**A multi-century Sierra Nevada snowpack reconstruction modeled using upper-elevation
coniferous tree rings**

Kai Lepley¹, Ramzi Touchan¹, David Meko¹, Eylon Shamir², Rochelle Graham², Donald Falk^{3,1}

¹Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ 85721 USA,
bangfour@email.arizona.edu, rtouchan@ltrr.arizona.edu, dmeko@ltrr.arizona.edu, 520-621-
1608, 0000-0003-4737-1098

²Hydrologic Research Center, San Diego, CA 92127 USA, EShamir@HRCwater.org,
rcampbell@hrcwater.org, (858) 798-9440

³School of Natural Resources and the Environment, University of Arizona, Tucson, AZ 85721
USA, dafalk@email.arizona.edu, (520) 621-7255

Abstract

Snowpack in the Sierra Nevada Mountains accounts for around one-third of California's water supply. Melting snow provides water into dry summer months characteristic of the region's Mediterranean climate. As climate changes, understanding patterns of snowpack, snowmelt, and biological response is critical in this region of agricultural, recreational, and ecological value. Here we investigated relationships between tree rings of montane conifer trees (*Tsuga mertensiana*, *Abies magnifica*, *Abies concolor*, *Calocedrus decurrens*, *Juniperus occidentalis*, and *Pinus ponderosa*) and regional climate indices with the goal of reconstructing April 1st snow-water equivalent (SWE) in the North Fork American River watershed of the Sierra Nevada. Chronologies were positively correlated with April 1 SWE of the year prior to ring formation. Temporal trends in correlation between tree-ring chronologies and climate indices indicate strengthening tree-growth response to climate over time. We developed a skillful, nested reconstruction for April 1 SWE, 1661 – 2013. Variability of the reconstruction is within the envelope of 20th and 21st-century variability; however, the 2015 record low snowpack is unprecedented in the tree-ring record, as in results from previous studies. Future research should focus on integrating modern snow-sensor data into paleoclimate research and understanding mechanistic linkages between snow and tree growth response.

Keywords: Tree rings, Sierra Nevada, reconstruction, snow, climate variability, snow-water equivalent

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1 Introduction

Snowpack is predicted to undergo significant changes in spatial and temporal distribution with increasing global mean temperatures (Musselman *et al.* 2017; I.P.O.C. Change 2014). The physical state of precipitation is also expected to shift with decreased fractions of snow and increased fractions of rain (Berghuijs *et al.* 2014). Combined effects of these changes are predicted to result in peak streamflow occurring earlier in the year and less residual water available in the summer and fall months when water use is highest (Barnhart *et al.* 2016; Berghuijs *et al.* 2014). These changes directly affect human societies around the world, particularly in regions with significant snowpack where snow-derived water is critical to well-being (Barnett *et al.* 2005).

The State of California is comprised of the Sierra Nevada Mountains in the east and the Pacific Ocean to the west with the Central Valley in between. The climate is characteristically Mediterranean defined by hot, dry summers and mild, wet winters (Mooney and Zavaleta 2016). The mountain range captures and retains snowpack that melts throughout spring and summer, feeding rivers and filling reservoirs (Carle 2015). Agricultural, residential, and ecological effects can be devastating when snowpack is low, particularly with increased vapor-pressure deficit and evapotranspiration from higher temperatures (Howitt *et al.* 2017; Chang and Bonnette 2016). Drought is implicated in increasing fire severity and duration in recent decades that has been linked to changes in amount of snow and timing of snowmelt (Westerling 2016; Wahl *et al.* 2019). An amalgam of intensified land use, population growth, and climate change have stressed groundwater supplies and resulted in depleted reservoirs throughout the state during recent droughts (Dettinger and Anderson 2015). The thoroughly studied 2012 – 2014 California drought stands out as among the most severe in the last 1,200 years based on paleoclimate records (Griffin and Anchukaitis 2014; Seager *et al.* 2015; Robeson 2015). Resource managers, policymakers, and scientists require a more complete understanding of snowpack variability on decadal to millennial scales to properly address the management of this critical resource.

Tree rings have been used as climate proxies to estimate temperature, precipitation, and numerous other climate indices prior to documented observations (Fritts 1976; Cook *et al.* 2007; Graham and Hughes 2007; Meko *et al.* 2011a; Touchan *et al.* 2011). However, few studies have used tree rings to study historical variability in the snowpack. Tunnicliff (1975) initially explored this topic estimating annual snow-water equivalent over a 500-year period around central Arizona using tree rings. Woodhouse (2003) explored April 1 snow-water equivalent (SWE) in the Gunnison-River basin region of Colorado using a network of tree-ring chronologies to reconstruct SWE over a 431-year period. The majority of studies have focused on April 1 SWE due to the broad availability of data for this date and its acceptance as a standard approximation of maximum snowpack prior to snow sensors (Montoya *et al.* 2014). Timilsena and Piechota (2008) used an approach similar to Woodhouse (2003) in identifying distinct regions of April 1 SWE variability using principal component analysis. They reconstructed April 1 SWE using a rich network of tree-ring chronologies, including those from Woodhouse (2003), for three regions within the Upper Colorado River Basin and used these reconstructions to estimate periodicity of historical drought. Anderson *et al.* (2012) revisited this region to reconstruct April 1 SWE in the Upper Green River Basin where Timilsena and Piechota (2008) were unable to produce a skillful reconstruction. The inclusion of six new region-specific tree-ring chronologies and reconstructed Pacific Decadal Oscillation (D'arrigo *et al.* 2001) and Southern Oscillation Index (Stahle *et al.* 1998) climate indices allowed Anderson *et al.* (2012) to create a skillful reconstruction explaining 58% percent of the variance in April 1 SWE for this region. Pederson *et al.* (2011) reconstructed SWE in this

same region for the purpose of assessing declines in snowpack during the latter 20th century compared to the previous 800 years. Pederson *et al.* (2011) among others (Appleton *et al.* 2018; Littell *et al.* 2016) discussed the value of using tree-ring records having negative correlations with SWE alongside those having positive correlations.

Belmecheri *et al.* (2016) performed a recent reconstruction of snowpack using 1,935 blue oak (*Quercus douglasii*) tree-ring time series from 33 sites in the Foothills of the Sierra Nevada (Stahle *et al.* 2013) and a gridded reconstructed February – March temperature time series (Wahl *et al.* 2014) to estimate April 1 SWE variability over the last 500 years. The reconstructed time series was the first principal component of 108 snow course time series of April 1 SWE throughout the Sierra Nevada mountain range. The 2015 snowpack was the lowest SWE value among both observed and reconstructed values. This low snowpack event has been characterized as extreme in the observed time period (Margulis *et al.* 2016), although no other studies have confirmed the magnitude of this event in the paleoclimate context.

Here we approach reconstructing April 1st SWE using tree-ring chronologies derived from conifers at seven sites along a 1000-meter elevation gradient in and around the North Fork American River watershed. This *in situ* reconstruction using coniferous trees that are directly reliant on moisture in winter snow provides a robust view of historical snowpack variability in a critical Sierra Nevada watershed. We investigate years of extreme snowpack using historical evidence of extreme events and specifically assess the severity of the 2015 record-low snowpack in the context of this watershed-specific paleoclimate record. The results of this study are compared to a spatially broad April 1 SWE reconstruction reflecting mid and high-elevation snowpack throughout the Sierra Nevada as verification and contrast of methodologies. We briefly discuss unstable climate signals in tree-ring records and concurrent changes in climate through time and the consistent relationship between tree-ring growth and prior-year snowpack at high-elevation sites.

2 Data and Methods

2.1 Site description

The Sierra Nevada, part of the American Cordillera, spans the north-south extent of California separating the basin and range province of western North America from California's Central Valley and the Pacific coast. The North Fork American River watershed is west of Lake Tahoe on the windward side of the Sierra Nevada (Figure 1). This watershed feeds the American River which is a tributary of the Sacramento River, California's largest river and a source of water for agriculture and residents throughout the state (Carter and Resh 2005). The Sierra Nevada receives enough rainfall to support growth of some of the largest trees in the world (Hughes *et al.* 1996; Hughes and Brown 1992). However, the seasonal distribution of precipitation results in the majority of growing-season moisture being derived from snowpack (Figure 2).

Mean annual temperatures at our tree-ring sampling sites ranged from 10.8 degrees Celsius at Fulda Creek (1500 m) to 5.0 degrees Celsius at Carpenter Ridge (2500 m). Mean precipitation is relatively consistent at windward sites, averaging 1600 mm per year with the exception of Carpenter Ridge, which receives 1000 mm per year. Truckee Ranger Station, on the leeward side, receives about 900 mm per year. Mean April 1 SWE ranges from 270 mm per year to 1100 mm per year, increasing roughly with elevation; the exception is Truckee Ranger Station receiving only 400 mm per year despite being located at about 2000 m elevation. These climate descriptions are drawn from PRISM Climate Group (2004) data used for this study described in detail below.

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Figure 1 Maps showing location of study area and tree-ring sites. The red shaded rectangles in panels A and B show the study area, while the stars in panel C represent tree-ring site locations.

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136 2.2 Tree-ring data

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138 During 2015 and 2016, we collected nine conifer chronologies from mid to high elevation at the
139 North Fork American, Yuba, and Truckee River Basins of the northern Sierra Nevada of
140 California. Sampled sites range in elevation from 1500 to 2500 m. Six study sites are located on
141 the windward side of the mountain range in the North Fork American River and Yuba watersheds.
142 The seventh study site is located on the leeward side of the mountain range along the western edge
143 of the Truckee River watershed. Tree-ring sites were located on hillslopes away from permanent
144 sources of water to ensure moisture-limited trees were being sampled.

145 Sampled species include *Tsuga mertensiana* (Bong.) Carrière (TSME) and *Abies magnifica*
146 A. Murray (ABMA) at Carpenter Ridge (CPRT and CPRA, respectively), *Abies concolor* Lindl.
147 (ABCO) and *Pinus ponderosa* P. Lawson & C. Lawson (PIPO) at Truckee Ranger Station (TRSA
148 and TRSP, respectively), ABMA at Huysink Lake (HYS), *Calocedrus decurrens* (Torr.) Florin
149 (CADE) at Onion Creek (ONC), *Juniperus occidentalis* Hook. (JUOC) at Rocky Ridge (ROR),
150 PIPO at Sierra View Mine (SVM), and PIPO at Fulda Creek (FUC) as shown in Table 1.

151 At each site we sampled between 15 and 40 trees of different sizes (Table 1). Trees with
152 signs of disturbance or competition were avoided. Two core samples were taken from each tree at
153 breast height using a 5mm increment borer following standard dendrochronological methods
154 (Stokes and Smiley 1996; Speer 2010). Core samples were mounted and sanded using
155 progressively finer grits until individual tracheid cells could be clearly resolved. Crossdating was
156 performed to assign calendar years to every ring and cores were measured at a precision of 0.001
157 mm to create total ring width time series. The computer program COFECHA (Holmes 1983) was
158 used to validate accuracy of crossdating and measurement.

159 We developed tree-ring chronologies using the R program (R Core Team 2015) *dplR* (Bunn
160 2008). Total ring width time series were detrended using a cubic smoothing spline with a 50%
161 response at a wavelength of 67% of the series length to remove non-climatic trend related to
162 influences of tree age and size on growth (Cook and Kairiukstis 1990). Detrended ring-width
163 indices were averaged using the bi-weight robust mean estimation method to create chronologies

164 (Cook 1985). Standard tree-ring chronologies (i.e., not adjusted for removal of autocorrelation)
165 were used for all analyses discussed in this manuscript to preserve the natural variability found in
166 these tree-ring records.

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169 **Table 1** Site information for the nine tree-ring sites.

Site Name	Site Code	Species*	Elevation (m)	Latitude (degree)	Longitude (degree)	Time Span	Total no. of Years	No. of Trees	No. of Cores
Carpenter Ridge	CPRA	ABMA	2478	39.4172	-120.3121	1540 – 2015	476	40	80
Carpenter Ridge	CPRT	TSME	2478	39.4167	-120.311	1615 – 2015	401	37	74
Huysink Lake	HYS	ABMA	2008	39.2822	-120.5278	1799 – 2014	216	20	40
Truckee Ranger Station	TRSA	ABCO	1980	39.2988	-120.1915	1896 – 2014	119	20	40
Truckee Ranger Station	TRSP	PIPO	1980	39.2246	-120.1917	1829 – 2014	186	20	40
Onion Creek	ONC	CADE	1865	39.2246	-120.4109	1732 – 2014	283	26	55
Sierra View Mine	SVM	PIPO	1825	39.1074	-120.5324	1621 – 2015	395	15	30
Rocky Ridge	ROR	JUOC	1809	39.2467	-120.3477	1600 – 2014	415	21	42
Fulda Creek	FUC	PIPO	1537	39.2583	-120.6857	1838 – 2014	177	20	40

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171 *Species Key: ABMA = *Abies magnifica*, TSME = *Tsuga mertensiana*, PIPO = *Pinus ponderosa*, CADE = *Calocedrus decurrens*,
172 JUOC = *Juniperus occidentalis*, ABCO = *Abies concolor*

173 174 2.3 Climate data

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176 We obtained 4-kilometer gridded monthly temperature and precipitation data for the period 1895
177 - 2016 from the PRISM Climate Group (PRISM 2004) for each tree-ring site based on the GPS
178 coordinates of the approximate center of the collection site. Regional time series of monthly
179 temperature and precipitation were developed by computing the arithmetic mean across all sites
180 for each month of mean PRISM temperature and total PRISM precipitation data, respectively.
181 Seasonal climate correlations were assessed using both site-specific climate indices and regional
182 time series. We calculated changes in regional temperature and precipitation over the calibration
183 period by computing annual time series from the monthly regional time series described above.
184 Mean annual temperature and total annual precipitation were computed from the January to
185 December period of each year for each variable, respectively.

186 We downloaded monthly SWE data from the California Data Exchange Center (CDEC)
187 and Natural Resources Conservation Service (NRCS). Continuous time-series of April 1 SWE
188 were developed from monthly snow course and daily snow sensor measurements near each tree-
189 ring site (mean distance of 2.2 km). Sensor data was used where available, and snow course data
190 was used to estimate sensor (or snow course) data using linear regression to cover the 1937 – 2016
191 period. Table S1 lists snow sensor and snow course data used to make these estimations for each
192 tree-ring site. Data from 50 snow course sites spread throughout the American and Yuba
193 watersheds provided an expanded regional dataset to validate local-scale findings. We used
194 singular value decomposition via the *prcomp* function in R to assess the spatial homogeneity of

195 this larger regional dataset. The data were centered and scaled with a common period of 1929 to
196 2016.

197 Characteristics, changes, and trends in the site and regional climatology were assessed
198 using statistical and graphical analyses in the program R as described below. The period for which
199 well-replicated SWE data is available and overlaps with tree-ring chronologies, 1937 – 2014, was
200 used for assessing the subsequent climate characteristics. In the case of investigating changes and
201 trends, statistics were assessed for early and late halves of this period; 1937 – 1975, and 1976 –
202 2014. Climographs of monthly temperature, precipitation, and SWE were used to initially check
203 climate data for inconsistencies. Boxplots of early and late halves of the assessed period were
204 compared to determine changes in mean state, variability, and occurrence of outliers in all climate
205 indices during this period. Linear regression was used to assess trends in early and late periods of
206 these climate indices.

207 208 2.4 Climate-growth relationships

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210 We assessed relationships between tree-ring chronologies and climate variables using the Matlab
211 program Seascorr (Meko *et al.* 2011b) and a seasonal climate correlation function we wrote for
212 the program R. Seascorr calculates correlations of tree-ring chronologies and seasonal means of
213 temperature and precipitation with detailed graphical and textual summaries. However, it lacks the
214 ability to provide information on the aggregation of monthly climate data over periods longer than
215 12 months. We wrote and applied an R function to extend functionality by providing Pearson's
216 correlations using ordinary least squares regression between any number of tree-ring chronologies
217 and a seasonally averaged, summed, or single time-series climate index over a 24-month period.
218 This allows the detection of lagged effects of climate on growth. The function calculates
219 correlations of mean or sum 1-month, 3-month, 6-month, 9-month, and 12-month seasonal
220 temperature and precipitation with tree-ring chronologies over the described 24-month window.
221 In the case of snowpack, the function calculates correlations of April 1 SWE values from the year
222 of ring formation and the year prior to ring formation with tree-ring chronologies. We assessed
223 correlation coefficients of tree-ring chronologies and climate indices for the analyzed seasons (1,
224 3, 6, 9, and 12-month) to determine which season most strongly influenced tree-ring growth.

225 The change through time in the strength of climate signal in tree-ring growth was analyzed
226 graphically and statistically in the program R. Running 31-year correlations between tree-ring
227 chronologies and climate indices were assessed over the common period of chronologies and each
228 climate index. Linear regression was used to calculate the trend in these running correlations as
229 well as to assess differences in correlation between chronologies and climate for the first half and
230 second half of the 1937 – 2014 period. The paired t-test (*paired.r* function) via the *Psych* package
231 (Revelle 2017) for R was used to assess the statistical significance of differences between
232 correlation coefficients in each half of this period.

233 234 2.5 Reconstruction

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236 We developed the SWE reconstruction using nested models calibrated on the 1953 – 2013 period
237 and truncated standard tree-ring chronologies to eliminate leading years before the expressed
238 population signal (EPS; Wigley *et al.* 1984; Cook and Briffa 1990) reached the commonly used
239 threshold of 0.85. Seasonal correlation analyses were used to select a SWE reconstruction target
240 and model predictor pool. Chronologies having significant ($p < 0.01$) correlations with SWE

including one-year lagged versions of these chronologies ($t + 1$) were added to a list of predictors in a forward stepwise linear regression.

Forward stepwise linear regression was performed using the *regsubsets* function in the *leaps* package (Lumley 2013) for R to determine reconstruction models for each nest. Predictors allowed in the final model were limited based on adjusted R^2 , predicted R^2 calculated from the predicted residual sum of squares (PRESS; Allen 1974), and the Mallows C_p statistic (Mallows 2000). We tested for potential multicollinearity by calculating the variance inflation factor for our model using the *fmsb* package for R (Nakazawa 2014). The shortest chronology was eliminated from predictor pools for each successive nest extending the reconstruction farther back in time. The split-period calibration-verification analysis was used to validate stability of model relationships throughout the calibration period; models were calibrated on one half of the calibration period and validated on the other half. The full period (1937 – 2013) was problematic as described in section 3.4, and this procedure was followed for each half of the reliable calibration period (1953 – 1983, 1984 – 2013). The starting year of the final chronology was based upon the expressed population static (Wigley *et al.* 1984; Cook and Briffa 1990).

We compared the reconstruction developed in this study and the Sierra Nevada SWE reconstruction developed by Belmecheri *et al.* (2016) using graphical and statistical techniques. We used simple Pearson's correlation to assess the similarity of the two reconstructions and plotted running correlations (20-, 40-, and 60-year) between the two reconstructions over the common period (1661 – 1980) to assess the stability of this relationship. The wettest and driest years of each reconstruction were classified by the 80th and 20th percentiles, respectively. We used the percent of wet years or dry years in common to each reconstruction as an additional measure of similarity.

3 Results

3.1 Chronology development

Nine chronologies were developed from the combination of trees sampled at each of the seven sites (Tables 1 and 3). Chronologies ranged in length from 119 years for ABCO at TRSA up to 476 years for ABMA at CPRA and spanned the years 1540 to 2015 C.E. Mean sample segment length, the average length in years of core samples for each chronology, varied from 77 to 245 years. Mean correlation among radii, a measure of common signal strength among cores within a chronology, ranged from 0.425 to 0.628 for eight of the chronologies; SVM was an outlier with a low mean correlation of 0.275. Explained variance of the first principal component of each chronology ranged from 33% to 65% including the SVM site and closely matched the pattern of mean correlation among radii. First-order (lag-1) autocorrelation of chronologies ranges from 0.05 (CPRT) to 0.59 (TRSP).

3.2 Climatology

Figure 2 Boxplot of study region monthly precipitation using PRISM data for the 1937 – 2014 period. The ends of boxes indicate 1st and 3rd quartiles, median line in the middle, and whiskers defined by base R calculation. Study region monthly minimum, maximum, and mean air temperatures are plotted on the secondary y-axis.

General climatology of sites explored in this study using PRISM data reflected expectations for a Mediterranean climate. Seasonal temperature and precipitation were inversely correlated, with high

precipitation and low temperature in winter and low precipitation and high temperature in summer (Figure 2). Linear regression of regional annual mean temperature among tree-ring sites against year showed an upward temperature trend of 0.022 °C/year over 1937 – 2014. The mean annual temperature rose 0.84 °C from the first half of this period to the second half of this period (Figure S1), in line with changes in global mean temperature (I.P.O.C. Change 2014). Regional annual mean precipitation had a wider range of variability in the second half of the study period (Figure S2). All extreme precipitation events (>75th percentile) occurred during the second half of the analysis period. There was no trend in regional annual mean precipitation.

April 1 SWE increased as a function of elevation among sites with the exception of Truckee Ranger Station on the leeward side of the mountain, which had relatively low snowpack given its elevation (Figure 3). There were no significant trends in SWE during the 1937 – 2014 period, yet there was higher variability in the second half of this period (Figure S1). Variability among SWE records was highly spatially coherent; the first principal component of the 50 snow courses examined explained 94% of the variability. Only the lowest elevation sites (< 1,560 meters in elevation) from this group showed deviations from the common signal. The SWE time series for Onion Creek was well replicated with snow course and sensor data and highly correlated ($r = 0.98$, $p\text{-value} < 0.001$) with the first principal component of the regional network of snow courses. This time series was thus chosen as a reconstruction target based on these results and the findings of seasonal correlation analyses.

Figure 3 Boxplot of SWE estimated at tree-ring sites in order of decreasing elevation (Table 1) during the 1937 – 2014 period. The ends of boxes indicate 1st and 3rd quartiles, median line in the middle, and whiskers defined by base R calculation.

3.3 Climate-growth relationships

Seasonal correlations between tree-ring chronologies and climate indices were used to identify predictor chronologies and reconstruction targets. Tree-ring chronologies were most strongly correlated with 9-month mean temperature and 12-month sum precipitation seasons predominantly in the year prior to tree-ring formation. Correlations of tree-ring chronologies and precipitation and temperature were more varied through time at shorter seasonal scales. Tree-ring chronologies were most strongly correlated with April 1 SWE of the year prior to tree-ring formation and at higher elevation sites. Seasonal correlations of tree-ring chronologies and climate indices are described for each season of the highest correlation for a given chronology and climate index below.

Six chronologies were significantly correlated at the 99% confidence level with 9-month mean temperature ending in November of the year prior to ring formation with coefficients ranging from -0.25 to -0.36 (Figure S3). CPRT and CPRA were significantly correlated at the 99% confidence level with 9-month mean temperature ending in October and August of the year prior to ring formation with coefficients of -0.32 and -0.29, respectively. TRSA was not significantly correlated with 9-month temperature. At a shorter season length of three months, a trimodal pattern appears over the 24-month correlation period. Chronologies below 1950 m elevation were correlated negatively with 3-month mean temperature ending in September of the year of ring formation. CPRT was positively correlated to three-month mean temperature ending in July and in August. Chronologies below 1950 m elevation, except ROR, also had positive correlations with 3-month mean temperature ending in March of the year of ring formation. The strongest correlations to 3-month mean temperature were negative and had ending months in the April to November period of the year prior to ring formation. The exception was TRSA, which had no significant correlation with three-month mean temperature.

Chronologies varied widely in the season of highest correlation with seasonal precipitation. Relationships will be described for each chronology in order of descending elevation. CPRA and

CPRT had positive correlations with 12-month sum precipitation ending in May and April of the year prior to ring formation with coefficients of 0.45 and 0.60, respectively (Figure S4). HYS correlated positively with 12-month sum precipitation ending in November of the year prior to ring formation with a coefficient of 0.48. TRSA and TRSP correlated positively with 12-month and 9-month sum precipitation ending in March of the year of ring formation and December of the year prior to ring formation with coefficients of 0.44 and 0.40, respectively. ONC correlated positively with 12-month sum precipitation ending in January of the year of ring formation with a coefficient of 0.47. SVM correlated positively with 3-month and 9-month precipitation ending in October and November of the year prior to ring formation both with coefficients of 0.38, respectively. ROR correlated positively with 3-month precipitation ending in October of the year prior to ring formation with a coefficient of 0.45. FUC correlated positively with 9-month precipitation ending in November of the year prior to ring formation with a coefficient of 0.49.

Figure 4 correlation matrix between April 1 SWE at Onion Creek and standard tree-ring chronologies. Color bars indicate Pearson's correlation coefficient. On the y-axis, "same year" indicates the year of ring formation, and "prior year" indicates the year prior to ring formation. Asterisks indicate p-values as follows: * < 0.05, ** < 0.01, *** < 0.00. Significance of correlations has not been adjusted for autocorrelation in the individual time series.

Correlations between tree-ring chronologies and SWE were consistent across snow sites and we will focus on correlations between chronologies and SWE at Onion Creek (Figure 4). The Onion Creek site was chosen as it is centrally located within the watershed and along the elevation gradient. The Onion Creek tree-ring site is nearly collocated (<1 km) with a snow sensor site and in close proximity (7 km) to a snow course at the same elevation. All tree-ring chronologies were significantly correlated with April 1 SWE at the 99% confidence level except for the lower elevation sites: SVM, ROR, and FUC. The higher-elevation chronologies were significantly correlated with April 1 SWE of the year prior to the year of ring formation with the exception of TRSA. TRSA showed significant correlations with SWE during the year of ring formation and the year prior to ring formation. CPRT, HYS, and ONC had correlation coefficients of 0.49, 0.54, and 0.51, respectively.

Running correlations between tree-ring chronologies and temperature, precipitation, and April 1st SWE increased through time over the common period (1937 – 2014). Trends were evident in running 31-year correlations through time. These trends were coincident with the changes in climate described previously such as the positive trend in mean annual temperature. Z-tests show significant differences between tree-ring chronology-climate correlations during early (1937 – 1975) and late (1975 – 2014) halves of the common period. These findings can be referenced in Figures S3, S4, and S5.

3.4 Reconstruction

April 1 SWE was reconstructed using nested models with CPRT, HYS, and ONC tree-ring chronologies as predictors of SWE over the period of 1661 to 2013 (Figure 6; Figure 7). Each nested reconstruction model was calibrated on the time period of 1953 to 2013. Models are named by the earliest year estimated for that nest as seen in Table S1 and Table S2. N1798, N1731, and N1615 explained 58%, 53%, and 44% of the variance, respectively, in instrumental SWE at Onion Creek over the calibration period; these models were used to estimate SWE for the time periods 1798 to 2014, 1731 to 1797, and 1615 to 1730, respectively.

Figure 5 Above: observed and reconstructed April 1 SWE at Onion Creek plotted over the common period of 1937 – 2013. **Below:** April 1st SWE reconstruction for years 1661–2013. The black line shows annual reconstructed values, the blue line shows the 10-year running mean, and the red line shows annual instrumental values. Grey shading represents the 95% prediction interval.

Split-period calibration-verification statistics for nested models are described in Table S2. Initially, the full available time period of 1937 to 2013 was used as the calibration period. However, validating the 1937 – 1975 time period using a model calibrated on the 1976 - 2013 time period resulted in poor correlation despite late-period and full-period correlations remaining strong. The poor correlation between early-period instrumental and modeled SWE was primarily due to poor characterization of the high snowpack. Correlation dropped precipitously upon including the 1952 snowpack in the calibration period. The 1952 year had the highest recorded snowpack (Figure 5) and was concurrent with above-average water year (October through September) precipitation and one of the lowest recorded water-year mean temperatures. Using a calibration period of 1953 to 2013 resulted in nearly identical regression coefficients and stable correlations for both early and late halves of the period.

Figure 6 Linear regression of observed and reconstructed April 1 SWE at Onion Creek over the common period of 1937 – 2013 with Pearson's correlation coefficient, p-value, and sample size indicated in the top left.

Table 2 Calibration and validation statistics for reconstruction models calibrated on the period 1953–2014.

Reconstruction Model	Variable	Coefficient	Adjusted-R ² Calibration	Predictive- R ²	Number of Chronologies
N1798	Constant	-423.0	0.58	0.54	4
	CPRT	-391.1			
	CPRT (t + 1)	700.1			
	HYS (t + 1)	458.2			
	ONC (t + 1)	639.9			
N1731	Constant	-488.3	0.53	0.48	3
	CPRT	-316.6			
	CPRT (t + 1)	895.0			
	ONC (t + 1)	888.9			
N1615	Constant	248.5	0.44	0.39	2
	CPRT	-432.1			
	CPRT (t + 1)	1145.8			

Table 3 Split-sample calibration and validation statistics of three reconstruction models.

Reconstruction Model	Calibration Period	Verification Period	Adjusted-R ² Calibration	R ² Verification	RE	CE
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N1798	1953 - 1983	1984 - 2013	0.49	0.51	0.57	0.52
	1984 - 2013	1953 - 1983	0.64	0.61	0.66	0.62
N1731	1953 - 1983	1984 - 2013	0.5	0.48	0.52	0.47
	1984 - 2013	1953 - 1983	0.52	0.52	0.57	0.51
N1615	1953 - 1983	1984 - 2013	0.34	0.35	0.42	0.36
	1984 - 2013	1953 - 1983	0.51	0.52	0.58	0.52

The reconstruction underestimated high-magnitude SWE in the early half of the period for which observed SWE and reconstructed SWE overlap (1937 – 2013; Figure 5). Years of discrepancy included 1969, 1958, 1952, and 1938. However, years with SWE values of similar magnitude in the late half of this period were accurately modeled in the reconstruction. These accurately modeled years include 1983, 1995, and 2011. The reconstruction appears to capture the signature of the 1861 – 1862 floods and preceding drought, however the magnitudes of these events cannot be accurately verified. The record low observed snowpack in 2015, marked by the dotted line in Figure 5, exceeds all reconstructed values over the 353-year period prior to this event. Low snowpack estimates of similar magnitudes occur in 1695 and 1861. However, few historical records exist prior to 1850 that can be used to verify the magnitude of the 1695 event.

The 2015 low snowpack exceeded all reconstructed SWE values over the last 500 years in a study by Belmecheri *et al.* (2016). The authors utilized low-elevation, precipitation-sensitive blue oak (*Quercus douglasii*) chronologies, and a high-elevation temperature reconstruction to predict a regional SWE signal back in time for the entire Sierra Nevada. The two reconstructions share 19% of their variance ($r = 0.44$) throughout the common period of 1661 – 1980 (Figure 10). The relationship between reconstructions is unstable through time with poor correlations prior to 1715 and periods of low correlation around 1760 and 1920 (Figure 11). Less than half (42%) of the 64 wettest years (80th percentile and above) in these reconstructions correspond. Similarly, less than half (41%) of the 64 driest years (20th percentile and below) correspond. It is notable that the 2015 low snowpack exceeds all estimates of SWE produced in both reconstructions while considering the different approaches used in each study.

Figure 7 10-year running means of North Fork American River April 1 SWE and Sierra Nevada April 1 SWE PC1 (Belmecheri *et al.*, 2016) reconstructions over the common period of 1661 – 1980.

4 Discussion and Conclusions

The objective of this study was to assess the dendroclimatic potential of selected Sierra Nevada conifers in the North Fork American River watershed with the goal of reconstructing April 1 SWE. As hypothesized, correlations between annual growth ring measurements and SWE were stronger at higher elevation sites where heavier snowpack occurs. All chronologies with significant correlations showed strong relationships with SWE from the spring of the prior year. PIPO and ABCO at Truckee Ranger Station (TRSP and TRSA, respectively) were the only two tree-ring chronologies with significant correlations with current-year SWE, snowpack prior to growing season, at the 99% confidence level. Truckee Ranger Station has less topographic variation than other sites studied and was subject to extensive logging during the Comstock Lode mining era resulting in the young age of trees observed (Wilson 1992). The location of TRS on the leeward side of the mountain accounts for reduced SWE compared to other sites at that elevation (Figure S3). However, these factors do not necessarily provide a mechanistic explanation for this differing response. The negative response of TSME growth to snowpack has been found previously throughout the states of Oregon and Washington (Peterson and Peterson 2001). Our results are also consistent with findings of Dolanc *et al.* (2013) that correlation of mountain hemlock growth in the Sierra Nevada with snowpack depth switches from positive in the previous year to negative in the current year. While TSME at CPRT shows a slightly negative growth response to current-year SWE, our correlations are not significant. These effects, commonly a result of energy limitation due to snowpack, are likely muted in the southern extent of the species' range. TSME, ABMA, and CADE at three different sites showed the strongest correlations and potential for use in SWE reconstruction. These results confirm that high-elevation, conifer trees can be used for paleoclimate snow studies in this region.

The strengthening correlations between tree-ring chronologies and the analyzed climate indices over the 20th century are coincident with observed increases in temperature and expanded variability in precipitation and SWE. A strengthening growth response to climate in several subalpine tree species has also been reported by Dolanc *et al.* (2013). Analogous to the "divergence" phenomenon in dendrochronology (D'Arrigo *et al.* 2008; Esper and Frank 2009), in which the relationship between some tree-ring chronologies and climate has weakened in recent decades, the change we observe here might be called "convergence." If valid in reflecting a general changing sensitivity of tree growth to Sierra Nevada snowpack, this phenomenon could pose a challenge to long-term reconstruction of SWE and other snowpack variables. This convergence may be indicative of increasingly stressful growth conditions. Higher mean temperatures are associated with earlier snowmelt, less water available throughout the growing season, and increased evaporative stress through higher vapor-pressure deficit (Musselman *et al.* 2017; I.P.O.C. Change 2014; Berghuijs *et al.* 2014). These factors create an environment where water is more limited, and the associated effects of extreme temperature years are more severe. Tree growth is therefore also more limited in this environment. The correlation between tree growth and these climate indices in this environment will likely continue to increase with predicted warming and associated effects. However, evidence described below indicates these changes in correlation and primary climate variables driving them could be due to teleconnections with broader-scale climate indices.

Chronologies developed from high-elevation conifer trees, specifically TSME, ABMA, and CADE, were most useful for reconstruction because of chronology length and strength of climate relationships. Predicting pre-instrumental SWE at this central location among tree-ring sites and within the study region is informative given the significance of this watershed and the high correlation between this SWE time series and broader regional SWE. Reconstructed SWE

values remain within the envelope of the 20th century observed variability although a larger proportion of reconstructed years fell below the observed mean (Figure 5). The uncertainty surrounding this estimate of historical SWE still leaves open the possibility of snowpack events matching or exceeding the 2015 record low. High snowpack events are also likely to be underrepresented due to the nature of precipitation-sensitive trees responding to large precipitation events with inconsistent and non-proportional tree-ring growth (Touchan *et al.* 1999). These factors must be considered when making inferences based on this and similar reconstructions of SWE.

Calibrating models on the 1953 – 2014 period instead of the 1937 – 2014 period improved model skill particularly by removing the extreme outlier year 1952. The reconstruction created by Belmecheri *et al.* (2016) also failed to accurately model April 1 SWE for this extreme year despite using different proxy records. Although tree-rings are known to characterize dry extremes more accurately than wet extremes in general (Fritts 1976; Touchan *et al.* 1999), this may not be the only cause of both reconstruction methods failing to capture the magnitude of the 1952 snowpack. Montoya *et al.* (2014) find that the April 1 measurement date frequently fails to accurately capture maximum snowpack based on comparison between long-used snow course measurements and modern, high-temporal-resolution snow pillow sensors. The authors find that the state of climate indices such as the Pacific Decadal Oscillation (PDO) are associated with offsets (from April 1) in maximum snowpack date. Cold PDO state is associated with later maximum snowpack, while warm PDO state is associated with earlier maximum snowpack. A polarizing shift in PDO occurred around 1977 flipping the climate index from a cool state to a warm state (Easterbrook 2011). If this shift in state caused maximum snowpack to fall on or closer to April 1 it could be partly responsible for increasing correlations found between tree-ring chronologies and climate indices described previously. Variation over time in the Pacific-North American (PNA) pattern has also likely been important to changing April SWE in our study area. Increasingly positive values of PNA over the last half-century have contributed to increasing elevation of freezing level, decreased precipitation, and lower percentage of precipitation falling as snow in the Sierra Nevada and other mountain ranges of the western United States (Abatzoglou, 2011).

Additionally, missing maximum snowpack by using April 1 SWE could potentially lead to poor modeling results for years where the difference between April 1 SWE and maximum SWE is significant. This could be the case for years such as 1952 for which multiple reconstruction methods do not accurately characterize SWE. The role of anthropogenic climate change in modulating the timing of maximum snowpack and snowmelt cannot be forgotten. For these reasons, we suggest future studies of tree-rings and snow use sensor-based measurements when available.

Extreme values in the reconstruction tended to occur prior to historical documented records. However, the drought leading up to the winter of 1861 and the subsequent 1861 - 1862 floods were recorded in both the reconstruction and historical documents (Ingram and Malamud-Roam 2013). Nearly two decades of drought preceded the floods of 1861 – 1862. These below-average values were apparent in the SWE reconstruction with the second lowest value in the reconstruction occurring in 1861. Around four times the average precipitation fell in December 1861 through February 1862 including heavy snowpack in the Sierra Nevada early in 1862. Atmospheric rivers led to a series of heavy, warm rains in late January and February that quickly melted the heavy snowpack leading to record flooding. The reconstructed 1862 SWE value exceeded all other years in magnitude. However, based on historical records reconstructed SWE for this year was likely an underestimate of actual SWE.

The record low 2015 snowpack exceeds any reconstructed estimate of SWE produced in this study and is in agreement with the findings of Belmecheri *et al.* (2016). This finding is notable especially because these two reconstructions share less than half of their variability (Figure 6) and capture less than half of the same positive and negative extreme years during their common period (Figure 7). These differences are not surprising given the different predictors used in each reconstruction and different scale of reconstruction targets. Meko *et al.* (2011a) found that historical precipitation anomalies derived from blue oak tree-ring chronologies reveal wet-dry gradients and even polarity in many years during the 1557 – 2001 period between northern and southern parts of the Central Valley. Many of these periods with north-south polarity align with periods of inverse relationships between the reconstructions seen in Figure 7. A north-south contrast in moisture anomalies in California would be expected whenever storm tracks tend to persist at particular latitudes, and on a larger scale can be related to shifts in the location of the node of precipitation anomalies associated with ENSO precipitation dipole (Dettinger *et al.*, 1998; Wise 2010).

Unfortunately, neither the conifer-based reconstruction produced in this study nor the blue-oak-based reconstruction developed by Belmecheri *et al.* (2016) had tree-ring data recent enough to encompass 2015. While collective findings indicate the extremity of the 2015 low snowpack, modeling this year explicitly within the calibration period of a tree-ring reconstruction will provide a better indication of its place within the range of paleoclimate variability. Future studies should utilize a combination of varied predictors such as precipitation-sensitive blue oak at low elevation and snow-sensitive conifers at high-elevation to more accurately characterize snowpack. Considering gradients and dipoles in broader precipitation patterns should also be used to inform targeted sampling and reconstruction methods.

The results of this study demonstrate the effectiveness of using tree-rings to inform past climate while highlighting points of discretion. Specifically, SWE is skillfully reconstructed using high-elevation coniferous tree rings in a central watershed of the Sierra Nevada mountains of California. The 2015 record low snowpack is unprecedented in the reconstruction and instrumental records supporting previous findings using alternative approaches. Using data from modern snow-pillow sensors may improve the skill of future snowpack reconstructions by replacing date-based estimates of maximum snowpack with accurate maximum snowpack measurements when possible and by providing means of calibration for conventional snow course measurements. The convergence of tree-ring growth signal and climate factors including temperature, precipitation, and SWE indicates a biological response to changing climate. This study highlights the need for further work on potential mechanisms responsible for lagged tree-growth response to snowpack, discrepancies between regional reconstructions of Sierra Nevada snowpack, and transient climate signal in tree ring records including divergence and convergence as described previously.

References

- Abatzoglou, J. T. (2011). Influence of the PNA on declining mountain snowpack in the western United States. *International Journal of Climatology*, 31(8):1135–1142.
- Aguado, E. (1990). Elevational and latitudinal patterns of snow accumulation departures from normal in the Sierra Nevada. *Theoretical and Applied Climatology*, 42(3):177–185.
- Allen, D. M. (1974). The relationship between variable selection and data augmentation and a method for prediction. *Technometrics*, 16(1):125–127.
- Anderson, S., Moser, C. L., Tootle, G. A., Grissino-Mayer, H. D., Timilsena, J., and Piechota, T. (2012). Snowpack reconstructions incorporating climate in the Upper Green River Basin

- (Wyoming). *Tree-Ring Research*, 68(2):105–115.
- Appleton, S. N. and George, S. S. (2018). High-elevation mountain hemlock growth as a surrogate for cool-season precipitation in Crater Lake National Park, USA. *Dendrochronologia*, 52:20–28.
- Barnett, T. P., Adam, J. C., and Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(7066):303.
- Barnhart, T. B., Molotch, N. P., Livneh, B., Harpold, A. A., Knowles, J. F., and Schneider, D. (2016). Snowmelt rate dictates streamflow. *Geophysical Research Letters*, 43(15):8006–8016.
- Belmecheri, S., Babst, F., Wahl, E. R., Stahle, D. W., and Trouet, V. (2016). Multi-century evaluation of Sierra Nevada snowpack. *Nature Climate Change*, 6(1):2.
- Berghuijs, W., Woods, R., and Hrachowitz, M. (2014). A precipitation shift from snow towards rain leads to a decrease in streamflow. *Nature Climate Change*, 4(7):583.
- Bunn, A. G. (2008). A dendrochronology program library in R (dplR). *Dendrochronologia*, 26(2):115–124.
- Carle, D. (2015). Introduction to water in California. *University of California Press*. Carter, J. L. and Resh, V. H. (2005). Pacific coast rivers of the coterminous United States. In *Rivers of North America*, pages 540–589. Elsevier.
- Chang, H. and Bonnette, M. R. (2016). Climate change and water-related ecosystem services: impacts of drought in California, USA. *Ecosystem Health and Sustainability*, 2(12):e01254.1
- Change, I. P. O. C. (2014). Climate Change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, RK Pachauri and LA Meyer (eds.)]. *IPCC*, Geneva, Switzerland.
- Cook, E. and Briffa, K. (1990). A comparison of some tree-ring standardization methods. *Methods of dendrochronology: applications in the environmental sciences*, pages 153–162.
- Cook, E. R. (1985). A time series analysis approach to tree ring standardization. Ph.D. thesis, University of Arizona Tucson.
- Cook, E. R. and Kairiukstis, L. A. (2013). *Methods of dendrochronology: applications in the environmental sciences. Springer Science & Business Media*.
- Cook, E. R., Seager, R., Cane, M. A., and Stahle, D. W. (2007). North American drought: Reconstructions, causes, and consequences. *Earth-Science Reviews*, 81(1-2):93–134.
- D’Arrigo, R., Villalba, R., and Wiles, G. (2001). Tree-ring estimates of pacific decadal climate variability. *Climate Dynamics*, 18(3-4):219–224.
- D’Arrigo, R., Wilson, R., Liepert, B., and Cherubini, P. (2008). On the ‘divergence problem’ in northern forests: a review of the tree-ring evidence and possible causes. *Global and Planetary Change*, 60(3-4):289–305.
- Dettinger, M. D., Cayan, D. R., Diaz, H. F., & Meko, D. M. (1998). North–south precipitation patterns in western North America on interannual-to-decadal timescales. *Journal of Climate*, 11(12), 3095–3111.
- Dettinger, M. D. and Anderson, M. L. (2015). Storage in California’s reservoirs and snowpack in this time of drought. *San Francisco Estuary and Watershed Science*, 13(2).
- Dolanc, C. R., Westfall, R. D., Safford, H. D., Thorne, J. H., and Schwartz, M. W. (2013). Growth–climate relationships for six subalpine tree species in a Mediterranean climate. *Canadian Journal of Forest Research*, 43(12):1114– 1126.

- Easterbrook, D. J. (2011). Geologic evidence of recurring climate cycles and their implications for the cause of global climate changes: The past is the key to the future: in evidence-based climate science.
- Esper, J. and Frank, D. (2009). Divergence pitfalls in tree-ring research. *Climatic Change*, 94(3):261–266.
- Fritts, H. (1976). Tree rings and climate. *Academic Press*.
- Graham, N. E. and Hughes, M. K. (2007). Reconstructing the mediaeval low stands of Mono Lake, Sierra Nevada, California, USA. *The Holocene*, 17(8):1197– 1210.2
- Griffin, D. and Anchukaitis, K. J. (2014). How unusual is the 2012–2014 California drought? *Geophysical Research Letters*, 41(24):9017–9023.
- PRISM Climate Group (2004). Oregon State University. PRISM Climate Data.
- Holmes, R. L. (1983). Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Society*.
- Howitt, R., MacEwan, D., Medellín-Azuara, J., Lund, J., and Sumner, D. (2017). Economic analysis of the 2015 drought for California agriculture. Center for Watershed Sciences, University of California.
- Hughes, M. K., & Brown, P. M. (1992). Drought frequency in central California since 101 BC recorded in giant sequoia tree rings. *Climate Dynamics*, 6(3-4), 161-167.
- Hughes, M. K., Touchan, R., & Brown, P. M. (1996). A multimillennial network of giant sequoia chronologies for dendroclimatology. *Tree rings, environment and humanity. Radiocarbon*, Tucson, Arizona, USA, 225-234.
- Ingram, B. L. and Malamud-Roam, F. (2013). The West without Water: What past floods, droughts, and other climatic clues tell us about tomorrow. *University of California Press*.
- Littell, J. S., Pederson, G. T., Gray, S. T., Tjoelker, M., Hamlet, A. F., & Woodhouse, C. A. (2016). Reconstructions of Columbia River streamflow from tree-ring chronologies in the Pacific Northwest, USA. *JAWRA Journal of the American Water Resources Association*, 52(5), 1121-1141.
- Liu, X., Zhao, L., Chen, T., Shao, X., Liu, Q., Hou, S., Qin, D., and An, W. (2011). Combined tree-ring width and $\delta^{13}\text{C}$ to reconstruct snowpack depth: a pilot study in the Gongga Mountain, west China. *Theoretical and Applied Climatology*, 103(1-2):133–144.
- Lumley, T. and Lumley, M. T. (2013). Package ‘leaps’. Regression Subset Selection. Thomas Lumley Based on Fortran Code by Alan Miller. Available online: <http://CRAN.R-project.org/package=leaps> (accessed on 18 March 2018).
- Mallows, C. L. (2000). Some comments on cp. *Technometrics*, 42(1):87–94.
- Margulis, S. A., Cortés, G., Giroto, M., Huning, L. S., Li, D., and Durand, M. (2016). Characterizing the extreme 2015 snowpack deficit in the Sierra Nevada (USA) and the implications for drought recovery. *Geophysical Research Letters*, 43(12):6341–6349.
- Meko, D. M., Stahle, D. W., Griffin, D., and Knight, T. A. (2011a). Inferring precipitation-anomaly gradients from tree rings. *Quaternary International*, 235(1-2):89–100.
- Meko, D. M., Touchan, R., and Anchukaitis, K. J. (2011b). Seascorr: A matlab program for identifying the seasonal climate signal in an annual tree-ring time series. *Computers & Geosciences*, 37(9):1234–1241.
- Montoya, E., Dozier, J., and Meiring, W. (2014). Biases of April 1 snow water equivalent records in the Sierra Nevada and their associations with large-scale climate indices. *Geophysical Research Letters*, 41(16):5912–5918.
- Mooney, H. and Zavaleta, E. (2016). Ecosystems of California. *University of California Press*.

- Musselman, K. N., Clark, M. P., Liu, C., Ikeda, K., and Rasmussen, R. (2017). Slower snowmelt in a warmer world. *Nature Climate Change*, 7(3):214.3
- Nakazawa, M. (2014). Functions for medical statistics book with some demographic data. R package version 0.4.3.
- Pederson, G. T., Gray, S. T., Woodhouse, C. A., Betancourt, J. L., Fagre, D. B., Littell, J. S., Watson, E., Luckman, B. H., and Graumlich, L. J. (2011). The unusual nature of recent snowpack declines in the North American cordillera. *Science*, 333(6040):332–335.
- Peterson, D. W. and Peterson, D. L. (2001). Mountain hemlock growth responds to climatic variability at annual and decadal time scales. *Ecology*, 82(12):3330–3345.
- R Core Team (2018). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
- Revelle, W. (2018). psych: Procedures for Psychological, Psychometric, and Personality Research. Northwestern University, Evanston, Illinois. R package version 1.8.4.
- Robeson, S. M. (2015). Revisiting the recent California drought as an extreme value. *Geophysical Research Letters*, 42(16):6771–6779.
- Seager, R., Hoerling, M., Schubert, S., Wang, H., Lyon, B., Kumar, A., Nakamura, J., and Henderson, N. (2015). Causes of the 2011–14 California drought. *Journal of Climate*, 28(18):6997–7024.
- Speer, J. H. (2010). Fundamentals of tree-ring research. *University of Arizona Press*.
- Stahle, D., Griffin, R., Meko, D., Therrell, M., Edmondson, J., Cleaveland, M., Stahle, L., Burnette, D., Abatzoglou, J., Redmond, K., et al. (2013). The ancient blue oak woodlands of California: Longevity and hydroclimatic history. *Earth Interactions*, 17(12):1–23.
- Stahle, D. W., D’Arrigo, R. D., Krusic, P. J., Cleaveland, M. K., Cook, E. R., Allan, R. J., Cole, J. E., Dunbar, R. B., Therrell, M. D., Gay, D. A., et al. (1998). Experimental dendroclimatic reconstruction of the Southern Oscillation. *Bulletin of the American Meteorological Society*, 79(10):2137–2152.
- Stokes, M. A. (1996). An introduction to tree-ring dating. *University of Arizona Press*.
- Timilsena, J. and Piechota, T. (2008). Regionalization and reconstruction of snow water equivalent in the Upper Colorado River Basin. *Journal of Hydrology*, 352(1-2):94–106.
- Touchan, R., Meko, D., and Hughes, M. K. (1999). A 396-year reconstruction of precipitation in southern Jordan 1. *JAWRA Journal of the American Water Resources Association*, 35(1):49–59.4
- Touchan, R., Woodhouse, C. A., Meko, D. M., and Allen, C. (2011). Millennial precipitation reconstruction for the Jemez Mountains, New Mexico, reveals changing drought signal. *International Journal of Climatology*, 31(6):896– 906.
- Tunncliffe, B. M. (1975). The historical potential of snowfall as a water resource in Arizona. The University of Arizona.
- Wahl, E. R., Diaz, H. F., Smerdon, J. E., and Ammann, C. M. (2014). Late winter temperature response to large tropical volcanic eruptions in temperate western North America: Relationship to ENSO phases. *Global and Planetary Change*, 122:238–250.
- Wahl, E. R., Zorita, E., Trouet, V., and Taylor, A. H. (2019). Jet stream dynamics, hydroclimate, and fire in California from 1600 CE to present. *Proceedings of the National Academy of Sciences*, 116(12):5393–5398.
- Westerling, A. L. (2016). Increasing western us forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1696):20150178.

735 Wigley, T. M., Briffa, K. R., and Jones, P. D. (1984). On the average value of correlated time
736 series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate*
737 *and Applied Meteorology*, 23(2):201–213.

738 Wilson, D. (1992). Sawdust trails in the Truckee Basin: a history of lumbering operations, 1856-
739 1936. Nevada County Historical.

740 Wise, E. K. (2010). Spatiotemporal variability of the precipitation dipole transition zone in the
741 western United States. *Geophysical Research Letters*, 37(7).

742 Woodhouse, C. A. (2003). A 431-yr reconstruction of western Colorado snowpack from tree rings.
743 *Journal of Climate*, 16(10):1551–1561.