A 431-Yr Reconstruction of Western Colorado Snowpack from Tree Rings

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ABSTRACT

A tree-ring-based reconstruction for 1 April snow water equivalent (SWE) is generated for the Gunnison River basin region in western Colorado. The reconstruction explains 63% of the variance in the instrumental record and extends from 1569 to 1999. When the twentieth-century part of the record is compared to the full record, the variability and extremes in the twentieth century appear representative of the long-term record. However, years of extreme SWE (low and high) and persistent low SWE events are not evenly distributed throughout the record. The twentieth century is notable for several periods that lack extreme years, and along with the nineteenth century and the second half of the eighteenth century, contains many fewer persistent low SWE events than the first half of the reconstruction. Low SWE in the western United States is associated with several circulation patterns, including the Pacific–North American (PNA) pattern and those related to El Niño–Southern Oscillation (ENSO), but the Gunnison River basin is on the edge of the area with a strong relationship to the PNA and is generally in a transitional zone with respect to regional ENSO influences. Tree-ring chronologies from Oregon and New Mexico, regions impacted by ENSO, were used as rough proxies of northwestern and southwestern U.S. winter precipitation to explore possible associations between Gunnison SWE and winter climate in these two regions over the past four centuries.

1. Introduction

Mountain snowpack is the source of 50%–80% of annual streamflow across the western United States (Natural Resources Conservation Service 2000). Snowpack is limited to a relatively small area (e.g., less than 15% of the land area in Colorado; Doesken and Stanton 1991), but because it is a major source of surface water supply, it is important to understand snowpack characteristics including the natural variability of seasonal snowpack and the range of extremes that can be expected. The focus of this paper is western Colorado, which contains the headwaters of the Colorado River, a vital water resource for seven western states. A dense network of snow measurement sites exists for the mountains of western Colorado, but even the longest records are only six or seven decades long. These relatively short records are inadequate for assessing the long-term variability in seasonal snowpack and for evaluating how well the twentieth-century instrumental record represents the temporal characteristics of snowpack over a longer period of time. An understanding of the long-term characteristics of snowpack variability is useful for guiding expectations for future variability. Baseline records of long-term natural variability are also necessary for understanding how large-scale oceanic–atmospheric features operating on decadal timescales interact with regional climate and influence snowpack.

Although instrumental climate records are limited in length, proxy climate data, such as from tree rings, have been useful in extending these records. Tree rings have successfully been used to reconstruct hydroclimatic variables such as precipitation, drought, and streamflow, (e.g., Stahle and Cleaveland 1988; Loaiciga et al. 1993; Hughes and Graumlich 1996; Haston and Michaelsen 1997; Cook et al. 1999; Cleaveland 2000; Meko et al. 2001). To date, tree rings have not been used to reconstruct snowpack, although several studies have investigated the response of tree growth to snowpack (e.g., Tunnicliffe 1975; Peterson and Peterson 1994; Perkins and Swetnam 1996). Reconstructions have likely not been generated primarily because of the short overlap between snow measurements and available tree-ring chronologies. A cooperative snow survey program directed by the U.S. Department of Agriculture's Natural Resources Conservation Service was started in the mid-1930s, but most tree-ring collections in western Colorado end in the 1960s, so the overlap between the two set of records has been only about 30 years at best. A new network of tree-ring chronologies collected in western Colorado during 2000 and 2001 now provides a dataset with an adequate period of overlap for the calibration and verification of tree-ring models for the reconstruction of snowpack in the Colorado River headwaters region.

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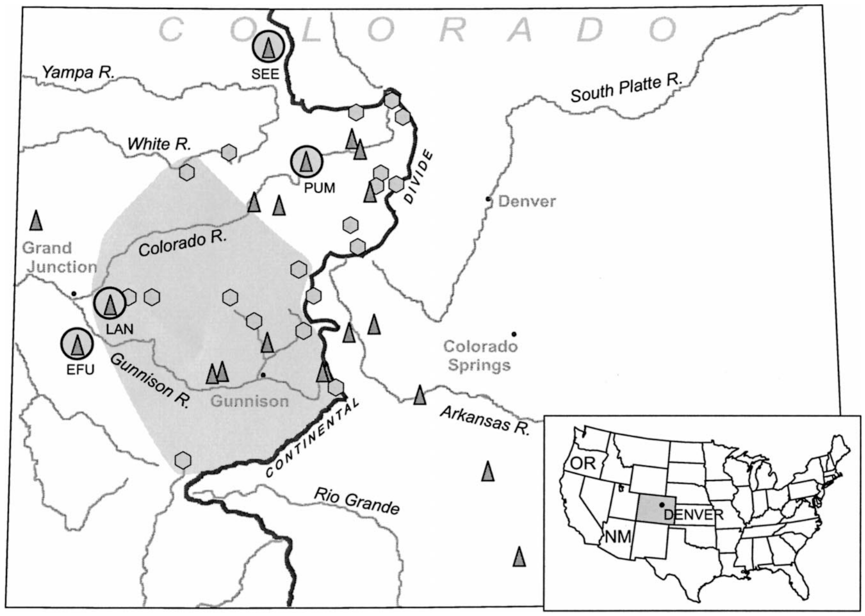

FIG. 1. Locations of the snow course sites in the White, Upper Colorado, and Gunnison River drainages (gray dots) and the tree-ring chronologies (triangles) used in this study. The shaded area represents the Gunnison region defined by the principal components analysis. The four tree-ring chronologies selected by the stepwise regression process for the reconstruction model (triangles with circles) are also indicated.

In this study, a tree-ring-based reconstruction of 1 April snow water equivalent (SWE) for a region that includes the Gunnison River basin and the southern headwaters of the main stem of Colorado River is described and analyzed with respect to the twentieth century. The Gunnison River accounts for about 42% of the total Colorado River flow at the Utah–Colorado state line (Ugland et al. 1990), and the southern headwaters account for an additional 12%, so this region represents an important contribution to the Upper Colorado River basin water supply. The SWE on or near 1 April is a good indicator of the water content in the maximum seasonal snowpack and the water supply for the coming months. It is also a measure that has been consistently recorded for many snow course sites (Cayan 1996).

2. Data

a. Snowpack data

The 19 Colorado snow course sites located west of the Continental Divide in watersheds that drain the Colorado, White, and Gunnison Rivers with complete or nearly complete records for 1 April SWE from at least 1942 to 1990 were selected for this analysis (Fig. 1). All but two of these contain data to 2000, with one of the two ending in 1990 and the other in 1996. Values were estimated to 2000 for these two sites using the collocated Snowpack Telemetry (SNOTEL) data (the two pairs of records overlap by about 10 years). A single missing value in one other record was estimated from a neighboring site.

A rotated principal components analysis (Richman 1986) was used to define snowpack regions within this area. The two principal components with eigenvalues greater than 1.0 were retained, together explaining 77% of the total variance in 1 April SWE. One region encompassed the upper headwaters of the main stem of the Colorado River and the other the Gunnison River headwaters and the southern headwaters of the Colorado River. The Gunnison–southern headwaters region was selected for reconstruction because a preliminary analysis showed high correlations between 1 April SWE in this region and the new western Colorado tree-ring chronologies. The nine snow course sites that fell within the Gunnison–southern headwaters region were averaged together to create a regional 1 April SWE series for 1938–2000 (Fig. 1). This series was the basis for the tree-ring reconstruction of the regional SWE.

b. Tree-ring data

Field work in the summers of 2000 and 2001 was undertaken to update and expand the existing set of six tree-ring chronologies (Grissino-Mayer and Fritts 1997) in the Yampa–White, Colorado main stem, and Gunnison River basins. The species ponderosa pine (*Pinus ponderosa*), pinyon pine (*Pinus edulis*), and Douglas-fir (*Pseudotsuga menziesii*), known to be sensitive to moisture (Schulman 1956; Hidalgo et al. 2001), were targeted for collection. A total of 28 sites was sampled, and at the time of this analysis, 15 had been developed into tree-ring chronologies (Fig. 1). All tree-ring sam-

TABLE 1. Reconstruction equation details (based on 1938–97 calibration).

Predictor variable/species*	Estimated regression coef	Standard error	P-value for significance of estimated regression coef
Pumphouse/pied	7.370	1.208	0.000
Escalante Forks Update/pied	1.559	1.066	0.149
Land's End/psme	6.993	2.820	0.016
Seedhouse/psme	−5.187	2.300	0.028

* pied = pinyon pine, psme = Douglas fir.

ples were crossdated and processed to create site chronologies according to standard dendrochronological methods (Stokes and Smiley 1968; Fritts 1976; Cook 1985; Cook and Kairiukstis 1990). Growth trends were removed from individual series using conservative detrending (negative exponential or a smoothing spline two-thirds the length of the series). Virtually all series contained significant low-order autocorrelation, generally considered to be biological in origin (Fritts 1976). This low-order autocorrelation was removed using autoregressive moving average (ARMA) modeling, and the resulting residual series were used in subsequent analyses. Sample depth within a chronology typically decreases back in time and may result in time-dependent variance changes and a weaker common signal (i.e., weaker climate signal) in the earlier part of the chronology. The variance in chronologies was stabilized in the chronology compilation process with the Briffa RBAR-weighted method, which uses average correlations between series in combination with sample size each year to make adjustments in the variance for changes in sample size (Osborn et al. 1997). The expressed population signal (EPS) is a measure of the common variance in the chronology and increases with sample size (Briffa 1984; Wigley et al. 1984). In each chronology, the EPS was evaluated for 50-yr segments, overlapped by 25 yr. An EPS of 85% has been suggested as a general cutoff (Wigley et al. 1984), and was used as a guide for truncating chronologies when sample size was too small to meet this guideline (i.e., when the common variance was lower than this threshold, indicating an unacceptable amount of noise in the chronology).

Correlations between monthly and seasonal climate data and this set of tree-ring chronologies indicate a sensitivity primarily to climate conditions from midwinter to late spring before the growing season. Although the monthly signal varies somewhat between species, tree growth is generally favored by wet winters and springs, and warm springs and early summers, suggesting that soil conditions at the onset of growth are key to growth during the growing season. All but one chronology displayed this relationship to climate (Seedhouse had a negative correlation with March precipitation and a positive correlation with June precipitation). Correlations between tree-ring widths and 1 April SWE were as high or higher than for precipitation alone (except Seedhouse), suggesting that the tree rings integrate a set of climate variables similar to the ones that influence 1 April SWE that includes a mix of both temperature and precipitation conditions.

3. Calibration and verification of the reconstruction model

The 15 chronologies, along with a set of five recently and similarly generated moisture-sensitive chronologies for the upper Arkansas River basin, were used as predictor variables for Gunnison regional SWE in a stepwise regression process. First, a regression was run on the full set of years common to both the tree-ring chronologies and the region SWE series, 1938–97. Four predictor variables were selected in the stepwise regression process and explained 63% of the variance in the regional SWE (Fig. 1; Table 1). Although the four chronologies are not all located within the Gunnison region, the stepwise regression results indicate that this is the set of chronologies that best reflects the regional climate conditions that also influence snowpack in this region. Residuals from this regression were found to be essentially normally distributed, showed no significant low-order autocorrelation, trends over time, or relation to any of the predictor variables. The ability of the four variables to predict SWE was then tested using a split sample calibration–verification scheme (Meko and Graybill 1995) as follows. The same four variables were used in a regression equation to predict SWE in the first half of the period (1938–67), and the resulting equation was tested on the second half of the period (1968–97). The four variables were then calibrated with the second half of the period and tested on the first half. Resulting statistics are shown in Table 2 and indicate the skill of the four variables in predicting regional SWE in the two sets of years. Also shown in Table 2 are the results of two other tests that assess the predictive ability of the regression model, the reduction of error (RE) test and the sign test. The RE tests the ability of the regression model to estimate SWE compared to estimates based on the calibration period mean. Values of RE can range from $-\infty$ to $+1$ and a positive value is desirable, indicating the model has some predictive skill (Lorenz 1956; Fritts 1976). The sign test shows the numbers of

TABLE 2. Calibration and verification statistics for stepwise regression.

Stepwise regression 1938–97	Stepwise regression split sample	
	Calibration	Verification
$r^2 = 0.626$	1938–67	1968–97
	$r^2 = 0.537$	$r^2 = 0.675$
		RE = 0.689
		Sign test 21/9*
	1968–97	1938–67
	$r^2 = 0.718$	$r^2 = 0.491$
		RE = 0.518
		Sign test 22/7**

* Significant at $p<0.05$.
** Significant at $p<0.01$.

TABLE 3. Contingency ananlysis. For both observed and reconstructed records, 1938–99, years were ranked and sorted into five classes ranging from very dry to very wet. Years in each of the classes for the reconstruction were compared to the classes of corresponding years in observed record. The class each year fell into was tabulated. For example, 7 of the 12 very dry years in the reconstruction were also very dry years in the observed record, 3 were dry, 1 moderate, and 1 wet, and 0 very wet in the observed record.

Reconstructed SWE	Observed SWE				
	Very dry	Dry	Moderate	Wet	Very wet
Very dry	7/12	3/12	1/12	1/12	0/12
Dry	2/13	6/13	5/13	0/13	0/13
Moderate	2/12	4/12	3/12	3/12	0/12
Wet	1/13	0/13	4/13	4/13	4/13
Very wet	0/12	0/12	0/12	4/12	8/12

agreements–disagreements in sign of departure from the mean in the observed and reconstructed series. Resulting RE statistics were positive and sign test results were significant at $p < 0.05$.

The same four variables were used in a linear neural network to generate 95% confidence intervals for the reconstruction. A linear neural network is numerically equivalent to a linear regression and results should be (and were) the same. Neural networks are calibrated, or trained, using an iterative process where weights are gradually adjusted with each iteration until an optimal value is reached. For more details on neural networks, see Hewitson and Crane (1994). Bootstrapping (Efron and Tibshirani 1993) was then employed to generate confidence intervals. Five hundred bootstrapped datasets (with the same number of cases as the original set) were drawn from the original data (with replacement), then the entire model fitting process was repeated for each of the 500 sets of bootstrapped data, each initiated with random weights. The linear neural network model estimates are shown with bootstrapped confidence intervals in Fig. 2. The correlation between the estimates generated from the stepwise regression and the linear neural network for the period 1938–97 was 0.999, indicating virtually identical results.

Although 63% of the variance in the instrumental record is explained by the tree-ring model, this statistic does not provide an evaluation of how well the tree rings reconstruct high snowpack extremes compared to low snowpack extremes. In general, tree-ring reconstructions are conservative estimates of the observed values, and there is a tendency in moisture-sensitive trees for dry extremes to be better replicated than wet extremes, as trees are limited in growth by dry conditions, but not usually by wet conditions (see Fig. 2, 1952, for an example of this). Here, as expected, the range of values for the reconstruction is less than that for the observed values (observed range is 16.3–70.3 cm; reconstructed range is 19.8–60.5 cm). However, a contingency table, which shows how often the tree-ring reconstructed values fall in the same class as the observed values (here, five even classes were used), shows that very wet extremes are slightly more often classified correctly than very dry extremes (Table 3). Overall, very

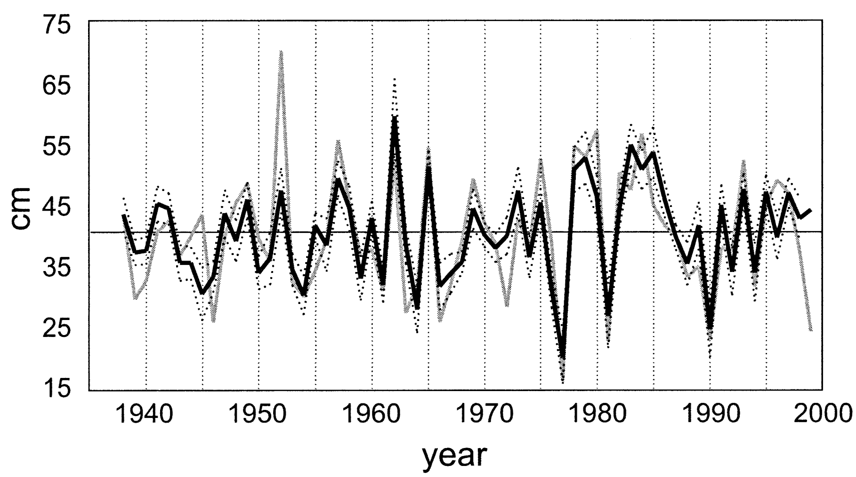

FIG. 2. Time series of observed (gray line) and reconstructed (black line) Gunnison regional SWE with 95% confidence intervals (dotted lines), 1938–99.

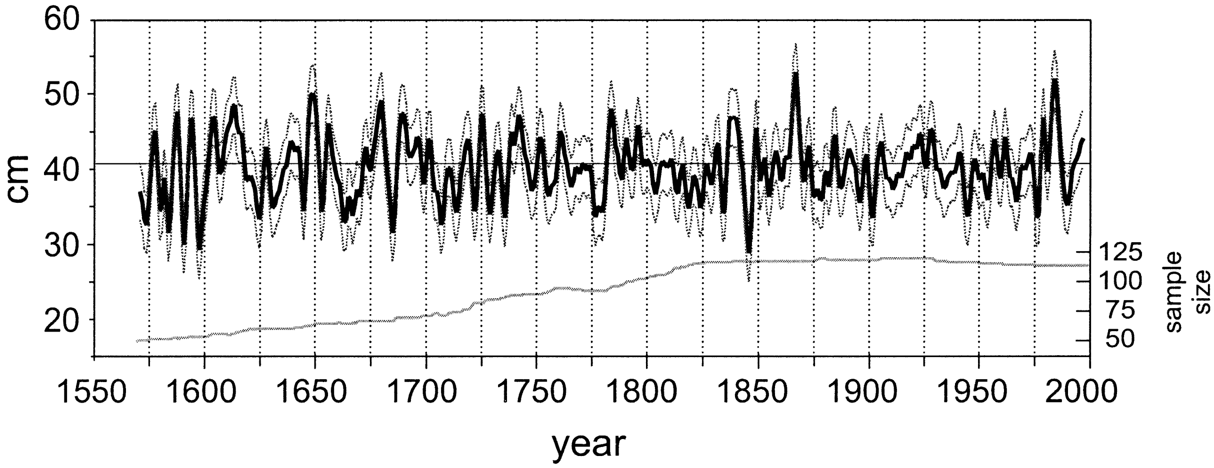

FIG. 3. Full reconstruction of Gunnison SWE, smoothed with a 5-weight binomial filter (heavy line), and error bars (thin lines), 1571–1997 (original unsmoothed years from 1569 to 1999, not shown). The thin line at the bottom of the graph indicates the change in total number of samples in the four chronologies used in the reconstruction over time (right-hand *y* axis).

dry, dry, and very wet values are the most reliably classified.

4. Reconstructed Gunnison 1 April SWE, 1569–1999

The linear neural network model was used to reconstruct Gunnison regional SWE for the years of the tree-ring record, back to 1569. Confidence intervals for the full reconstruction were conservatively estimated from the linear neural network bootstrapping on the calibration period, using the upper quartile value of the bootstrapped series. The full reconstruction, with estimated confidence intervals, smoothed with a 5-weight binomial filter, is shown in Fig. 3. The reconstruction displays many features found in other hydroclimatic reconstructions for the western and central United States, such as the widespread sixteenth-century drought, periods of dryness around 1820 and the late 1840s, and the wetness in the early twentieth century (e.g., Stockton and Jacoby 1976; Stockton and Meko 1975; Stahle and Cleaveland 1988; Meko et al. 1995; Stahle et al. 2000). In addition, the reconstruction shows some regional hydroclimatic signatures that differentiate climate east and west of the Continental Divide. For example, this region was not as severely impacted by the 1930s drought as regions to the east (McKee et al. 1999), and this is reflected in this reconstruction. A sustained period of drought in the mid-nineteenth century, especially notable in reconstructions of streamflow for the Colorado Front Range and summer drought in eastern Colorado (Woodhouse 2001; Woodhouse and Brown 2001), is evident only as a severe but relatively short 4-yr period of low SWE in the Gunnison region.

Tree-ring reconstructions of climate allow the twentieth-century instrumental record to be evaluated in the context of a longer period of time. This is useful in determining whether planning based on the instrumental record incorporates the range of variability and extremes that is representative of long-term natural variability, and the range of natural variability that is likely to occur in the future. In the following sections, the Gunnison reconstruction is evaluated with regard to variability, distribution of extreme years, and persistent low SWE events over the past four centuries.

a. *Variability and extremes in SWE*

Box and whisker plots are used to show median, interquartile range, and range of extreme values of the reconstructed SWE for the full reconstruction and by century (note that the sixteenth century contains only the last 31 yr) (Fig. 4). Median values for all centuries hover around the long-term median of 40.7 cm, with very little spread (high of 40.9 cm in the seventeenth century and a low of 38.8 cm in the sixteenth). The twentieth century interquartile range is almost exactly that of the full record, but this range is more variable from century to century. The sixteenth century displays the greatest spread in interquartile values, although this is based on less than one-third as many years than in the other periods. The range of maximum and minimum values show that only the seventeenth century had higher maximum SWE values than the twentieth, but several centuries (e.g., sixteenth, seventeenth) had lower minimum SWE values.

Extreme snowpack years are defined here as those years with values more than one standard deviation (plus or minus) from the average. When graphed, the distribution of extreme values over time can be assessed (Fig. 5). Although there are several clusters of extreme years in the twentieth century, the century is notable for the long period of few or no extremely low snowpack years; none between 1909 and 1934 and only three from 1934 until the cluster of dry years in the 1960s. The instrumental record, which begins in 1938, also shows only

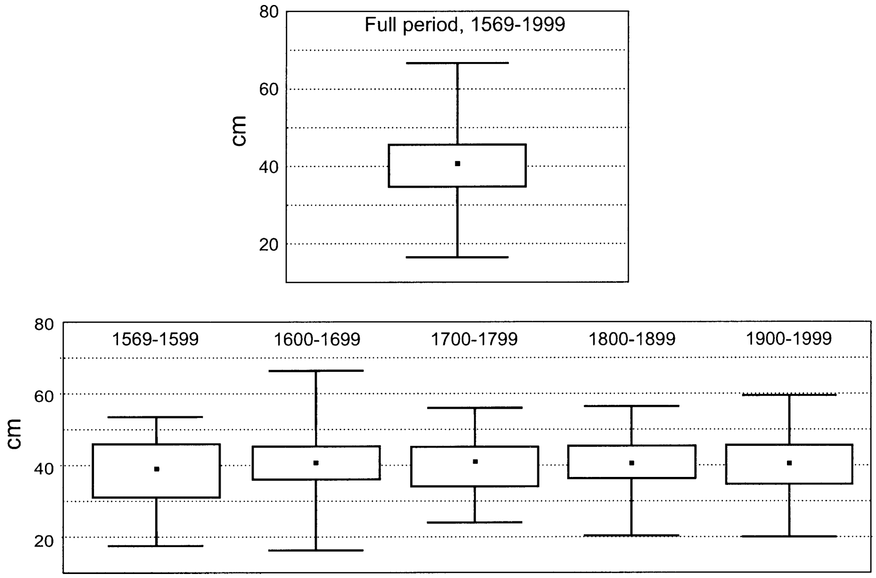

FIG. 4. Box and whisker plots for Gunnsison SWE reconstruction: (top) full period and (bottom) by century (sixteenth century is 1569–99 only). The box delineates the 25th and 75th percentiles, with median (dot in box). Whiskers are max and min values.

three extreme dry years between 1938 and the 1960s. The 1950s, a severe period of drought elsewhere, including the Front Range, contained several short sequences of below-average snowpack years (1954 is the only extreme dry year) but this was not an extremely severe drought in this area. Also within this period of few dry extremes is a stretch of years with no wet extremes (1930–56). In the full record, there are examples when one type of extreme dominates for a period of time. In the nineteenth century, there are no extremely wet years until 1837, but a number of extremely dry years. The last quarter of the seventeenth century is notable for a lack of extremely dry years, except 1685. There are other instances when wet and dry extreme years alternate. The most remarkable example of this occurs in the seventeenth century when 1654, the driest snowpack year in the reconstruction, was followed by 1655, the wettest year. The most marked period of alternating wet and dry extremes is at the end of the sixteenth century, when several series of one or two extremely wet years alternate with several dry years, a number of which are more than two standard deviations drier than average. When dry extremes are tabulated by century, the sixteenth century shows the highest percent of dry extremes (22% of all years), while the twentieth century shows the lowest percent (13% of all years). Changes in the frequency of extremes over the four centuries is unlikely due to changes in samples depth as the chronology variance due to sample size was stabilized and sample size was determined to be adequate for the full period, as evaluate by the EPS.

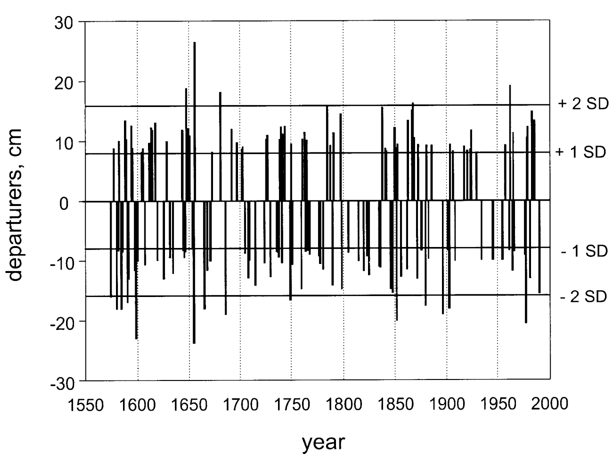

FIG. 5. Distribution of extreme years (those with values greater than ± one std dev from average) over time. Horizontal lines above and below the zero line are one and two std dev from average.

b. *Persistent low SWE events*

Persistence of low SWE years was evaluated by assessing the periods for which SWE was below average for three or more consecutive years. The severity of these low SWE periods was quantified by calculating the cumulative departures of the below-average years and dividing this total by the number of consecutively below-average years for an annual average severity. Three- and 4-yr dry periods were the most common, with one occurrence each of 5, 6, and 7 consecutively dry years. In general, the most persistent (i.e., longest) dry periods tended to be less severe on an annual average basis. The distribution of the persistent dry periods is shown graphically in Fig. 6. The nineteenth and twen-

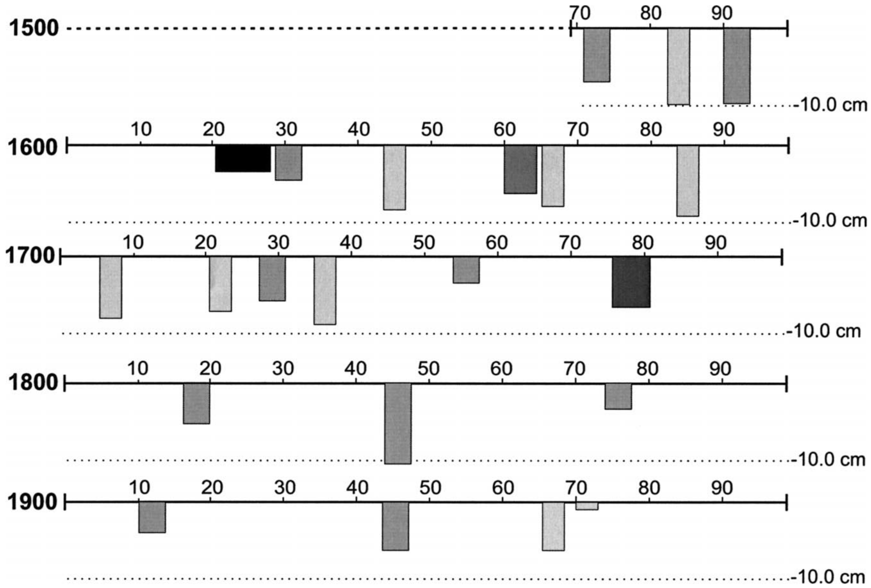

FIG. 6. Persistent low SWE events (3 yr or more with values consecutively below average) and their distribution by century (a century per row). The width and shade of the bar indicate number of years below average (3–7 yr, narrow to wide, light to dark shade), and the bar height indicates the annual average departure for the event. Light dotted lines indicate a negative departure of −10.0 cm (the full reconstruction average is 40.2 cm).

tieth centuries have the lowest occurrence of dry events, although the nineteenth century contains the dry period with the most severe annual average departure, the 4-yr period 1844–47. In contrast, the end of the sixteenth, seventeenth, and the first half of the eighteenth centuries have a much higher frequency of persistent dry periods. Autocorrelation functions for each of the five centuries show no significant positive lags.

5. Gunnison SWE and relationships to large-scale climate patterns

In the Colorado Rocky Mountains, the most important seasonal, large-scale atmospheric circulation pattern in terms of snowpack and water resources, is a midwinter pattern in which frontal storms bring Pacific moisture, with enhanced snowfall at high elevations due to the orographic effect of the mountains (Doesken and Stanton 1991). McCabe (1994) identified the 700-mb pattern most strongly associated with 1 April SWE in and near the Gunnison River basin as one characterized by negative height anomalies over the western United States in wet years and by positive height anomalies in dry years. The pattern also includes a pressure anomaly of the opposite sign (positive in wet years, negative in dry years) coinciding with the position of the Aleutian low (McCabe 1994). This pattern is similar to the Pacific–North American pattern (PNA; Wallace and Gutzler 1981). Cayan (1996) found a PNA-like pattern to be a common feature accompanying low 1 April SWE conditions throughout the western United States, although this pattern was weakest in the regions including Colorado and New Mexico. In the current study, December–January PNA (data from the Climate Prediction Center, see online at ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/tele_index.nh) was found to be negatively correlated ($r = -0.389$, $\alpha = 0.01$, 1950–99) with the Gunnison instrumental regional SWE, indicating a tendency for low SWE in the Gunnison region during positive phase PNA, (i.e., low pressure over the central North Pacific, and high pressure over the Pacific Northwest) and the reverse during negative phase PNA.

El Niño–Southern Oscillation (ENSO) has been found to influence winter climate in many parts of the western United States (Redmond and Koch 1991; Cayan and Webb 1992). Snowpack tends to be low in the northern Rocky Mountains and higher in the southwestern United States in the spring after a mature El Niño, and the reverse pattern is seen, but more strongly, following La Niña conditions (Cayan 1996). Previous research suggests that the Gunnison River basin is in a transition zone with respect to ENSO impacts, but adjacent to the southwestern United States, a region more consistently impacted by ENSO (Cayan and Peterson 1989; Cayan and Webb 1992; Cayan 1996). Gunnison River basin SWE shows no significant ($\alpha = 0.01$) correlation to the Southern Oscillation index (1867–1999; Ropelewski and Jones 1987). However, when Gunnison SWE values are compared to La Niña years [from Cayan and Webb (1992); based on the boreal spring following the strongest development of cool conditions in the tropical Pacific; updated with Wolter and Timlin (1998)] 9 of the 10 La Niña years, 1938–99, correspond to below-average SWE, although some of these values are only

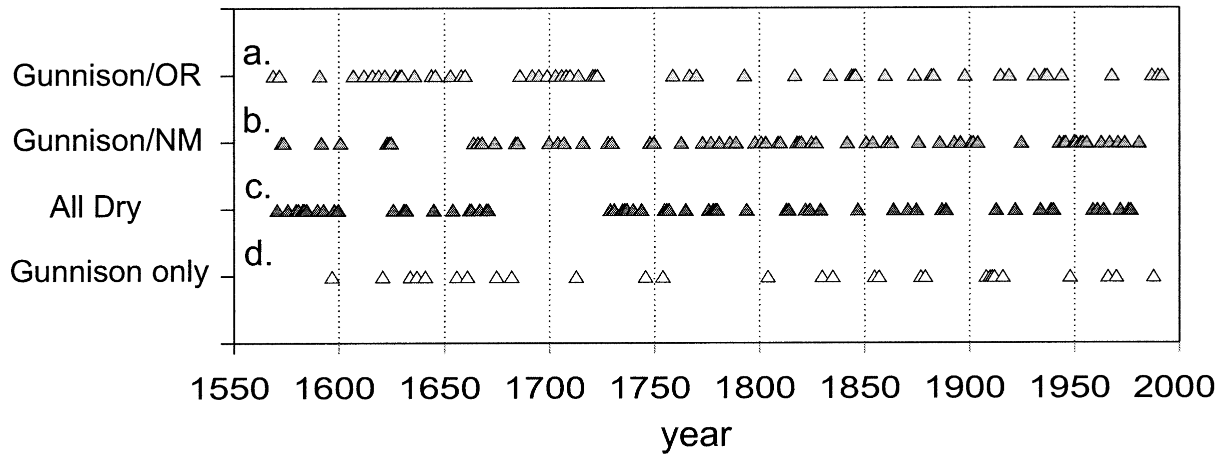

FIG. 7. Time series of years when below-average Gunnison SWE coincides with years of below average growth in (a) Oregon, (b) New Mexico, (c) in both Oregon and New Mexico, or (d) in neither Oregon nor New Mexico. Note that the top two rows represent those years when it was dry in Oregon and the Gunnison region (not in New Mexico) or dry in Oregon and the Gunnison region (not in Oregon), while the third row shows years when it was dry in all three regions.

slightly below average. This result supports a stronger ENSO teleconnection pattern in the western United States during La Niña events (Cayan 1996), and suggests a possible expansion of ENSO impacts into the Gunnison River basin during this type of event. Since El Niño and La Niña teleconnection patterns have been found to be only approximately symmetric (Dettinger et al. 2000), it appears that, in this region, the teleconnection is strongest during La Niña events.

Taken together, these results and the analyses from Cayan (1996) and McCabe (1994) imply that low snowpack in the Gunnison region may be associated with a positive PNA circulation pattern, which influences snowpack over much of the central and northwestern United States, or a with La Niña–type circulation (typically characterized by low pressure over western North America, and high over the northcentral Pacific), which accompanies dry winters in the southwestern United States. To further investigate the transitional nature of Gunnison SWE, the reconstruction was compared to moisture-sensitive tree-ring chronologies in the southwestern and northwestern United States. Three moisture-sensitive tree-ring chronologies from central Oregon (Meko et al. 2001) were selected to represent the northwestern United States and three from northcentral New Mexico (Grissino-Mayer and Fritts 1997) to represent the southwestern U.S. (Fig. 1 inset). The sets were averaged into region composite chronologies (within the two sets, correlations between chronologies were $\geq$0.67). Although the climate–tree growth response in the two regions is not identical, trees at both sites share sensitivity to winter precipitation. Tree growth departures are thus taken to be rough approximations of regional winter season precipitation. Years of below-average Gunnison SWE were compared to the two tree-ring records to assess when Gunnison SWE corresponded to dry winters in either Oregon or New Mexico, in both, or in neither.

Figure 7 shows the temporal distribution of these associations. One notable feature is the high concentration of low SWE–dry Oregon years in two episodes between the early seventeenth century and first quarter of the eighteenth century (Fig. 7a). After the mid-eighteenth century, low SWE–dry Oregon years are much less frequent and fairly evenly spaced, about four to five every half-century, with slightly more in the first half of the twentieth century. In contrast, few incidents of low SWE–dry New Mexico winters occur until the 1660s (Fig. 7b). After this, these events are more frequent, particularly in the twentieth century, from the 1940s to the mid-1970s. Other periods of time are characterized by dry winters in all regions, Oregon, New Mexico, and the Gunnison region (Fig. 7c). The late sixteenth century is an example of this and is a demonstration of the widespread nature of a drought that has been documented by many others (e.g., Stahle et al. 2000). A shorter period of persistent widespread winter drought occurred in the 1730s–40s. Widespread drought is notably absent for the 59-yr period between 1671 and 1729, when SWE–Oregon years dominate, but are intermixed with some SWE–New Mexico years as well. In addition, many sequences of years are characterized by a mix of types of winters indicating a high degree of variability, and in about 13% of the low SWE years, neither Oregon nor New Mexico is experiencing dry winters (Fig. 7d).

This comparison suggests that although there is a fair amount of year-to-year variability, there are periods of time when low SWE in the Gunnison region may be influenced by conditions that also cause dry winters in the northwestern United States and other periods of time when low SWE is probably more closely related to conditions causing dry winters in the southwestern United States. This may be the result of a trade-off in the influence on Gunnison SWE of conditions in the North Pacific, which have a stronger influence over dry winters in the northwestern United States and equatorial Pacific conditions, which are associated with dry winters in the southwestern United States (Cayan 1996).

It is also possible that the North Pacific may exert an indirect influence on low Gunnison SWE in years when this region behaves like the southwestern United States. Cole and Cook (1998) show that ENSO teleconnections to the southwestern United States expand north and east at times over a 130-yr analysis of spatial patterns of ENSO and U.S. moisture balance, and suggest this relationship may be influenced by conditions in the North Pacific. Conditions in the North Pacific have been also shown to exert a modulating effect on ENSO, and in particular, La Niña teleconnections appear to be stronger and more spatially coherent when the North Pacific is anomalously warm (Gershunov and Barnett 1998). A period of anomalous warm North Pacific sea surface temperatures (SSTs) from 1947 to 1976 (known as negative phase Pacific decadal oscillation (PDO); Mantua et al. 1997) does coincide with the high occurrence of SWE–dry New Mexico winters about the same time (Fig. 7b), suggesting an enhancement of La Niña teleconnections. However, during the negative phase PDO at the beginning of the twentieth century (1901–24, but starting in 1901 because this is the beginning of the instrumental record), there is no indication of a strengthened SWE–New Mexico relationship. Cold North Pacific SSTs (positive phase PDO) act to enhance El Niño teleconnections (Gershunov and Barnett 1998), which would exacerbate drought in the northwestern United States. There is some indication of a relatively higher occurrence of low SWE–dry Oregon winters during periods 1925–46 and 1977–92, positive PDO phases. If the association between low SWE and dry winters in Oregon or New Mexico is any indication of the low-frequency modulation of the North Pacific on ENSO teleconnections, these results suggests the PDO phases identified in the twentieth century have not occurred at the same intervals in the past.

The rather abrupt change in frequency of SWE–dry Oregon winter that occurs in the early eighteenth century (Fig. 7a) coincides with the change from a higher frequency of persistent low SWE events to a lower frequency (Fig. 6). This points to a possible drought regime shift, from more frequent winter droughts when the Gunnison region is under the influence of the same circulation features that impact the northwestern United States to a regime of less frequent winter droughts when associations with southwestern climate are more frequent. Alternatively, this shift could be a manifestation of very low frequency, centennial-scale variability.

6. Summary and conclusions

Tree rings have been used to reconstruct 1 April SWE for the Gunnison River basin region. The resulting reconstruction explains 63% of the variance in the instrumental record and extends from 1569 to 1999. The reconstructed record reflects large-scale hydroclimatic variability, indicated in comparisons with other reconstruction for the western and central United States, but also contains a regional signal that may be used to investigate differences in climate east and west of the Continental Divide. The reconstruction shows that the variability and range of extreme values in the twentieth century are generally representative of the past four centuries as a whole, although there are other centuries with lower minimum and/or higher maximum SWE values. An assessment of extreme snowpack years indicates that these years are not evenly distributed. The twentieth century is notable for several periods that contain few or no extreme years, for both low (1909–60) and high (1930–56) SWE extremes. The twentieth century also contains the lowest percent of extreme low SWE years. When persistent (3 yr or more) low SWE events are evaluated, the frequency of these event was three to four a century from the mid-eighteenth century through the twentieth century. In contrast, from the beginning of the record to the mid-eighteenth century, frequency of persistent events was about twice that rate. These results collectively suggest that while general characteristics of the twentieth-century SWE (e.g., mean, standard deviation, range of values) seem representative of the long term, the distribution of extreme years and/or persistent events over time indicates that the twentieth century may have been moderate with regard to extremes, both high and low, and persistent low SWE events.

Studies of 1 April SWE across the western United States have identified a disconnect between the northern and southern Rockies (Changnon et al. 1993; Cayan 1996), suggesting that different patterns of circulation influence winter snowpack in these two general regions. In the Gunnison region, both the PNA pattern (McCabe 1994; Cayan 1996) and ENSO have been found to have some influence over low snowpack conditions. Although a correlation exists between winter PNA and Gunnison SWE, the region appears to be on the margin of regions to the north and west that are more consistently influenced by PNA (Cayan 1996). Previous work (Cayan 1996 and others) as well as this study indicates that the region is also in a transitional zone with respect to ENSO teleconnections, with stronger teleconnections to the south. The positive PNA circulation pattern that corresponds to low SWE across the much of the western United States coincides with the composite anomaly pattern for El Niño events, while the La Niña pattern tends to correspond to a PNA pattern with reverse polarity (i.e., high pressure over eastern Alaska and low over western North America; Yarnal and Diaz 1986). Thus, the two circulation patterns that appear to have some influence on low SWE appear to be the opposite in terms of signs of pressure anomalies. In addition, as suggested above, conditions in the North Pacific may influence low SWE in the Gunnison in two ways: 1) when dry years in the northwestern United States also occur in the Gunnison region, and 2) by enhancing La Niña teleconnections over decadal timescales, thus strengthening and expanding dry conditions in the southwestern United States. The PDO, which shows decadal-scale variability in the instrumental record, has been reconstructed by several researchers (Biondi et al. 2001; d'Arrigo et al. 2001; Gedalof and Smith 2001), but it is not clear how well the three reconstructions correspond to each other, and there are no obvious consistent similarities between the SWE reconstruction and any of these PDO reconstructions. However, it is possible that in prewhitening the chronologies in the reconstruction, some of the low-frequency variability reflecting the PDO may have been removed.

As a transition zone, the Gunnison region presents both challenges in terms of investigating influential oceanic–atmospheric circulation features, and opportunities to learn more about the spatial behavior of these circulation features. This analysis presents a very simple comparison between winter moisture conditions in the Gunnison region and in the northwestern and southwestern United States using composite tree-ring chronologies as estimates of regional winter precipitation to examine possible decadal-scale regional relationships. However, these composite chronologies also contain some sensitivity to nonwinter climate, and future work will include reconstructions of SWE for the northwestern and southwestern United States, which will quantify the strength of winter seasonal moisture in the proxy record. Long-term hydroclimatic reconstructions for the Gunnison region analyzed in conjunction with reconstruction for regions with more consistent relations to Pacific Ocean–driven circulation features may help refine the results of this study and define the roles of the Pacific in modulating regional winter snowpack.

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