Number of Winter Precipitation Days Reconstructed from Southwestern Tree Rings

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ABSTRACT

The potential of reconstructing the number of winter precipitation days from tree-rings in the southwestern United States is explored in this study. This variable, an alternative to the measure of total precipitation, has not previously been used in dendroclimatic reconstructions. However, it may be a more meaningful measure of seasonal rainfall and indicator of anomalies in atmospheric circulation features than total precipitation in areas such as the arid Southwest, where the distribution of rainfall is spatially variable. The number of precipitation days in the region encompassing southwestern New Mexico and southeastern Arizona was reconstructed for the time period 1702–1983 from a collection of tree-ring chronologies in this area. Results from this study show that tree-ring chronologies explain 71% of the variance in the regional record of the number of precipitation days. The reconstruction is statistically verified and validated with independent data. Tree-ring chronologies in this region are better able to explain variations in precipitation-day numbers than total precipitation, suggesting that other dendroclimatic studies may benefit from the use of this variable as well.

1. Introduction

Precipitation frequency, as measured by number of precipitation days in a month or season, has been found to be more normally distributed and spatially coherent than precipitation totals, most notably in the southwestern United States (Englehart and Douglas 1985). The frequency of precipitation days might better reflect the actual delivery of moisture by circulation patterns than precipitation totals in the semiarid Southwest, where the spatial distribution of precipitation amounts varies greatly. Long-term information on changes in frequency of precipitation days therefore has potential value in furthering our understanding of the natural variability of circulation systems.

The objective of this paper is to explore the usefulness of tree-ring data for quantifying the temporal variability of winter precipitation-day frequency over the past 3 centuries in the southwestern United States. The climatological variable, number of precipitation days, has not previously been used in dendroclimatic reconstructions. It is reasonable to expect that the number of precipitation days might be more strongly related than total precipitation to seasonally aggregated moisture conditions sensed by trees, especially in areas where rainfall from infrequent, heavy storms may run off before much moisture is absorbed into the soil. The southwestern United States is a good region for testing the relationship between tree growth and the number of precipitation days because trees in this area are highly sensitive to variations in climate and have been found to be suitable for reconstructions of past climate. In this paper we use a network of tree-ring chronologies with the common time period of 1702–1983 to reconstruct the number of winter precipitation days for a subregion within the Southwest. We are particularly interested in investigating numbers of precipitation days at subregional scales. Variations in precipitation do exist on this scale and may have an important impact on natural ecosystems and human activities.

2. Precipitation climatology

Winter precipitation in the Southwest, defined for the purpose of this study as the geographic region from southern California to western New Mexico, is usually associated with extratropical cyclones imbedded in the westerlies. At any given location, the precipitation associated with these cyclones depends on a number of factors, including topography, stability of the air mass, orientation of the storm track, availability of moisture, and strength of low-level convergence (Pyke 1972). Typically, a semipermanent high pressure ridge off the West Coast keeps the winter storm track to the north, such that most Pacific storms enter the continent in the Pacific Northwest. Under these conditions, the Southwest is likely to remain dry. More favorable conditions

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for winter precipitation in the Southwest exist when the Pacific high shifts westward and a low pressure trough forms over the western United States, allowing Pacific storms to enter the continent at lower latitudes and encouraging further development inland (Sellers and Hill 1974). Infrequently, amplification of the Pacific high pressure ridge is associated with development of upper-level cutoff lows off the coast of California or Baja California. These cutoff lows can deliver heavy widespread precipitation as they drift across the Southwest (Sellers and Hill 1974).

Upper-level circulation patterns favorable to precipitation in the Southwest are the exception rather than the rule. A study of 24 yr of daily precipitation and 500-mb height data revealed that well-defined trough axes between 105° and 120°W existed on fewer than 30% of the total days for the months of January, April, and October, but such days accounted for more than 60% of the January precipitation over southern Arizona and southwestern New Mexico (Burnett 1994).

Although many of the same atmospheric circulation features impact winter climate across the entire Southwest, the impacts vary spatially. For example, fronts associated with cyclones passing to the north in the westerlies frequently deliver precipitation to northern Arizona, but only clouds and windy conditions to southern Arizona. Storms traveling east from the coast sometimes deliver substantial precipitation to coastal California, but little or none to the Arizona deserts because much of the moisture falls west of the low mountains of southern California (Bryson and Hare 1974).

Precipitation anomalies in the Southwest are closely linked with important atmospheric and oceanic indices of large-scale circulation. Upper-level troughing over the Southwest has been likened to a reverse Pacific–North American pattern (Burnett 1994). The split jet stream often related to warm El Niño–Southern Oscillation (ENSO) events may favor advection of moisture to the Southwest. While ENSO-related circulation may influence fall and winter climate across the region (e.g., Cayan and Peterson 1989), some studies show that the most consistent effect is on central and southeastern Arizona and western New Mexico—areas that are, because of topography, most susceptible to the effects of moist unstable Pacific air (Andrade and Sellers 1988; Kiladis and Diaz 1989).

3. Data

The region of interest for this study is located in southeastern Arizona and southwestern New Mexico (SAZNM). This region is one of six regions defined within the southwestern United States for a broader study (Fig. 1a). The larger study area was divided up into climate regions since it has been shown that there are important subregional differences in the ways that atmospheric circulation influences climate in this area (Woodhouse 1997). Climate regions were based primarily on a rotated principal components analysis (RPCA) grouping of stations, but the mean precipitation patterns and the relationships between number of precipitation days and influential circulation patterns were also considered. The regions suggested by the RPCA reflected common spatial patterns of climate variability over time, but because of the large domain of the study area combined with a somewhat coarse distribution of climate stations (in some areas), this analysis did not seem to be sensitive to some important regional differences due to physical elements that influence climate, such as topography (White et al. 1991). Consequently, the other factors were also considered in defining regions.

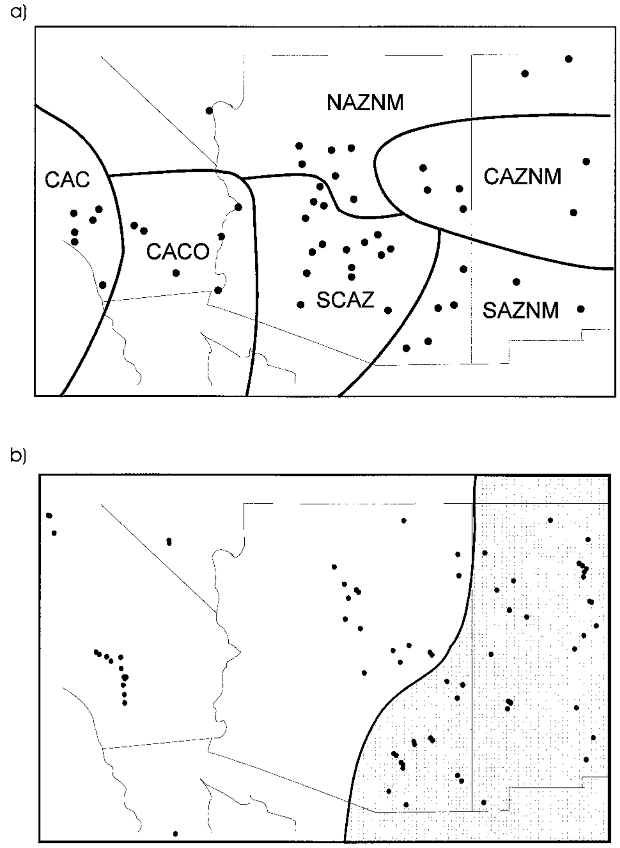

FIG. 1. (a) Location of precipitation-day stations and climate regions. CAC is the California coast region, CACO is the California–lower Colorado River region, NAZNM is northern Arizona and New Mexico, SCAZ is south and central Arizona, CAZNM is central Arizona and New Mexico, and SAZNM is southern Arizona and New Mexico. (b) Location of tree-ring chronologies. Shaded areas shows chronologies used for this study.

The number of precipitation days in the winter wet season, November through March, was the seasonal climate variable selected for reconstruction. Daily precipitation data were obtained from the National Climatic Data Center and were evaluated for homogeneity using double mass plots and the Mann–Kendall statistic (Mitchell et al. 1966). Missing climate data were esti-

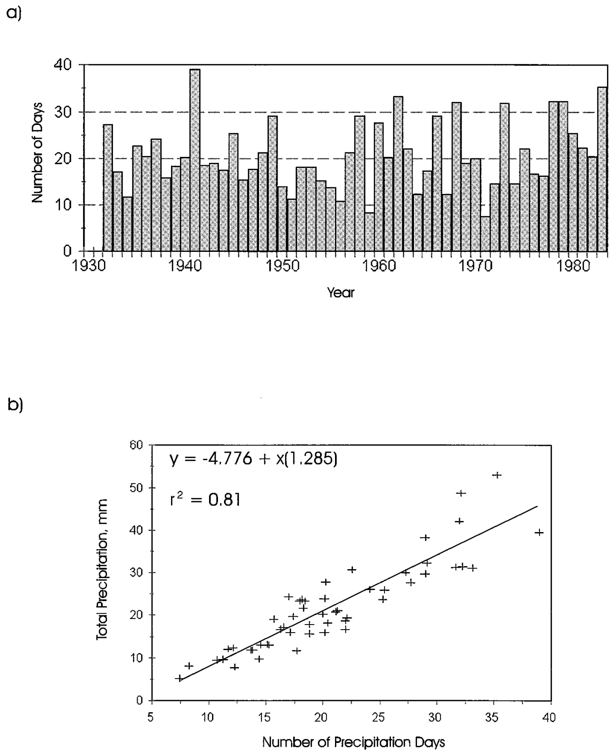

FIG. 2. (a) Number of precipitation days for SAZNM region, 1932–83. (b) Number of precipitation days compared to total precipitation for winter for the SAZNM region, 1932–83.

mated using the median ratio technique (Bradley 1976). Seven stations in the SAZNM region were averaged together to generate a regional number of precipitation-day series (Fig. 1a). All climate stations included in the regional series have data for the period of 1932–83 (the common time period for tree-ring chronologies and the daily precipitation data), with records 90% complete or better. The 52-yr mean of the series is 21 days, indicating that on average precipitation fell on 14% of the days in the November–March window. The regional climate series contains no persistence as measured by the first-order autocorrelation coefficient ($r1 = 0.137$), which is not significant at the 95% level in a one-sided test. Days with a trace of rain or more recorded were counted. The temporal distribution of precipitation days for the regional SAZNM series is shown in Fig. 2a. Much variability is evident in this record for the time period 1932–83, both at lower and higher frequencies. The relationship between precipitation days and total winter precipitation is shown in Fig. 2b. The graphs show the close linear relationship between numbers of precipitation days and total precipitation in winter. The few outliers suggest that a high number of precipitation days does not always coincide with high total precipitation, especially in years with 30 days or more of precipitation. These values indicate conditions of light rain over a number of days, a weather pattern not common in southwestern winters. Numbers of precipitation days and total

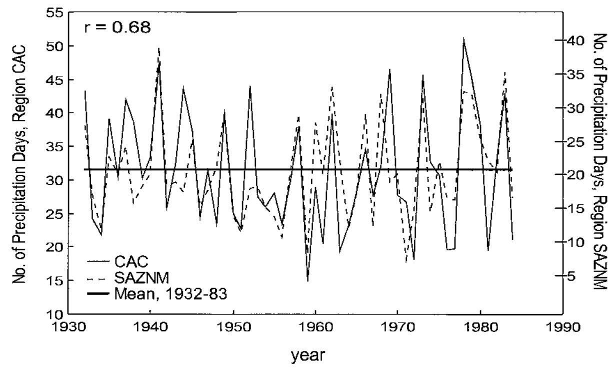

FIG. 3. Number of precipitation days in November–March 1932–83 for precipitation-day regions CAC and SAZNM. Long-term means are 31.4 days for CAC and 20.6 days for SAZNM.

precipitation are not measures of the same climatic variable, but the two are obviously related. The correlation between numbers of precipitation days and total precipitation is 0.90 for southern Arizona and New Mexico.

To illustrate some similarities and differences between numbers of precipitation days in southwestern regions, the precipitation-day records for two regions within the Southwest, the far western, California coast (CAC), and far southeastern (SAZNM) regions, were contrasted. The correlation between numbers of precipitation days in winter for these two regions is $r = 0.68$. Observed numbers of precipitation days from 1932 to 1984 for CAC and SAZNM are shown in Fig. 3. Plots of the precipitation-day records show that there are years and periods of time when the two records are very similar and other times when they are different. Spatial variations in atmospheric circulation are likely responsible for these opposing anomalies.

A set of 88 tree-ring chronologies with a common time period of 1700–1984 was selected for use in the larger study referred to above (Fig. 1b). Chronologies were obtained from the International Tree-Ring Data Bank and from unpublished collections (see the acknowledgments). For the SAZNM regional reconstruction, we used only the 48 chronologies in New Mexico and southeastern Arizona (Fig. 1b). No attempt was made to screen chronologies by elevation or species. All chronologies are coniferous species, and site elevations range from 1760 to 2950 m. Almost all of the chronologies are positively autocorrelated, as indicated by one or more significant autocorrelation coefficients at low lags. Because such autocorrelation is believed to result from biological rather than climatic factors (Fritts 1976), the chronologies were filtered with low-order autoregressive moving average (ARMA) models before their subsequent use in climate reconstructions. Such models are commonly used to model the short-term memory in tree growth arising from such factors as accumulation of food reserves, production of root and shoot masses, and multiyear retention of needles. The model was chosen to be flexible enough to remove significant autocorrelation at low lags—usually ARMA (1, 1) was used, with some chronologies requiring autoregressive models of order 2 or 3.

4. Reconstruction of precipitation-day series

The dendroclimatic reconstruction of precipitation-day frequency was generated by a standard technique of principal components regression (Fritts 1976; Cook and Kairiukstis 1990). The principal components analysis (PCA) step in this technique reduces the full set of original tree-ring chronologies to a more manageable reduced set of transformed variables. The transformed variables, or principal component scores, are then used as predictors in the climate reconstruction model. In this study, we used a rotated PCA (Varimax) instead of an unrotated PCA as it provided intermediate diagnostic information about the geographic groupings of the chronologies.

In climatic reconstruction, the tree-ring chronologies used as predictors are often selected with a view to enhancing regional-scale climate responses within the tree-ring chronologies. For this study, we selected only tree-ring chronologies in New Mexico and in the southeastern portion of Arizona. In using a smaller set of chronologies, we hoped to retain local-scale variance in the chronologies. The initial step in the analysis was an RPCA on the set of 48 chronologies. The reduced set of tree-ring variables were the six components with eigenvalues equal to or greater than 1.0. Scores for these components, lagged forward and backward 1 yr, made up the pool of 18 potential predictor variables for the stepwise regression. Lagged variables were included to account for any lagged response of tree growth not properly adjusted for in prewhitening the chronologies.

The regional precipitation-day series was calibrated with the set of independent variables by stepwise regression. A subsample replication scheme was used to generate an independent series for model verification. A standard practice in tree-ring reconstructions is to divide the period of time common to climate data and tree-ring chronologies into two sections—one part for calibrating the relation between the tree-ring series and climate data and the other part for independently verifying the calibration. The common period (1932–83) is too short in this study for such a split-sample approach. Instead, cross validation as described by Michaelson (1987) was used for verification of the reconstruction model. In cross validation, the regression model is first calibrated on all cases to obtain a set of predicted values and their residuals (analogous to calibration series). The regression model is then recalibrated iteratively, each time deleting one case and applying the model to estimate that value and its residual, until all cases have been estimated independently. The resulting time series of estimates for the deleted observations is analogous to the verification series. These estimates and their residuals are compared with the estimates and residuals for the full-period model as a means of evaluating the predictive power of the regression equation.

TABLE 1. Calibration and verification statistics for the precipitation-day reconstruction model.

Statistic	Calibration	Verification
r	0.86	0.80
RE	0.75	0.67
Sign test	45/7	45/7

The regression model calibrated as described above explains 75% of the total variance in the precipitation-day series from a set of 7 of the possible 18 predictor variables derived from the tree-ring chronologies. The seven predictor variables included five of the original components as well as one forward-lagged and one backward-lagged variable. The most important predictor variable with regard to the contribution to explained variance was the component that contained chronologies from northwestern New Mexico, followed by the two components that included chronologies from the southwestern edge of the shaded area in the map in Fig. 1b and from the southern part of the border between Arizona and New Mexico. A variety of statistics are traditionally used to evaluate the quality of a dendroclimatic reconstruction model (Fritts 1976). The correlation coefficient (r) between observed and reconstructed number of precipitation days, the reduction of error (RE) statistic, and the sign test are used in this study. The sign test is based on the numbers of agreements/disagreements in sign of departures from the mean in observed and reconstructed values. Statistics for the reconstruction are shown in Table 1.

The correlation coefficients and sign tests were all significant ($\alpha = 0.01$), and the RE value for the verification was high and positive. Any positive value of RE is considered ''encouraging'' in dendroclimatic reconstructions (Fritts 1976). Statistics for calibration and verification series are quite similar, indicating that the regression model has good predictive strength and that the model has not been overfit. The explained variance for the reconstruction of precipitation-day numbers is greater than that for the reconstruction of total winter precipitation (adjusted $r^2 = 0.71$ compared with adjusted $r^2 = 0.60$) for the same region (Woodhouse 1996).

Residuals for the regression equation were plotted against time, estimated values, and independent variables. No trends of increased or unstable variance were detected, nor was there evidence for misspecification of the model or systematic errors. A histogram of the residuals was also generated, and the distribution of values appeared to be approximately normal. The residual series had a Durbin–Watson D statistic greater than the upper critical level ($\alpha = 0.01$), indicating no first-order autocorrelation.

A plot of the observed series and the reconstructed series illustrates the ability of the regression model to explain the variance in the actual data (Fig. 4a). Al-

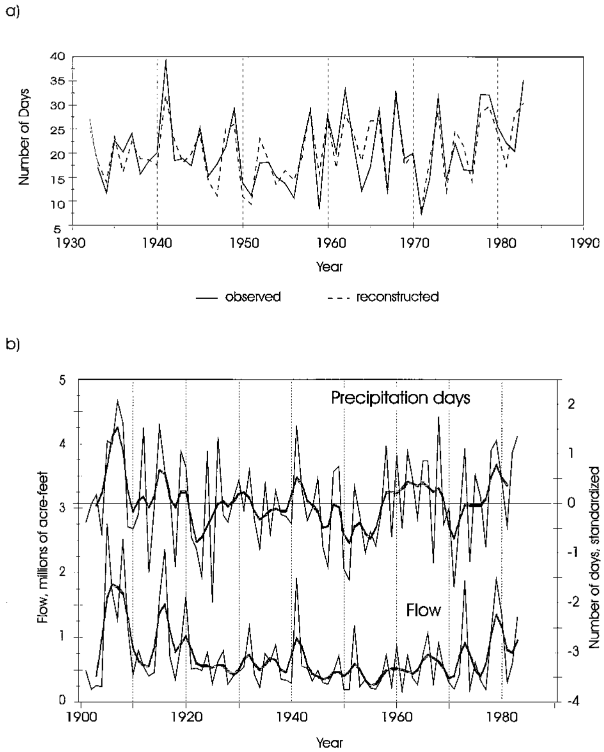

FIG. 4. (a) Observed precipitation days compared to reconstructed precipitation days for SAZNM, 1932–83. (b) Annual flow of Salt River in Arizona compared to reconstructed precipitation days, 1901–83. Flow data for 1914–83 from U.S. Geological Survey gage ‘‘near Roosevelt.’’ Data for 1901–13 for gauge ‘‘at Roosevelt’’ from Smith (1981)—except data for 1908–10, which are tree-ring estimates from Smith and Stockton (1981). Smoothed versions (thick lines) are the result of applying 5-weight binomial filters.

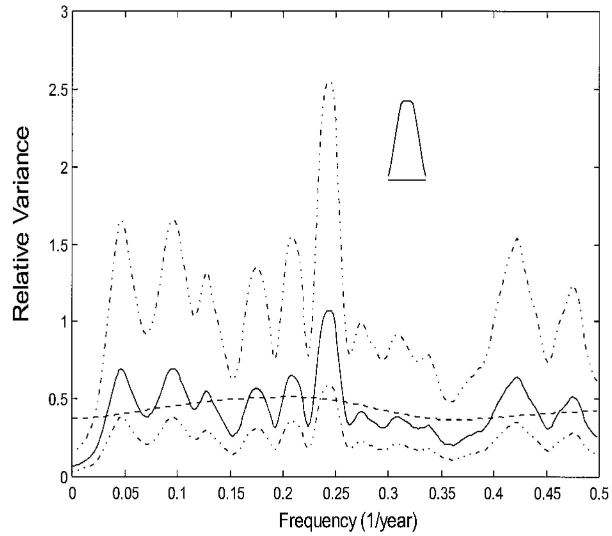

FIG. 5. Sample spectrum of precipitation-days reconstruction for 1702–1983 in region SAZNM. Spectrum (solid) computed by successive filtering of periodogram by 7-weight and 13-weight Daniell filters (Bloomfield 1976). Inset shows filter width and shape. Null continuum estimated by smoothing periodogram with 33-weight, 55-weight, and 77-weight Daniell filters. Dashed–dotted line is 95% confidence band.

though the reconstructed values are somewhat conservative in some years, as tree-ring estimates tend to be and as is common to all empirical statistical models, the fit is good in most years.

The SAZNM reconstruction compares well with other reconstructions of winter precipitation from tree rings for this general region (Fritts 1991; D'Arrigo and Jacoby 1992). It is especially important to check reconstructions with independent information on climatic variation if the calibration period is short. We have compared the major fluctuations in reconstructed precipitation days with the gauged flow record from 1901 to the present for the Salt River in Arizona, as obtained from U.S. Geological Survey publications and computer files. The headwaters of the Salt River are partially located in the SAZNM region. Smoothed time series plots (Fig. 4b) indicate that the reconstruction of precipitation days parallels the prominent decrease in flow from 1900 to 1950, as well as the recovery that began in the 1960s.

As a test of our hypothesis that a climatic reconstruction utilizing chronologies from a limited geographic area may better reflect regional variations in climate, we also tried an alternative approach for obtaining predictor variables for the regression equation. In this approach, instead of using only the 48 chronologies from New Mexico and southeastern Arizona, we used the full set of 88 southwestern chronologies. The set of 11 component scores from a PCA on the 88 chronologies was lagged forward and backward 1 yr, as in the smaller set, to produce 33 predictor variables. Stepwise regression results were not as good as those from the reconstruction using the smaller set of chronologies (adjusted r^2 of 59% vs 71%). When compared to the independent data from the Salt River gauge record, this reconstruction did not duplicate the marked decrease in flow from 1900 to 1950 nearly as well as the reconstruction using the subset of chronologies. These results validate the decision to use a set of chronologies from a smaller region and, in this case, bear out the supposition that details of regional climate may be better reproduced with the smaller set of chronologies. Reconstructions of more spatially coherent variables such as temperature and pressure field might produce results that do not necessarily support this supposition, but in the case of more regionally variable precipitation, important small-scale variations may be preserved.

5. Low-frequency characteristic of the reconstructed precipitation-day series

Time series characteristic of the reconstructed precipitation-day series were examined through spectral analysis and smoothing of the time series. In a sample spectrum for the precipitation-day reconstruction, the most important peak appears at a period of slightly greater than 4 yr, with a secondary peak at around 21

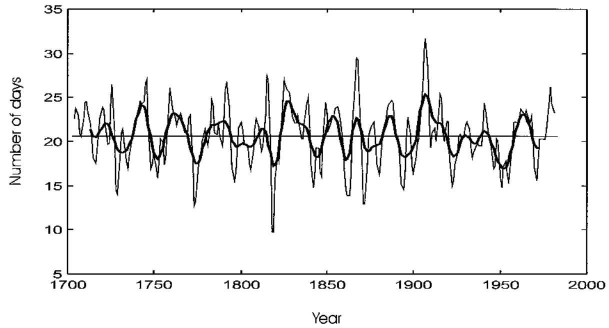

FIG. 6. Smoothed reconstruction of number of precipitation days for region SAZNM. Series smoothed by 5-weight binomial filter (thin line) and 23-weight Hamming filter; these filters retain approximately 27% and 7.5% of the variance of the annual reconstruction. Frequency response amplitude of binomial filter is 0.9, 0.5, and 0.1 at periods of 13.8, 5.5, and 3.2 yr, respectively Frequency response amplitude of Hamming filter is 0.9, 0.5, and 0.1 at periods of 34.2, 14.7, and 9.2 yr, respectively.

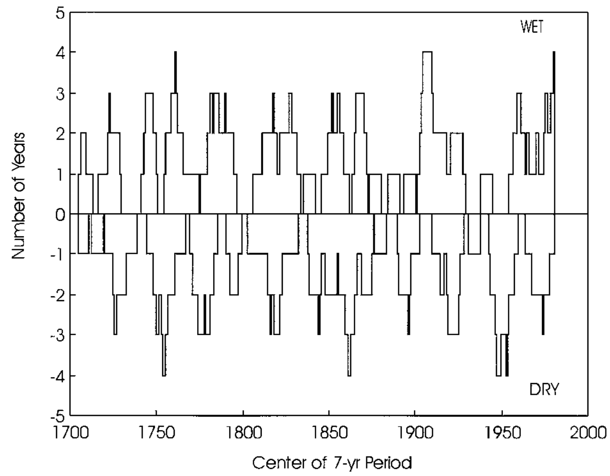

FIG. 7. Number of dry years and wet years in sliding 7-yr window of precipitation-days reconstruction for 1702–1983 in region SAZNM. A dry year is defined as the reconstructed number of precipitation days in the lowest quintile (0.2 quantile) of the 282 reconstructed values. A wet year similarly defined using the highest quintile (0.8 quantile). Dry periods are plotted below the axis (with negative labeling) and wet periods above.

yr (Fig. 5). The greatest part of the variance seems to be concentrated at frequencies of lower than 4 yr. Similar spectral characteristics have been found in other analyses of tree-ring chronologies in Arizona, and a major peak at periods greater than 21 yr has been found in chronologies throughout the western United States (Meko 1992). A 400-yr dendrochronological reconstruction of October–April discharge of the Salt River in Arizona also exhibits a spectral peak near 21 yr (Smith and Stockton 1981).

The reconstruction was smoothed using two filters, allowing for an assessment of variations at wavelengths roughly greater than about 5 yr (5-weight binomial filter) and 15 yr (23-weight Hamming filter) (Fig. 6). The downward trend in the reconstructed series from 1900 to 1950, also noted in the gauged Salt River record, appears to be unprecedented in the past three centuries. However, there have been shorter-term extremes in past centuries that have not been equaled in the last 80 yr. In particular, the latter half of the nineteenth century displays alternating wet and dry periods at shorter intervals than the rest of the record.

The clustering of wet or dry years can be conveniently summarized by a count of the number of years with more than or fewer than some arbitrary threshold of number of precipitation days in various subperiods. A tabulation based on a sliding 7-yr window and thresholds equal to the upper and lower quintile of the number of reconstructed precipitation days is plotted in Fig. 7. This plot suggests that unusual clustering of dry years (4 of 7 below threshold) has occurred roughly once a century—around the 1750s, 1860, and 1950. A wet cluster closely followed the dry cluster in the 1750s. Another very wet period occurred in the early 1900s (which was the most prolonged extreme wet period of the record), along with one in the most recent years of the reconstruction. Periods of dry extremes appear to be fairly evenly and consistently spaced over the past three centuries. Wet extremes are less even, with the longest periods without many extremes in the latter part of the nineteenth century and from the 1930s to the 1950s.

6. Conclusions

This study demonstrates the usefulness of tree-ring chronologies for reconstructing the number of precipitation days in a region within the southwestern United States. The variance in the precipitation-day record explained by the tree-ring chronologies exceeds 60%, a level characteristic of high quality climate reconstructions from arid-site trees in western North America (DeWitt and Ames 1976). Calibration and verification statistics are highly significant, and a comparison with the independent Salt River gauge record helps validate the reconstruction. Conceptually and by the objective criterion of the percentage variance explained, the number of precipitation days appears, for this region, to be superior to the total winter precipitation as a climatic variable for tree-ring reconstruction.

The number of precipitation days, as a measure of moisture, may be successfully reconstructed in other regions, especially in areas where a record of precipitation-day frequency may be more meaningful than precipitation totals. The use of this climatic variable in reconstructions may provide a way to improve reconstructions of precipitation in areas where rainfall occurs sporadically, with variable spatial distributions. Although the compilation of precipitation-day series is more of an undertaking than simply obtaining a record of total precipitation, this study demonstrates that precipitation-day reconstructions may potentially be more robust than reconstructions of precipitation.

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REFERENCES

Andrade, E. R., and W. D. Sellers, 1988: El Niño and its effect on precipitation in Arizona and western New Mexico. *J. Climatol.,* **8,** 403–410.

Bloomfield, P., 1976: *Fourier Analysis of Time Series: An Introduction.* Wiley and Sons, 258 pp.

Bradley, R. S., 1976: *Precipitation History of the Rocky Mountain States.* Westview Press, 334 pp.

Bryson, R. A., and F. K. Hare, 1974: *The Climates of North America.* Vol. 11, *World Survey of Climatology,* Elsevier, 1–47.

Burnett, A. W., 1994: Regional-scale troughing over the southwestern United States: Temporal climatology, teleconnections, and climate impacts. *Phys. Geogr.,* **15,** 80–98.

Cayan, D. R., and D. H. Peterson, 1989: The influence of North Pacific atmospheric circulation on streamflow in the West. *Aspects of Climate Variability in the Pacific and Western Americas, Geophys. Monogr.,* No. 55, Amer. Geophys. Union, 371–397.

Cook, E. R., and L. A. Kairiukstis, 1990: *Methods of Dendrochronology: Applications in the Environmental Sciences.* Kluwer Academic, 394 pp.

D'Arrigo, R. D., and G. C. Jacoby, 1992: A tree-ring reconstruction of New Mexico winter precipitation and its relation to El Niño/Southern Oscillation events. *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation,* H. F. Diaz and V. Markgraf, Eds., Cambridge University Press, 243–257.

DeWitt, E., and M. Ames, 1976: *Tree-Ring Chronologies of Eastern North America.* Chronology Series VI, Vol. 1, The Laboratory of Tree-Ring Research, 42 pp.

Englehart, P. J., and A. V. Douglas, 1985: A statistical analysis of precipitation frequency in the conterminous United States, including comparisons with precipitation totals. *J. Climate Appl. Meteor.,* **24,** 350–362.

Fritts, H. C., 1976: *Tree Rings and Climate.* Academic Press, 567 pp.

——, 1991: *Reconstructing Large-Scale Climatic Patterns from Tree-Ring Data.* The University of Arizona Press, 286 pp.

Kiladis, G. N., and H. F. Diaz, 1989: Global climatic anomalies associated with extremes of the Southern Oscillation. *J. Climate,* **2,** 1069–1090.

Meko, D. M., 1992: Spectral properties of the tree-ring data in the United States Southwest as related to El Niño/Southern Oscillation. *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation,* H. F. Diaz and V. Markgraf, Eds., Cambridge University Press, 227–241.

Michaelson, J., 1987: Cross-validation in statistical climate forecast models. *J. Climate Appl. Meteor.,* **26,** 1589–1600.

Mitchell, J. M., B. Dzerdzeevski, H. Flohn, W. L. Hofmeyr, H. H. Lamb, K. N. Rao, and C. C. Wallén, 1966: Climate change. WMO Tech. Note 79, 64–65.

Pyke, C. B., 1972: Some meteorological aspects of the seasonal distribution of precipitation in the western United States and Baja California. University of California Water Resources Center Contribution 139, 205 pp. [Available from Water Resources Center Archives, 410 O'Brien Hall, University of California, Berkeley, Berkeley, CA 94720-1718.]

Sellers, W. D., and R. H. Hill, 1974: *Arizona Climate 1931–1972.* 2d ed. The University of Arizona Press, 616 pp.

Smith, L. P., 1981: Long-term streamflow histories of the Salt and Verde Rivers, Arizona, as reconstructed from tree rings. U.S. Army Corps of Engineers Contract Rep. DACW-09-80-C-0071, 129 pp. [Available from Hydrologic Engineering Section, U.S. Army Corps of Engineers, P.O. Box 532711, Los Angeles, CA 90053-2352.]

——, and C. W. Stockton, 1981: Reconstructed streamflow for the Salt and Verde Rivers from tree-ring data. *Water Resour. Bull.,* **17,** 939–947.

White, D., M. Richman, and B. Yarnal, 1991: Climate regionalization and rotation of principal components. *Int. J. Climatol.,* **11,** 1–25.

Woodhouse, C. A., 1996: Climate variability in the southwestern United States as reconstructed from tree-ring chronologies. Ph.D. dissertation, The University of Arizona, 230 pp. [Available from The University of Arizona, Main Library, Tucson, AZ 85721.]

——, 1997: Winter climate and atmospheric circulation patterns in the Sonoran Desert region, U.S.A. *Int. J. Climatol.,* **17,** 1–15.