray) and a 20-year low-pass filter smoothing spline (blue).

3. Results

The CAN Rocky Mountain juniper chronology comprises a total of 76 measured series with an interseries correlation of 0.76 and mean segment length of 450 years. The expressed population signal—a metric that relates to the signal strength within a time series—of the CAN chronology remains high from 2015 back to 492 BCE. The number of trees included in the chronology drops to 4 ca. 80 BCE (Figure S2A), and although the expressed population signal remains >0.80, this part of the reconstruction should be interpreted with caution (Figure S2B). We find strong and positive correlation between the CAN chronology and scPDSI from previous May through current October, with the highest association during the current-year May ($r = 0.72$, $p < 0.001$; Figure S3A). Forward correlation analysis reveals the CAN-hydroclimate relationship to be stable throughout the instrumental period, thus yielding high confidence for the use of the CAN record as robust predictor of pre-observed period hydroclimate (Figure S3B). We also find the drought signal in the CAN chronology is extensive spatially and representative of the American Southwest region (Figure S3C).

We provide a 2,508-year (492 BCE–2015 CE) annual reconstruction of hydroclimate that accounts for 53% of the instrumental period scPDSI (hereafter PDSI) variability (1902–2015; Table S1; Figure 1). Calibration and verification (RE, CE) statistics for the reconstruction were strong and positive. Within the context of the past 2,500 years, hydroclimate conditions during the 20th–21st centuries are characterized by substantial variability (Figures 2 and S4). The 20th–21st century is characterized by seven hydroclimate flips (five negative, two positive), more than any other century (14th and 19th centuries = 5 total). Also unique to the 20th century are back-to-back flip events (1966–1968; 1995–1997) both characterized by three consecutive years of extreme wet-dry-wet conditions (P_{75}-P_{25}-P_{75}). The only other back-to-back flip event since 80 BCE is 1336–1338 (P_{25}-P_{75}-P_{25}). Since 492 BCE, the reconstruction distributions highlight a number of noteworthy centuries during which drought conditions were more extreme (e.g., lower mean, higher variance) within the context of the instrumental data (Figure S4). Some of the driest centuries include the 2nd BCE, 2nd CE, 10th CE, and 16th CE, with each containing a noteworthy drought event (e.g., Pre-Ancestral Puebloan, Medieval Drought). With three flip events each, other centuries such as the 3rd, 5th, 8th, 11th,

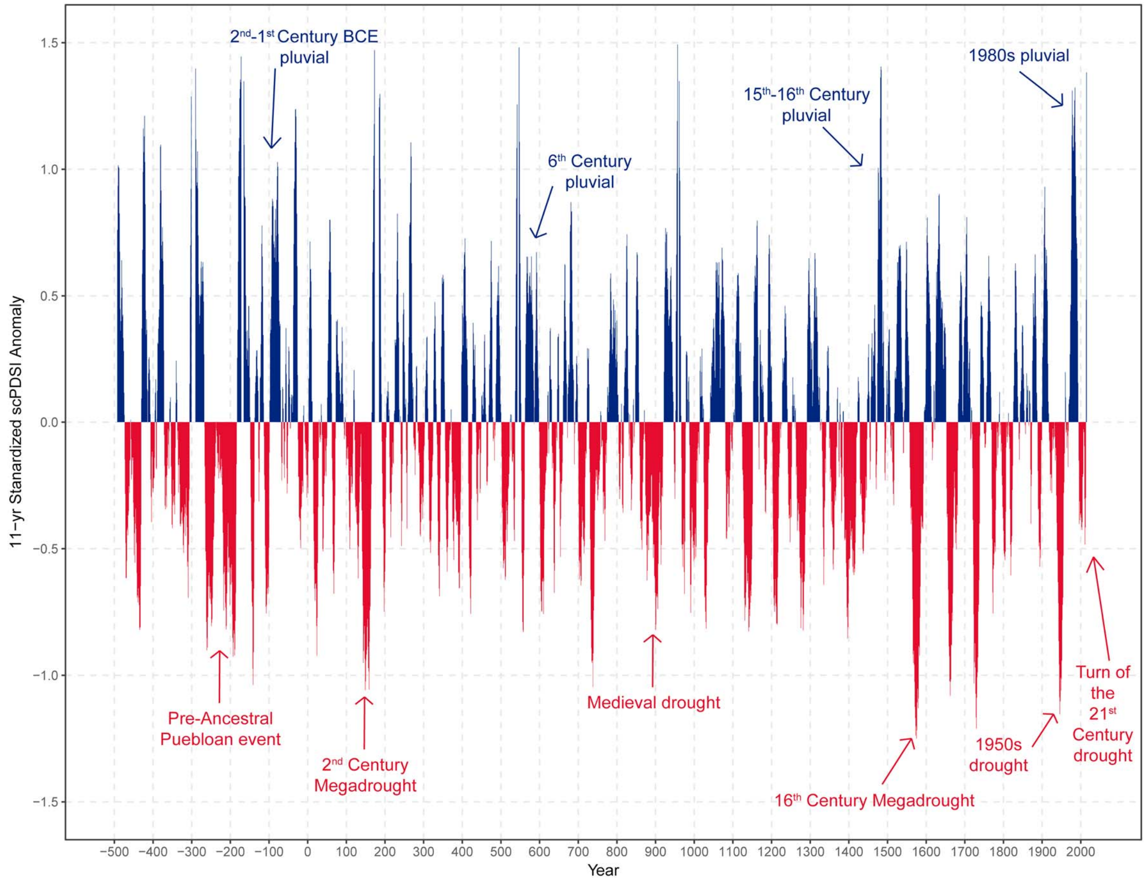

Figure 2. New Mexico hydroclimate flips. (a) Total count of hydroclimate flips per century plotted with (b) positive (blue), negative (red), and total (purple) flips during the period −80 BCE–2015 CE. Flips calculated as annual values exceeding the 75th percentile (wet) and 25th percentile (dry) in the Candelaria scPDSI reconstruction. Positive flips are defined as consecutive years where: $t > P_{25}$, $t + 1 > P_{75}$, with negative flips $t > P_{75}$, $t + 1 > P_{25}$. scPDSI = self-calibrating Palmer Drought Severity Index.

13th, and 18th CE are characterized by extreme variability and rapid transitions in hydroclimate conditions.

Runs analysis reveals a total of 260 drought and 239 pluvial events, of which we report the top 10 of each in Table 1 (see Tables S3 and S4 for top 25). The 1950s drought and the 1980s pluvial are both top 10 events (both rank as fifth). Two other distinct twentieth century pluvial events (1906–1917 and 1990–1995) rank in the top 25 (Table S3 and Figure S5). Since ca. 80 BCE, the top-ranked 20th–21st century pluvial (1980s) is eclipsed by at least two events (176–190, 545–556 CE) in duration and magnitude. Juxtaposed to the twentieth century pluvial events is the 17-year Southern Great Plains/Southwest drought of the 1950s (1943–1959), which ranks as the fifth most severe with a cumulative PDSI of −21.7. Although short, one of the wettest episodes was a distinct 3-year pluvial from 1484 to 1486 with a cumulative PDSI magnitude of 14.3. Each year in the sequence was the 4th, 5th, and 24th wettest, respectively.

Since ca. 500 BCE, 58 drought events have surpassed the severity of recent 21st century conditions (Figure S5). With regard to cumulative PDSI and intensity, the two most severe and sustained drought events occur during the 18th (−41.5, −1.8) and 16th (−37.1, −1.7) centuries (Table 1). The 1730s is the driest decade by far, with extremely dry single-year conditions in 1730 and 1734 (−4.8), then back-to-back years with estimated PDSI values of −5.2 and −5.1 in 1739 and 1740, respectively. Drought conditions in the 1730s were likely devastating to vegetation, as suggested not only by the reconstructed PDSI values, but also by the many locally absent growth rings we observe in Rocky Mountain juniper during this time period (data not shown).

We find a noteworthy and extreme drought event that occurs from 264–179 BCE, during the Pre-Ancestral Puebloan period, unreported previously in the literature (Figure 3). Although this event occurs during a time

Table 1
Candelaria Drought and Pluvial Events

Event rank	Period	Duration (year)	Magnitude	Intensity	Duration rank	Magnitude rank	Overall score
1	1724–1746	23	−41.56	−1.81	17	260	277
2	1566–1587	22	−37.09	−1.69	16	259	275
3	900–916	17	−29.03	−1.71	15	258	273
4	1661–1674	14	−26.69	−1.91	13	257	270
5	**1943–1959**	17	−21.71	−1.28	15	255	270
6	738–751	14	−23.66	−1.69	13	256	269
7	878–889	12	−19.48	−1.62	11	254	265
8	420–431	13	−19.10	−1.47	12	253	265
9	158–173	16	−17.89	−1.12	14	250	264
10	1213–1225	13	−18.67	−1.44	12	251	263
1	BC178–BC158	21	56.55	2.69	14	239	253
2	176–190	15	41.44	2.76	13	238	251
3	545–556	12	31.72	2.64	11	236	247
4	BC295–BC287	9	37.61	4.18	8	237	245
5	**1978–1988**	11	30.01	2.73	10	235	245
6	57–68	12	25.50	2.12	11	233	244
7	BC285–BC274	12	23.93	1.99	11	232	243
8	BC422–BC415	8	26.22	3.28	7	234	241
9	683–691	9	23.29	2.59	8	231	239
10	960–968	9	22.74	2.53	8	230	238

Note. Top 10 drought (top) and pluvial (bottom) events (ranked by overall score) in the Candelaria self-calibrating Palmer Drought Severity Index reconstruction (−492 BCE–2015 CE) identified by runs analysis. Bold events denote 20th or 21st century events. Magnitude = mean cumulative departure from the long-term self-calibrating Palmer Drought Severity Index mean (−1.29); Intensity = duration (years) divided by the magnitude; after ranking, overall score = duration rank + intensity rank. The 1906–1917 instrumental-period pluvial is ranked as the #11 event (Table S3).

of low sample depth (four trees), this extremely dry period lasts for 86 years and is punctuated only by a few years during which hydroclimate conditions improve slightly, and thus only a portion of this event ranks in the top 25 (249–238 BCE; magnitude = −13.1, intensity = −1.1). Other prolonged and severe drought events occurred during the periods 900–916 (Medieval drought), 1661–1674, and 1943–1959 (1950s Drought), with cumulative PDSI (intensity) values of −29.03 (−1.71), −26.7, −26.7 (−1.9), and −21.7 (−1.3) respectively (Table 1 and Figure 3).

The spectral periodogram of the CAN reconstruction demonstrates frequencies, significantly different from a red-noise assumption, of 33, 12.5, and 2–5 years at $\alpha = 0.01$ and periods of 60 and 9 years at

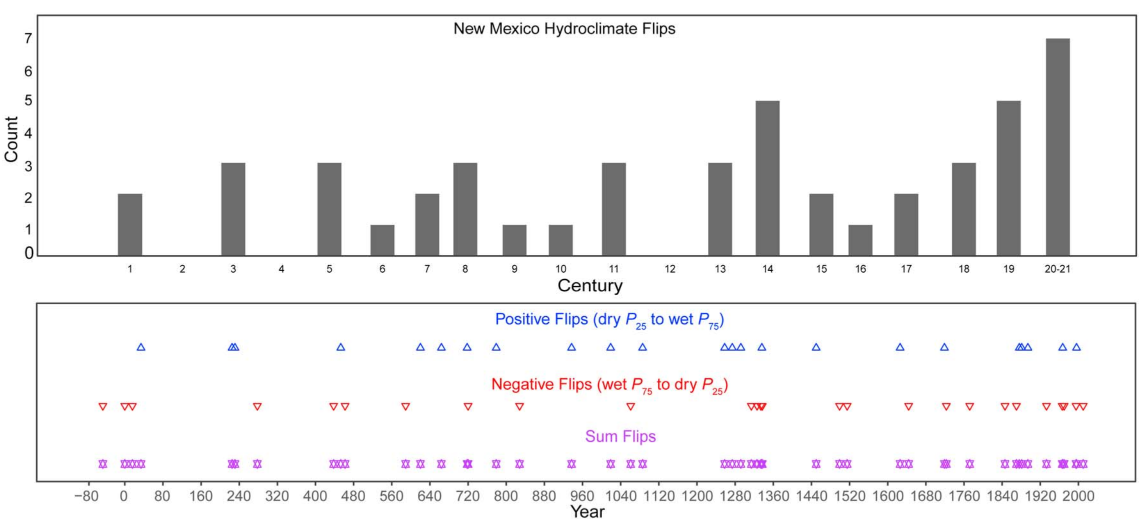

Figure 3. Reconstructed drought anomalies. Standardized self-calibrating Palmer Drought Severity Index anomalies (11-year) showing pluvial (blue) and drought (red) periods relative to the long-term mean (492 BCE–2015 CE) of reconstructed hydroclimate, west-central New Mexico. Highlighted are pluvial and drought events of interest as discussed in text.

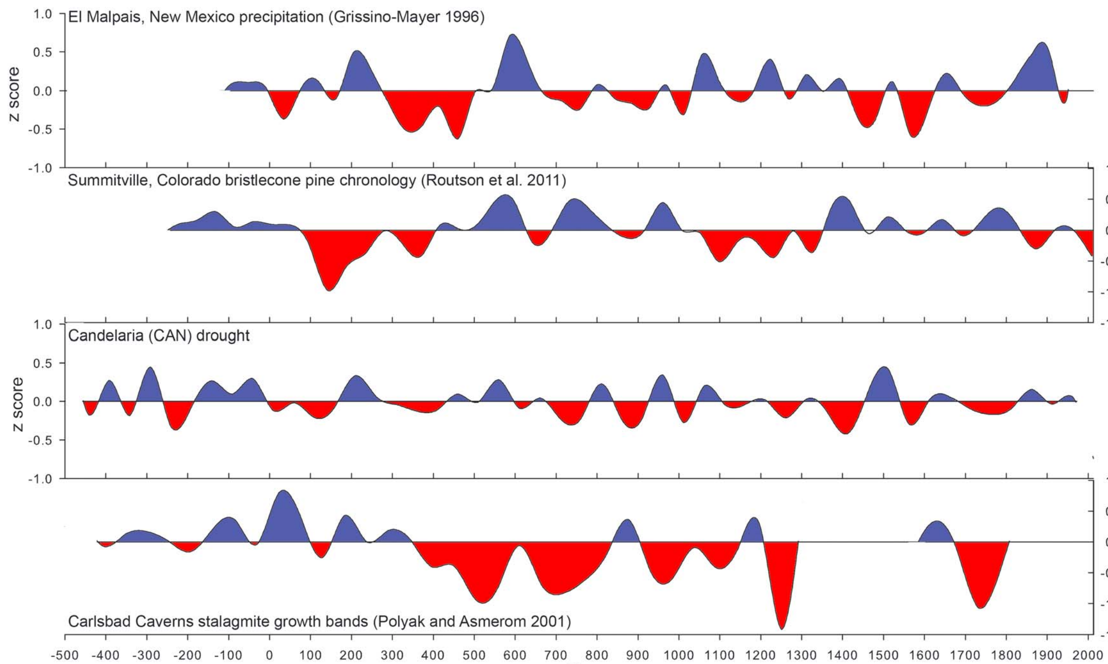

Figure 4. Long-term regional hydroclimate comparisons. Shown are z-scores for the water-year precipitation reconstruction from El Malpais National Monument, New Mexico (Grissino-Mayer, 1996); the bristlecone pine tree-ring chronology from Summitville, Colorado (Routson et al., 2011); the Candelaria Rocky Mountain juniper drought reconstruction; and a record of stalagmite growth band thickness from southeast New Mexico (Polyak & Asmerom, 2001). A map of record locations can be found in Figure S1.

$\alpha = 0.05$ (Figure S6A). The wavelet, however, shows the 30- to 60-year periods are stronger and more consistent over time compared to higher frequency, interannual periods (e.g., 2- to 5-year; Figure S6B).

4. Discussion and Conclusions

Droughts since the turn of the 21st century have garnered recent attention as being ranked among the worst droughts in the paleorecord across California (e.g., Griffin & Anchukaitis, 2014), Colorado (e.g., McCabe & Wolock, 2007; Udall & Overpeck, 2017), and across the American West (e.g., Ault et al., 2016; Mankin et al., 2017); however, in the context of the past 2,500 years, the instrumental record does not capture the full range of hydroclimate variability and extremes over west-central New Mexico. Over the past two millennia, hydroclimate extremes are common, but the range of variability since the Industrial Revolution—12 hydroclimate flips since ca. 1840—stands out in the CAN record (i.e., Figure 2). Both the 1950s drought and the 1980s pluvial events rank as the fifth most severe. Although our record suggests drier than average conditions during the Turn of the 21st century drought (2000–2006), drought severity since the beginning of the 21st century has been eclipsed by more prolonged and severe events in the past. The severity and duration of the 1950s drought notwithstanding, the twentieth century is one of the wettest since ca. 500 BCE. One aspect of the CAN record that is noteworthy is the hydroclimate variability during the 20th–21st centuries exceeds the extreme annual flips in conditions during any other century since 80 BCE.

The two back-to-back flip events of the 20th century that occur during the periods 1966–1968 and 1995–1997 (both wet-dry-wet) are likely a result of the imprint of the El Niño-Southern Oscillation (ENSO) on Southwest hydroclimate (e.g., McCabe & Dettinger, 1999). Both flips events are coeval with rapid transitions in the tropical Pacific from strong/moderate El Niño (wet) to La Niña (dry) and back to El Niño conditions (e.g., D'Arrigo et al., 2005; MacDonald et al., 2008). The 2- to 8-year periodicities identified by the wavelet and spectral analyses are within the range of variability associated commonly within ENSO. We also note the influence of Pacific Decadal Variability (PDV) on hydroclimate conditions via positive agreement between sea-surface temperatures and both the instrumental PDSI data and the CAN tree-ring chronology (Figures S7a and S7b). Previous research also indicates that PDV influences hydroclimate in the American Southwest (e.g., Seager & Ting, 2017; Sheppard et al., 2002). The significant 30- to 60-year periodicity identified by both the spectral periodogram and wavelet is similar to that of the PDV (Figure S7). Yet, given the temporal and spatial complexities of the PDV (e.g., Newman et al., 2016), this mode is less understood compared to ENSO. Collectively, these results suggest that ocean-atmospheric teleconnections have influenced regional hydroclimate for at least the past 2,500 years.

One of the longest tree-ring records in the Southwest United States is the 2,129-year El Malpais Long Chronology. First developed by Grissino-Mayer (1995) and updated by Stahle et al. (2009), this chronology is composed of living and remnant Douglass-fir (*Pseudotsuga menziesii*) from El Malpais National Monument, adjacent to the CAN site, and spans the period 137 BCE–2004 CE. The CAN record extends beyond the El Malpais record by 255 years and provides the potential to discover drought and pluvial events previously unreported, as in the Pre-Ancestral Puebloan drought. Although the number of trees during this time period is low ($n = 4$), the expressed population signal—a metric describing the agreement between these 4 tree-ring samples—is high (Figure S1). While the spatial extent of this event is currently difficult to ascertain, [1] increased sample depth during this period of the CAN chronology and [2] additional multi-millennial tree-ring records from the region will increase our understanding of this drought event.

Annually resolved hydroclimate paleorecords that span multiple millennia are scarce. The CAN drought reconstruction shows multidecadal correspondence with a 2,129-year El Malpais precipitation record (Grissino-Mayer, 1996), a 2,277-year bristlecone pine chronology (*Pinus aristata*, Summitville, Colorado; Routson et al., 2011), and a lower-resolution (temporal) record of stalagmite growth band thickness from Carlsbad Caverns (southeast New Mexico; Polyak & Asmerom, 2001; Figure 4). The Polyak and Asmerom (2001) stalagmite record provides evidence of lower-frequency hydroclimate variability of wetter-than-present conditions persisting from ca. BCE 800–200 CE, followed by a drier hydroclimate regime through the common era. The 18th century drought and the well-documented 16th Century Megadrought are the most pronounced events in both the CAN record and El Malpais precipitation reconstruction. Yet, Routson et al. (2011) note the most pronounced drought event in their 2,277-year *Pinus aristata* tree-ring chronology from south-central Colorado occurred during the second century. In the CAN record, the 149–155 and 158–173 CE drought events rank as the 9th and 16th most severe. Yet, if not for 2 years (156–157 CE) above the reconstructed mean, the second century drought would be more pronounced in our record. All four regional records demonstrate pluvial conditions before the common era, followed by a synchronous dry period during the second century, suggesting this drought was widespread across the region. Other periods of hydroclimate synchrony across the region are the 3rd, 6th, and 17th century pluvials, and the 5th, 12th, and 13th century droughts. Yet, there are three distinct periods during which hydroclimate conditions are out of phase across the region. The Medieval Drought (ca. 900 CE) is pronounced in southern Colorado to central New Mexico, while the stalagmite record suggests pluvial conditions in southern New Mexico. During the 8th and 18th centuries, the CAN, El Malpais, and stalagmite records suggest southern and central New Mexico are dry, while the higher elevations of southern Colorado are wet, as suggested through the Routson et al. (2011) bristlecone pine record.

Over 50 drought events occurred since ca. 500 BCE that were more severe than 20th–21st century hydroclimate conditions in west-central New Mexico. This finding, coupled with the extreme hydroclimate flips of the 20th–21st centuries, has important implications for current and future regional water planning efforts during this time of steadily increasing air temperature. Droughts in the Southwest United States are coupled commonly with increased temperatures (Durre et al., 2000; Salzer & Kipfmueller, 2005; Woodhouse et al., 2010). Both the 1950s Southern Great Plains/Southwest and the Turn of the 21st century droughts were coupled with increased temperature. Warmer temperatures often bring increased atmospheric pressure that blocks storm tracks and discourages adiabatic cooling, resulting in prolonged and severe drought conditions. Moreover, the current warming trend in land surface temperature will likely contribute to increased variability in extreme dry and wet conditions (Easterling et al., 2000; Meehl et al., 2000; Swain et al., 2018), which is consistent with the demonstrated hydroclimate flips in the CAN record since the 19th century. Twenty-first century hydroclimate predictions for the American Southwest are hindered by the lack of annually resolved, precisely dated temperature-sensitive proxies (Anchukaitis et al., 2013; Anchukaitis et al., 2017; Wilson et al., 2016). Developing millennial-length temperature records will facilitate better understandings of the long-term relationship between temperature and hydroclimate across the American Southwest and thus, is of critical importance.

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