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# Asynchronous Droughts in California Streamflow as Reconstructed from Tree Rings

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**Streamflow since 1560 A.D. for four rivers within the Sacramento River Basin, California, has been reconstructed dendroclimatically. Both the highest and the lowest reconstructed streamflows occurred during the historical period, with high flows from 1854 to 1916 and low flows from 1917 to 1950. Prolonged (decade-scale) excursions from the mean have been the norm throughout the reconstructed period. The periods of high and low streamflow in the Sacramento Basin are generally synchronous with wet and dry periods reconstructed by dendroclimatic studies in the western United States. The record indicates a number of asynchronous droughts or wet years. The strongest contrasts are developed between northern (western Washington and Oregon or the Columbia Basin) and southern (the Sacramento Basin or central California) climate regions. These asynchronous events may be due to variation in the latitude of the subtropical high and in the latitudinal position of winter storms coming off the Pacific. No association was found with El Niño–Southern Oscillation events.** ©1993 University of Washington.

## INTRODUCTION

Records of streamflow are a valuable source of information about climatic variation within a drainage basin. They are useful to both water resources planners and those concerned with the study of climatic variation. However, the utility of these records is limited by their length; rarely do streamflow records cover as much as a century. The study of variations in climate over longer time scales requires a longer, quantitative record of past flows. Such a record can be approximated by the use of tree rings as a climate proxy (Stockton and Fritts, 1971; Stockton, 1975; Stockton and Jacoby, 1976; Fritts, 1976; Cook and Jacoby, 1983; Jones *et al.*, 1984). In trees growing in semiarid regions, in warm climates or near the lower treeline, the width of the annual ring is primarily limited by available moisture (Fritts *et al.*, 1965; Kienast *et al.*, 1987). Thus, ring-width variation is often statistically associated with measures of available moisture such as rainfall or streamflow. In this approach, a regression model is developed that describes annual streamflow as a function of some suite of variables that represent tree-ring widths in trees sampled from the same region. This model can be used to estimate past streamflows over the length of the tree-ring record (Stockton, 1975). The accuracy of the reconstruction is determined from its ability to estimate correctly independent streamflow data that were withheld from the regression model.

This paper presents the results of one such study, involving several streams in the Sacramento River Basin of northern California. Tree-ring data derived from 17 tree-ring chronologies previously developed for California and eastern Oregon (Holmes *et al.*, 1986) are used to reconstruct streamflow histories for the Sacramento, Feather, Yuba, and American rivers. These reconstructions reveal much about the frequency and intensity of past droughts in the Sacramento River Basin, a finding of great concern to water resources planners in California. Comparison of these reconstructions to one another, and to dendroclimatic reconstructions previously done for California and the Pacific Northwest, reveals both a general uniformity of climatic variation across the region and the presence of occasional significant contrasts between northern and southern regions.

## STUDY AREA

The Sacramento River Basin occupies the central part of northern California. The regional climate is strongly Mediterranean, with cool wet winters (December to February average precipitation 474 mm, January average temperature 4.5°C) and warm dry summers (July to September average precipitation 21 mm, July average temperature 22.7°C). The basin is bounded on the west, north, and east by mountains, which support pine forests at montane elevations and sclerophyllous shrubland and woodland in the foothills. The interior of the basin is an important agricultural region. The principal rivers (Fig. 1) contain numerous dams and other waterworks, such as canals, for distributing runoff to the farmlands. Seasonal streamflow is dominated by the winter rains, with a secondary contribution from snowmelt in the spring and early summer.

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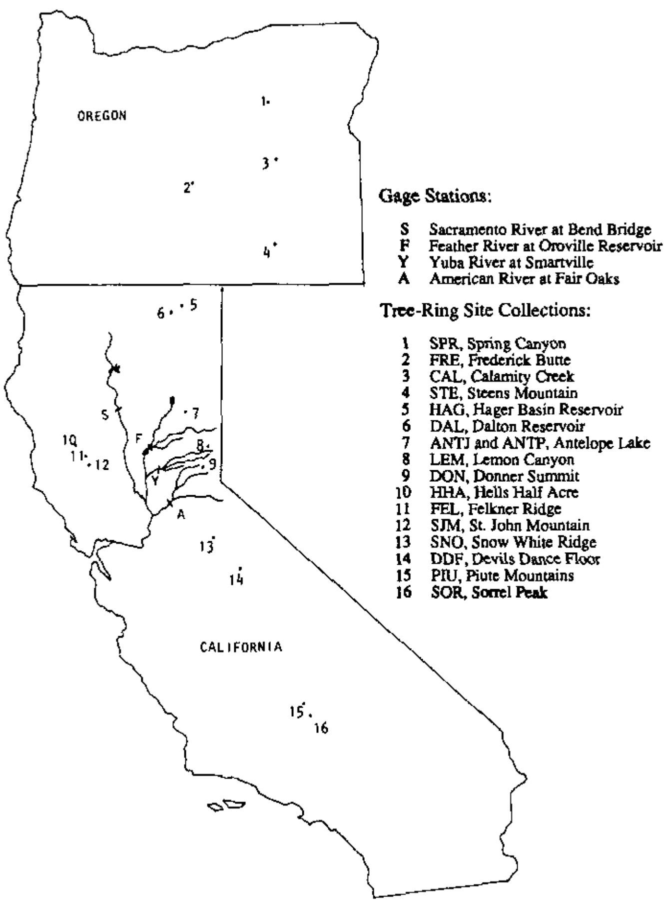

FIG. 1. Map showing location of the rivers, and streamflow gage stations, and tree-ring site collections.

## DATA

The streamflow data, prepared by the California Department of Water Resources, consisted of (1) monthly gage records for each of the four streams for the period 1906–1980 and (2) approximate (±10%) yearly flows for each stream for the period 1872–1905. The data were corrected by the Department for station relocations, diversions, and impoundments. All years were water years, beginning on October 1 of the preceding calendar year.

The tree-ring chronologies were developed from 1980 to 1985 at the Laboratory of Tree-Ring Research, University of Arizona (Holmes *et al.*, 1986). Chronologies represent single-species collections of *Pinus ponderosa*, *Pinus jeffreyi*, *Pinus lambertiana*, or *Juniperus occidentalis*. Each chronology is derived from increment cores from 30 to 40 trees sampled at a single site, usually with two cores per tree. These cores were dated and measured according to standard dendrochronological methods (Stokes and Smiley, 1968). The dated series were then standardized to remove age-related trends. This procedure involved fitting linear, negative exponential, or stiff cubic spline curves to ring-width series. Each measured ring width was then divided by the curve-fitted value to produce a dimensionless index. Indices of all ring-width series at a site were averaged using a robust mean function to produce a site chronology of annual indices. Details of the procedures are documented by Holmes *et al.* (1986). The chronologies were used in two forms, including: (1) the 17 tree-ring chronologies and (2) the 10 primary principal components of these chronologies as determined by eigenvector analysis. Principal components analysis is thought to emphasize large-scale patterns in tree-ring data (Fritts, 1982).

## RECONSTRUCTION METHODOLOGY

This study used a reconstruction model similar to those described by Fritts (1976). The steps in forming this model (Earle and Fritts, 1986) were as follows:

*Variable selection.* The dependent variables were recorded annual streamflow for each of the four rivers. The independent variables included 17 tree-ring chronologies and the principal components of this set of 17 chronologies, hereafter termed the "chronology data" and the "principal components data." These variables were also lagged for periods of −1, 1, 2, and 3 yr relative to the streamflow data because there can be a significant association between climate in a given year and tree growth in the preceding year or up to 3 yr following (Fritts, 1976) due to biological lags in the response of tree growth to climate and autoregressive properties of the time series involved.

*Correlation analysis.* Pearson correlation coefficients were calculated between each tree-ring variable and each streamflow variable for two time periods, 1906–1942 and 1943–1979. Two intervals were used in order that the selected variables show a strong correlation with climate at different times; this would suggest that the relationship between tree growth and streamflow is constant through time (Cook and Jacoby, 1983).

*Model calibration.* Tree-ring variables that showed a strong (significant at 95% confidence level) correlation with streamflow for both intervals were selected for input to stepwise multiple linear regression models. Each model was calibrated using either chronology data or principal components to predict the streamflow for one river and was run twice, first with a 1906–1942 calibration period and then with a 1943–1979 calibration period.

*Model verification.* The regression equations so derived were used to develop streamflow reconstructions, and these reconstructions were then compared with streamflow data withheld during model calibration. Such testing against independent data is termed "verification" (Fritts, 1976). For example, predictions of a model calibrated with 1906–1942 data were verified with 1943–1979 data. All models were also verified using the approximate streamflow data for the period 1872–1905. Verification relied on four statistics: (1) Explained variance, $R^2$, is a common measure of the ability of a regression model to predict accurately values of the independent variable. All values herein have been adjusted for the number of predictor variables in the model. (2) The "sign test" for agreement in the sign of the first-differenced series is widely used in dendrochronology because it tells whether the sequence of wet and dry years is accurately matched by the reconstructed series, independent of the quantitative accuracy for individual years. (3) Correlation coefficient is a familiar measure of the similarity between actual and reconstructed series. (4) Reduction of error, RE, is commonly used to test the accuracy of a dendroclimatic reconstruction. A positive value indicates agreement between two series, with a value of 1.0 indicating perfect agreement. RE is calculated as

$$RE = 1 - SSR/SSM,$$

where SSR is the sum of the squared model residuals and SSM is the sum of the squared differences of the actual data from the mean of the data used to develop the model (Fritts, 1976).

*Model selection.* The models were ranked on the basis of these four statistics, calculated for both verification periods. Two highly ranked models were selected for each river, one using chronology data, the other using principal components data. Reconstructions using these two models were averaged together to produce a composite reconstruction using both types of tree-ring data. Fritts (1982) has observed that this technique may enhance the climate signal and reduce the noise in a reconstruction. Verification statistics were compared for the composite vs simple reconstructions. These included only the 1872–1905 verification data because four of the five composite reconstructions contained models using both the 1906–1942 and 1943–1979 data for calibration. A preferred regression model, either the highest-ranked simple model or the composite model, was then selected for each river.

*Reconstruction.* The preferred regression models were used to reconstruct streamflow back to 1560, when sample sizes in the shortest tree-ring chronologies dropped below 10 cores. Low-pass filtered flows, passing variance at wavelengths of more than 8 yr, were also calculated for each reconstruction.

## RESULTS

### *Principal Components*

Table 1 indicates which chronologies were important in principal components (PCs) that later appeared in reconstruction models. The first four PCs explained 56% of the variance in the tree-ring chronologies; PCs 8 and 9 were only selected in a few models and then were lightly weighted. Generally, the first PC emphasized several climatically sensitive chronologies throughout the study area. The second PC assigned strong positive weights to two chronologies within the Sacramento Basin and strong negative weights to two northern chronologies. The third and fourth PCs again gave strong positive weights to intrabasinal chronologies, while strong negative weights went to the two southernmost chronologies.

TABLE 1

**Chronologies Making an Important Contribution to Principal Components Used in the Reconstructions**

| PC | Positive | Negative |
|---|---|---|
| 1 | None | LEM DAL SNO ANTJ ANTP HAG PIU |
| 2 | HHA DON | CAL STE FRE |
| 3 | HHA SPR SJM | PIU SOR |
| 4 | ANTP ANTJ | SOR PIU |
| 8 | FRE SPR | HAG |
| 9 | SPR FEL DON | HHA FRE |

*Note.* Chronology site codes are listed in Figure 1. Chronologies contributing a total of 50% of the weights in a given principal component are listed. "Positive" chronologies are given positive eigenvector weights. Chronologies are listed in decreasing order of importance.

### *Reconstruction Models*

The 16 simple reconstruction models collectively chose 5 chronologies and 6 PCs as model predictors (Table 2). Regression models for all of the rivers selected the Frederick Butte tree-ring chronology as a predictor, and the Sacramento reconstructions chose this chronology as the only predictor. This chronology was developed from a stand of western juniper (*Juniperus occidetalis*) in eastern Oregon. Chronology descriptive statistics (Holmes *et al.*, 1986) suggest this is the most climatically sensitive of the 17 chronologies. The other chronologies were located within the Sacramento Basin and also show strong chronology descriptive statistics. The first and second PCs, emphasizing chronologies within and north of the Sacramento Basin, dominated the PC-based models.

### *Verification of Reconstruction Models*

For all rivers, regression models using chronology data displayed generally stronger verification statistics than models using principal components data (Table 3). The difference is strongest for the RE statistic and weakest for the sign test. The best regression model for each river explained from 36 to 48% of the variance in the streamflow data for the standard verification period. Most reconstructions showed low and nonsignificant values for all verification statistics for the 1872–1905 verification period, but significant values for the RE statistic are found for the Sacramento and American rivers for the

TABLE 2
**Predictor Variables Used in Regression Models**

| | Model[b] | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sacramento R. | | | | Feather R. | | | | Yuba R. | | | | American R. | | | |
| Predictor[a] | T1 | T2 | P1 | P2 | T1 | T2 | P1 | P2 | T1 | T2 | P1 | P2 | T1 | T2 | P1 | P2 |
| ANTJ | | | | | 28 | | | | | | | | | | | |
| ANTJ* | | | | | 20 | | | | | | | | | | | |
| ANTP | | | | | 18 | | | | | | | | | | | |
| FEL | | | | | 11 | | | | | | | | | | | |
| FRE | 59 | 55 | | | 6 | 44 | | 63 | 63 | 37 | | | 71 | 33 | | |
| LEM | | | | | | 39 | | | | 41 | | | | 41 | | |
| LEM* | | | | | 13 | | | | | | | | | | | |
| PC1 | | | 6 | 4 | | | 6 | 5 | | | 5 | 6 | | | | 7 |
| PC2 | | | 11 | | | | 10 | 7 | | | 12 | | | | 10 | |
| PC3 | | | | | | | | | | | | | | | | 14 |
| PC3* | | | | | | | | 10 | | | | 13 | | | | |
| PC4* | | | | 7 | | | | | | | | | | | 15 | |
| PC8 | | | | 13 | | | | 14 | | | | 12 | | | | |
| PC9* | | | | 10 | | | | | | | | | | | | |
| Constant | 41 | 45 | 84 | 66 | −3 | 17 | 84 | 63 | 37 | 22 | 83 | 69 | 29 | 25 | 76 | 79 |

*Note.* Weights are expressed as a percentage of the sum of all coefficients in each model.

[a] Predictors in the regression models. Variables beginning "PC" represent principal components. Other variables are site codes for tree-ring chronologies (*cf.* Fig. 1) Suffix* indicates predictor series was lagged by −1 yr relative to the streamflow series.

[b] The reconstruction model used: T, the model employed tree-ring chronologies as predictors; P, the model employed the principal components of those chronologies as predictors; 1, calibration using 1906–1942 streamflow data; 2, calibration using 1943–1979 streamflow data.

1872–1905 period. The composite reconstructions generally show verification statistics intermediate between those of their component reconstructions.

For the Sacramento River, the composite model was found to be superior because the chronology-based part of the reconstruction, although showing strong verification statistics, relies upon a single extrabasinal chronology (FRE) as the predictor; the principal components part of the reconstruction weights a number of chronologies located within the Sacramento Basin, and also shows strong sign test and correlation statistics. For the American River, reconstruction P2 shows strong verification statistics and primarily relies on chronologies located within the Sacramento Basin.

## DISCUSSION

### *Reconstruction Accuracy*

These streamflow reconstructions have the same limitations in accuracy as other tree-ring reconstructions of past climate. Two limitations are direct consequences of using linear regression to develop the reconstructions: (i) flows close to the mean will tend to be estimated accurately, whereas high or low flows will be estimated less accurately (Draper and Smith, 1981); and (ii) the reconstructions display lower variance than the instrumental records of streamflow because the variance of the instrumental records is equal to the variance of the reconstruction plus the variance of the model residuals (Ezekiel and Fox, 1959). This means that high flows will tend to be underestimated by the reconstructions, and low flows will tend to be overestimated. Third, all tree-ring reconstructions must assume that the statistical relationship between climate and tree growth has not changed through time and that errors in estimation are unbiased and randomly distributed. Both assumptions cannot be tested for the period before the start of the instrumental data record. The latter assumption was tested for the instrumental data record and found to be acceptable at the 95% confidence level. Generally, these reconstructions are acceptable and meaningful, with verification statistics (explained variance and RE) intermediate between those found by workers in arid regions (Stockton, 1975; Stockton and Jacoby, 1976) and by workers in mesic regions (Cook and Jacoby, 1979; Jones *et al.*, 1984) using comparable methods of analysis.

The failure of many reconstructions to display significant verification statistics for the 1872–1905 data, while showing good verification statistics for the instrumental data period, may be due to either of two causes: (1) the reconstructions may be poorly estimating streamflow for the 1872–1905 period, or (2) the 1872–1905 data may be inaccurate estimates of actual streamflow. Many reconstructions show a modest decrease in the sign test between the regular and early verification periods, while showing a very strong loss in RE values. Since RE, in particular, is sensitive to qualitative differences between series, possibility (2) is quite real.

TABLE 3
Verification Statistics and Ranks for All Reconstructions

| Recon.[a] | Sign test V[b] | Sign test E | Corr.[c] V | Corr.[c] E | RE[d] V | RE[d] E | Adj. $R^2$[e] (%) V | Adj. $R^2$[e] (%) E | Rank[f] V | Rank[f] E |
|---|---|---|---|---|---|---|---|---|---|---|
| Sacramento River | | | | | | | | | | |
| T1 | +24 −13 | +22 −12 | 0.55* | 0.18 | 0.28* | 0.13* | 28.8 | 0.4 | 9 | 19 |
| T2 | +30 −7 | +21 −13 | 0.70* | 0.18 | 0.48* | 0.05 | 48.0 | 0.4 | 16 | 13 |
| P1 | +23 −14 | +22 −12 | 0.36* | −0.07 | −0.03 | −0.08 | 10.4 | 2.7 | 2 | 17 |
| P2 | +27 −10 | +19 −15 | 0.61* | 0.01 | 0.04 | −0.06 | 35.7 | 3.1 | 11 | 13 |
| T1P2 | | +22 −12 | | 0.11 | | 0.09* | | 2.0 | | 18 |
| Feather River | | | | | | | | | | |
| T1 | +24 −13 | +20 −14 | 0.39* | −0.07 | −0.06 | −0.25 | 13.1 | 2.6 | 3 | 8 |
| T2 | +28 −9 | +17 −17 | 0.68* | −0.07 | 0.39* | −0.23 | 44.8 | 2.6 | 15 | 7 |
| P1 | +23 −14 | +17 −17 | 0.46* | −0.27 | 0.13* | −0.25 | 18.6 | 4.6 | 65 | 6 |
| P2 | +28 −9 | +18 −16 | 0.57* | −0.09 | −0.12 | −0.46 | 30.6 | 2.4 | 9 | 3 |
| T2P2 | | +22 −12 | | 0.15 | | −0.01 | | 0.9 | | 17 |
| Yuba River | | | | | | | | | | |
| T1 | +24 −13 | +21 −13 | 0.62* | 0.06 | 0.33* | 0.00 | 36.6 | 2.7 | 12 | 17 |
| T2 | +25 −12 | +19 −15 | 0.68* | −0.01 | 0.31* | −0.23 | 45.3 | 3.1 | 14 | 11 |
| P1 | +23 −14 | +19 −15 | 0.44* | −0.20 | 0.07 | −0.26 | 17.2 | 0.9 | 4 | 3 |
| P2 | +25 −12 | +20 −14 | 0.46* | −0.11 | −0.35 | −0.54 | 19.3 | 1.8 | 6 | 4 |
| T1P2 | | +22 −12 | | −0.06 | | −0.17 | | 2.8 | | 17 |
| American River | | | | | | | | | | |
| T1 | +24 −13 | +17 −17 | 0.59* | 0.01 | 0.27* | −0.06 | 32.4 | 3.1 | 10 | 11 |
| T2 | +28 −9 | +18 −16 | 0.62* | −0.08 | 0.26* | −0.25 | 36.2 | 2.5 | 14 | 5 |
| P1 | +21 −16 | +19 −15 | 0.39* | −0.15 | −0.33 | −0.34 | 13.1 | 0.8 | 1 | 1 |
| P2 | +26 −11 | +22 −12 | 0.52* | 0.28 | 0.19* | 0.10* | 25.0 | 5.0 | 7 | 20 |
| T1P2 | | +21 −13 | | 0.17 | | 0.06 | | 0.0 | | 11 |

*Note*. For correlation and RE, * indicates result significant at 95% confidence level.

[a] The reconstruction model used: T, the model employed tree-ring chronologies as predictors; P, the model employed the principal components of those chronologies as predictors; 1, calibration using 1906–1942 streamflow data and verification using 1943–1979 data; 2, calibration using 1943–1979 streamflow data and verification using 1906–1942 data.

[b] V, result calculated for verification period data; E, result for early-period (1872–1905) streamflow data.

[c] Pearson product–moment correlation coefficient.

[d] Reduction of error.

[e] Variance in streamflow data explained by the reconstruction, adjusted for degrees of freedom.

[f] Determined by ranking the test statistics (sign test, Correlation, RE, and adjusted $R^2$) for all rivers, summing these scores, and ranking the results. Composite reconstructions could not be assigned ranks for the regular verification period because they may include calibration data from both 1906–1942 and 1943–1979; thus, there are 16 ranks for the regular verification period and 20 ranks for the early verification period.

### *Streamflow Reconstructions*

The Sacramento River reconstruction (Fig. 2) was most representative of the group of four reconstructions in that the Sacramento, Feather, and Yuba river models all chose similar predictor variables (Table 2), and these reconstructions all show strong cross-correlation throughout the reconstruction period. For this reason, results for the Feather and Yuba rivers are not detailed. For the Sacramento River, the lowest reconstructed flows occurred during the 1930s, during a period when low-pass filtered flows remained below average for 34 yr. Other periods of prolonged below-average flow occurred in 1574–1584, 1614–1631, 1676–1691, 1775–1788, and 1838–1853. Conversely, flows were above average for more than a decade in 1597–1613, 1641–1657, 1664–1675, 1725–1735, 1741–1754, 1798–1821, 1854–1869, 1874–1887, 1891–1916, and 1962–1973. The last four periods fall within historical time for northern California, indicating that even though this period contains the longest reconstructed low-flow episode, it was generally wet in the context of the last 420 yr. These results indicate that flows have seldom been "average"; prolonged excursions from the mean are the rule. The reconstruction for the American River (Fig. 3) is similar, except that the American River did not experience the low flows of 1591–1599, 1614–1631, and 1717–1724, but did experience low flows in 1653–1658 and 1666–1670. The Sacramento and American rivers differ in that their gage stations (Fig. 1) are located at the north and south ends, respectively, of the Sacramento Basin. Also, their reconstruction models differ in the choice of predictors; the Sacramento River reconstruction strongly weights the Frederick Butte chronology and principal components dominated by chonologies within and north of the Sacramento Basin, whereas the American River reconstruction

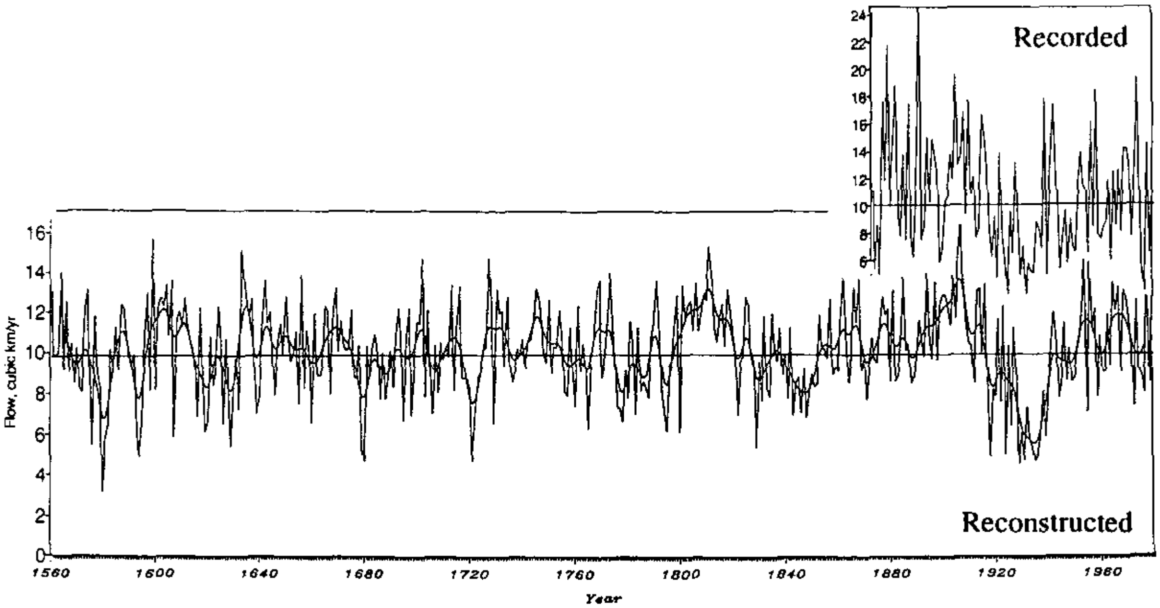

FIG. 2. Reconstructed and recorded flows for the Sacramento River at Bend Bridge, showing mean of both series for the 1906–1980 period. Reconstruction plot includes 8-yr low-pass filtered flows.

incorporates principal components weighting chronologies within and well south of the Sacramento Basin.

### *Comparison with Other Dendroclimatic Reconstructions*

Results of a visual comparison between the filtered Sacramento and American river reconstructions and published reconstructions for Pasco Basin (Washington) precipitation, Colorado River (Utah/Arizona) streamflow, Salt River (Arizona) streamflow, and south-coastal California precipitation are summarized in Table 4. These reconstructions show many dry periods that are synchronous with low flow events in the Sacramento Basin. The American River record, in particular, largely agrees with the reconstructions of Salt River (Smith and Stockton, 1981) and Colorado River (Stockton and Jacoby, 1976) streamflow and coastal California winter precipitation (Michaelsen *et al.*, 1987). There is little agreement with

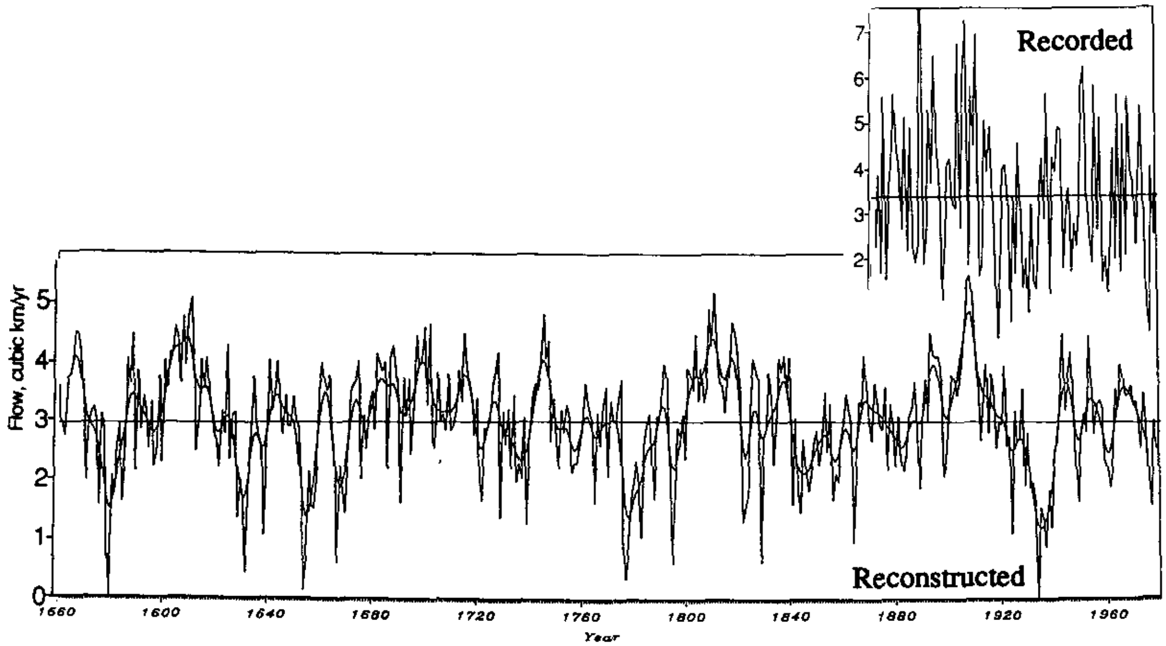

FIG. 3. Reconstructed and recorded flows for the American River at Fair Oaks, showing mean of both series for the 1906–1980 period. Reconstruction plot includes 8-yr low-pass filtered flows.

TABLE 4

**Drought[a] Events on the Sacramento and American Rivers Compared to Other Dendroclimatic Reconstructions for the Western United States**

| Sacramento | | | | | American | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Drought | Salt[b] | Colo[c] | Pasco[d] | SantB[e] | Drought | Salt | Colo | Pasco | SantB |
| 1577–1583 | *[f] | + | | | 1577–1584 | + | + | | |
| 1592–1595 | * | + | | | 1629–1633 | + | + | + | * |
| 1618–1621 | * | – | – | + | 1638 | – | – | – | * |
| 1627–1630 | * | + | + | + | 1653–1658 | + | + | * | + |
| 1678–1681 | * | – | + | – | 1666–1670 | + | + | * | + |
| 1719–1723 | – | – | * | * | 1737 | * | * | – | * |
| 1777–1779 | + | + | * | + | 1776–1784 | + | + | * | * |
| 1794–1795 | + | * | * | + | 1795–1796 | + | * | * | + |
| 1830 | * | + | * | – | 1843–1848 | + | + | + | + |
| 1843–1850 | + | + | + | + | 1857 | * | + | * | + |
| 1918–1920 | * | * | + | + | 1930–1940 | * | * | + | + |
| 1924–1940 | * | * | + | + | | | | | |
| Score | 3/12 | 6/12 | 5/10 | 7/10 | Score | 7/11 | 7/11 | 3/10 | 6/10 |
| Ratio | 0.25 | 0.50 | 0.50 | 0.70 | Ratio | 0.64 | 0.64 | 0.30 | 0.60 |

[a] Drought is defined as a period of flows at least 0.5 standard deviations below the mean, with mean and standard deviation calculated for the *low-pass filtered reconstruction of Sacramento and American River flows.*

[b] Reconstruction of annual Salt River, Arizona streamflow (Smith and Stockton, 1981).

[c] Reconstruction of upper Colorado River annual streamflow (Stockton and Jacoby, 1976).

[d] Reconstruction of annual precipitation for the Pasco Basin, eastern Washington (Cropper and Fritts, 1984).

[e] Reconstruction of 5-yr moving average winter precipitation for Santa Barbara, CA (Michaelsen *et al.*, 1987).

[f] +, agreement; –, a wet period; *, near-average conditions.

reconstructed precipitation for the Pasco Basin in eastern Washington (Cropper and Fritts, 1984).

Data provided by Fritts (Fritts and Gordon, 1980) and Graumlich (1987) have permitted quantitative comparison between reconstructions for central California precipitation, Sacramento River streamflow, northern California precipitation, Columbia Basin precipitation, and western Washington and Oregon precipitation (Fig. 4). Although these reconstructions cover a subcontinental region and are derived from an extremely diverse set of tree-ring data, they show many periods of great similarity across the last 300 yr. Synchronous drought peaks occur in 1720, 1757, 1795, and 1930, and synchronous wet peaks occur in 1702, 1790, 1861, 1914, 1942, and 1954. The 1720

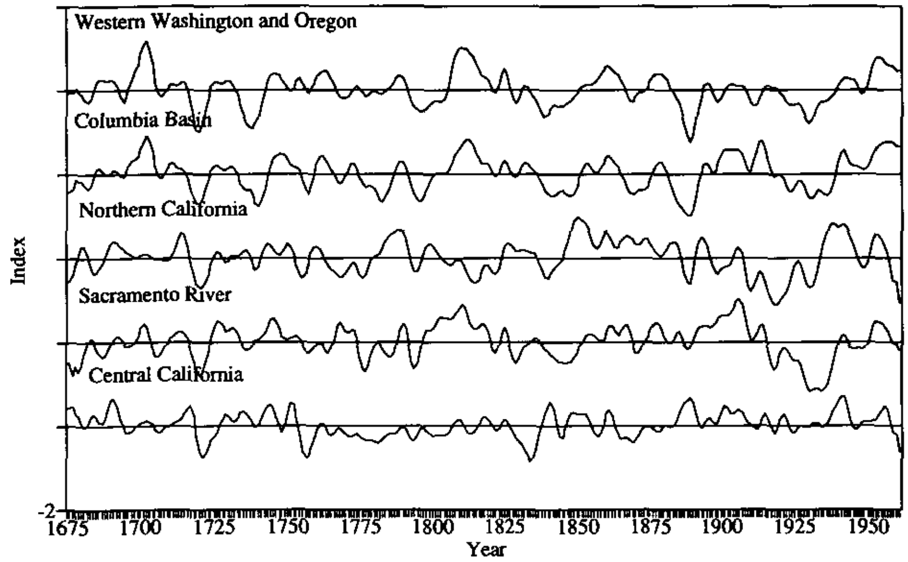

FIG. 4. Climate reconstructions for (top to bottom) western Washington and Oregon precipitation, Columbia Basin precipitation, northern California precipitation, Sacramento River streamflow, and central California precipitation. Sacramento River and central California series have been prewhitened with autoregressive models. All series have been normalized to zero mean and unit variance, and low-pass filtered with an 8-yr filter.

drought, in particular, is the most intense and widespread in the region, although it is not as prolonged as some of the more local droughts. This drought (Graumlich, 1987) may have been a consequence of the failure of cool season precipitation, due to the formation of a high pressure ridge that diverted precipitation northward into Canada (Namias, 1983).

Correlation coefficients between the reconstructions, calculated for overlapping 50-yr periods (Table 5), indicate the highest correlations between the Sacramento, western Washington and Oregon, and Columbia Basin reconstructions. Correlations with and between the northern and central California reconstructions are generally lower. In the case of the central California reconstruction, these low correlations may be partly due to the tree-ring data used. This reconstruction was developed using *Pinus longaeva* chronologies collected at elevations near 3000 m. Trees of this subalpine species are strongly influenced by temperature as well as precipitation (LaMarche, 1974), and this influence contributed low-frequency variance to the reconstruction which did not actually exist in precipitation data for the reconstructed period (H. C. Fritts, personal communication, 1986). In fact, this reconstruction had significant autocorrelation at lags of over 10 yr. The reconstruction was thus fitted with an AR(3) model, yielding a time-series structure comparable to the other reconstructions. The other reconstructions were developed from trees growing at sites near the lower treeline (elev. 910–2190 m). This suggests that the observed differences between the reconstructions are due to differences in climate between the tree-ring collection sites. Climate contrasts appear at the synoptic level as well. In many cases, low correlations between reconstructions (Table 5) can be traced to isolated events in which drought was observed in one region while other regions experienced a wet year. I have already noted such contrasts in the American and Sacramento river reconstructions. In her reconstructions, Graumlich (1987) notes that a wet period from 1810 to 1835 in the Columbia Basin and western Washington and Oregon was a time of drought in northern California, whereas a wet period in northern California from 1850 to 1890 was a time of drought in western Washington and Oregon and the Columbia Basin. Of the 50 yr with the greatest such contrasts, 32 were found between the central California reconstruction and one of the others. As previously noted, this may in part be due to the unusual tree-ring data used in this reconstruction. Among the other reconstructions, the most common contrasts were between the western Washington and Oregon reconstruction and the Sacramento River or northern California reconstruction (a total of 10 yr); the least common contrasts were found between adjacent climate regions, such as between northern California and the Columbia Basin (1 yr). Such a pattern of contrasting precipitation has also been observed in instrumental records of streamflow (Meko and Stockton, 1984). In that study, the authors noted (p. 891) that "the pattern of correlation indicates that distances [between streamflow regions] are sufficiently great compared to the size of weather systems for shifts in the storm tracks to produce compensating anomalies in the extreme reaches" of the western United

TABLE 5

Correlation Coefficients between Selected Climate Reconstructions

| Interval | *N* | SAC[a] WO | SAC CB | SAC NC | SAC CAL[e] | WO[b] CB | WO NC | WO CAL | CB[c] NC | CB CAL | NC[d] CAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1672–1725 | 54 | 0.47 | 0.49 | 0.40 | 0.30 | 0.90 | 0.33 | 0.14* | 0.36 | 0.07* | 0.04* |
| 1700–1750 | 51 | 0.40 | 0.40 | 0.44 | 0.40 | 0.87 | 0.33 | 0.07* | 0.49 | 0.11* | 0.27 |
| 1725–1775 | 51 | 0.32 | 0.34 | 0.22* | 0.21* | 0.79 | 0.05* | 0.04* | 0.36 | 0.14* | 0.33* |
| 1750–1800 | 51 | 0.38 | 0.38 | 0.34 | 0.33 | 0.83 | 0.26 | 0.14* | 0.35 | 0.18* | 0.23 |
| 1775–1825 | 51 | 0.48 | 0.39 | 0.33 | 0.42 | 0.83 | 0.27 | 0.35 | 0.21* | 0.38 | 0.20* |
| 1800–1850 | 51 | 0.57 | 0.42 | 0.22* | 0.37 | 0.75 | 0.44 | 0.29 | 0.29 | 0.30 | 0.28 |
| 1825–1875 | 51 | 0.34 | 0.35 | 0.27 | 0.38 | 0.74 | 0.31 | 0.25 | 0.33 | 0.22 | 0.09* |
| 1850–1900 | 51 | 0.16* | 0.41 | 0.29 | 0.16* | 0.70 | 0.29 | 0.04* | 0.44 | 0.02* | −0.12* |
| 1875–1925 | 51 | 0.34 | 0.55 | 0.61 | 0.30 | 0.71 | 0.47 | 0.19* | 0.53 | 0.20* | 0.15* |
| 1900–1950 | 51 | 0.53 | 0.68 | 0.50 | 0.56 | 0.75 | 0.42 | 0.32 | 0.49 | 0.27 | 0.35 |
| 1925–1961 | 37 | 0.56 | 0.63 | 0.52 | 0.44 | 0.80 | 0.19* | 0.25 | 0.23* | 0.17* | 0.55 |
| Average | | 0.41 | 0.46 | 0.29 | 0.33 | 0.79 | 0.31 | 0.19 | 0.37 | 0.19 | 0.22 |

*Note.* SAC and CAL reconstructions have been prewhitened by AR(3) models; WO, CB and NC reconstructions were developed with ARIMA models by Graumlich (1987).

[a] SAC, Sacramento River streamflow reconstruction (this work).

[b] WO, western Washington and Oregon precipitation reconstruction (Graumlich, 1987).

[c] CB, Columbia Basin precipitation reconstruction (Graumlich, 1987).

[d] NC, northern California precipitation reconstruction (Graumlich, 1987).

[e] CAL, central California precipitation reconstruction (Fritts and Gordon, 1980).

* Significance LESS than 95%.

States. This may explain the episodes of asynchronous low flow seen in the tree-ring reconstructions. For example, the American River lies just south of the latitude at which the surface westerlies divide to flow north or south around the Sierra Nevada during the winter months (Bryson and Hare, 1980). The northward airflows converge and are associated with cyclonic storms, while the southern airflows are divergent and are affected by coastal upwelling which follows divergence in the California Current (Lydolph, 1985). In some years, weather in the American River Basin may have been dominated by these southern airflows while the northern circulation dominated the greater part of the Sacramento Basin. The northern circulation is particularly influenced by mid-latitude events (Schonher and Nicholson, 1989), with summer drought and winter rainfall both controlled by latitudinal variation in Pacific pressure systems. Thus, the latitude of the polar jet stream in winter will tend to determine which region receives the heaviest winter rainfall, while the latitude of the Pacific subtropical high will determine which region experiences an intense summer drought. Regions lying on different sides of these lines will tend to experience contrasting precipitation anomalies. It is worth noting that none of these reconstructions show a significant correlation with a long-term record (Quinn *et al.,* 1987) of El Niño–Southern Oscillation events (see also Schonher and Nicholson, 1989).

## CONCLUSIONS

A long dendroclimatic reconstruction of streamflow provides information about variation and change in climate that cannot be inferred from a shorter instrumental record. Reconstructions based on a small set of tree-ring chronologies may display stronger verification statistics than reconstructions based on the principal components of a larger tree-ring data set, but the latter data set is more likely to reflect accurately the long-term and large-scale patterns of variation that are typically associated with climate. The combination of both forms of tree-ring data may produce an optimum reconstruction.

Streamflow in the Sacramento Basin over the last 440 yr has included several periods of prolonged high and low flows; indeed, prolonged excursions from the mean have been the norm. Both the wettest and driest episodes occurred during the historical period, with 1854–1916 being a wet interval and 1917–1950 a dry one. Most periods of high and low streamflow in the Sacramento Basin are synchronous with wet and dry periods reconstructed by other dendroclimatic studies done in the American west. Streamflow variations in the northern and southern Sacramento Basin and in the Pacific Northwest are similar, but there have been a number of episodes of contrasting flow (or precipitation) between northern and southern climatic regions. These episodes may be due to changes in the latitude of the Pacific subtropical high and of winter storm tracks over the Pacific. None of the reconstructions show a correlation with El Niño–Southern Oscillation events.

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