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Are Climate-Tree Growth Relationships Changing in North-Central Idaho, U.S.A.?

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Abstract

An 861-yr Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) tree-ring chronology has been recently developed for the Salmon River Valley, Challis National Forest, Idaho. Its potential for climatic reconstruction is investigated using monthly instrumental records of precipitation, temperature, and Palmer Drought Severity Index from 1895 to 1995. The temporal stability of climate-tree growth relationships is analyzed by means of evolutionary (backward and forward) and moving response functions. When precipitation and temperature are used as predictors, the strongest (and temporally stable) signal is a negative response to July temperature. Another relevant signal, albeit less temporally consistent, is a positive response to May precipitation. When the Palmer Drought Severity Index is used as an integrated predictor to highlight response to summer moisture stress, the strength of the association with tree growth increases in recent decades. This information can be used to maximize the reliability of dendroclimatic reconstructions, and has important implications for expanding the range of recent studies on altered climate-tree growth relationships during the 20th century.

Introduction

Multicentury-long proxy records of climate provide baseline information to assess the full range of natural variability (National Research Council, 1995). Tree-ring chronologies have proved particularly useful to reconstruct monthly, seasonal, and annual climate variables (Stahle et al., 1988; Briffa et al., 1995; Jacoby et al., 1996; Mann et al., 1998). On a global scale, relatively few such records are long enough to cover most of the last millennium, and even fewer are capable of effectively resolving multidecadal variability because of the "segment length curse" (Cook et al., 1995). As part of ongoing studies on long-term climate variability in the western United States, I have developed an 861-yr Douglas-fir tree-ring chronology for the Salmon River Valley, Challis National Forest, Idaho. Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) is a widespread forest species in western North America, and it is one of the world's most important timber species. Its dendrochronological properties have been studied extensively (e.g., Fritts et al., 1965), and many long-lived individuals have been found, up to an age of 1274 years (Grissino-Mayer et al., 1997).

The objective of this paper is to investigate the potential of multicentury climate reconstruction using the newly developed Idaho tree-ring record (Biondi, 1997). A first step is the identification of the prevalent climatic signals present in the chronology (Fritts, 1976; Cook and Kairiukstis, 1990). After combining tree-ring samples in a site chronology, "response functions" (Fritts et al., 1971; Blasing et al., 1984) provide quantitative information on the climatic variables whose time-series variability is linearly related to the time-series variability of the proxy record. An implicit assumption of these (and other) regression techniques is that climate-tree growth relationships are stable over time. Since statistical models are rarely computed systematically changing the calibration interval to look for changes in parameter estimates.

Altered climate sensitivity of tree-ring records has recently been reported by Briffa et al. (1998a, 1998b) in connection with global change phenomena. They considered two time intervals, 1881–1960 and 1881–1981, and found a reduction in sensitivity of tree-ring chronologies to summer air temperature in several areas of the Northern Hemisphere. However, in northwestern and southwestern North America ring widths, the "reduction in correlation" effect is almost absent at the interannual timescale, and correlations actually increase at the decadal timescale (see Table 1 in Briffa et al., 1998a). When decadal patterns are emphasized, regional ring widths in western North America rise and fall in opposition to June–August temperatures (see Fig. 2 in Briffa et al., 1998a). As Briffa et al. (1998a, 1998b) point out, testing the temporal stability of climate-tree growth relationships has fundamental implications not only for reconstructions of natural climate variability, but also for estimating future changes in the global carbon cycle associated with anthropogenic greenhouse emissions.

Materials and Methods

The study area was chosen according to dendrochronological criteria to maximize the likelihood of obtaining multicentury tree-ring series sensitive to moisture stress (Douglass, 1919; Fritts, 1976). The sampled population is a pure, uneven-aged, Douglas-fir stand located on a rocky, 60% slope at the lower forest border (Biondi et al., 1999). Trees at this remote site are old-looking, with large branches, irregular crowns, and stem diameters up to 130 cm. There is little or no understory vegetation, and intertree distances usually exceed 10 m. Living trees were cored twice at about 1 m above ground level, in opposite directions parallel to the topographic contour. Annual wood incre-
Summary statistics of the Douglas-fir chronology prior to pre-whitening

<table>
<thead>
<tr>
<th>Start</th>
<th>End</th>
<th>N</th>
<th>SD</th>
<th>MS</th>
<th>$A_i$</th>
<th>S/N</th>
<th>PC1</th>
<th>ACWT</th>
<th>ACBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1895</td>
<td>1995</td>
<td>101</td>
<td>0.25</td>
<td>0.19</td>
<td>0.45</td>
<td>24.4</td>
<td>66.6</td>
<td>0.80</td>
<td>0.64</td>
</tr>
</tbody>
</table>

* SD = standard deviation; MS = mean sensitivity; $A_i$ = lag-1 autocorrelation; S/N = signal-to-noise ratio; PC1 = % variance explained by the first principal component; ACWT = average correlation within trees; ACBT = average correlation between trees.

The Douglas-fir tree-ring chronology was computed with the purpose of enhancing the year-to-year climatic signal by minimizing individual variability in ring-width series (Fritts, 1976; Cook, 1987; Biondi, 1993). Both long-term trends and short-range autocoherence were removed from ring-width series according to the formula:

$$I_t = q_p(B) \odot [\log(w_t + k) - y_i]$$

with $I_t =$ chronology value at year $t$; $q_p(B) =$ autoregressive operator of order $p$ (Box and Jenkins, 1976); $\odot =$ biweight robust mean (Mosteller and Tukey, 1977) of the $i$-values, $i = 1, \ldots, n_i$ ($n_i$ is the number of measured specimens that included year $t$); $w_t =$ ring width at year $t$ in specimen $i$; $k =$ positive constant added to avoid taking the logarithm of zero; $y_i =$ intrinsic growth trend at year $t$ in specimen $i$, estimated by a modified negative exponential or straight line with slope $\leq 0$ (Fritts et al., 1969). The order $p$ of fitted autoregressive models was chosen according to a combination of objective and subjective criteria, fully described by Biondi and Swetnam (1987).

A response function is a form of principal component regression designed to account for the multicollinearity of the monthly climatic predictors (Briffa and Cook, 1990; Morzuch and Ruark, 1991). Computational details are given in the Appendix. A 14-month window, from the previous September to the current October, is used to identify climate signals. Monthly temperature, precipitation, and Palmer Drought Severity Index (PDSI) for Idaho Climate Division 8 (NOAA, 1997a) are chosen as predictors of Douglas-fir annual growth from 1895 to 1995. Those instrumental records are averaged over climatically consistent regions, and include a “time bias correction” for mean temperature (Karl et al., 1986). The Palmer Drought Severity Index integrates temperature, precipitation, insulation, and soil properties to represent departures from average moisture conditions (Palmer, 1965; Briffa et al., 1994). It has proven useful to represent drought patterns in the conterminous United States (Karl, 1983), and it also correlates strongly with tree-ring records in different habitats (Meko et al., 1980, 1993; Stahle et al., 1985, 1988; Cook et al., 1996).

Climate in Idaho northeast valleys (division 8) is cold and dry, with annual mean temperature of 5.2°C and annual total precipitation of 239 mm. From November to March mean monthly temperature remains below 0°C; July is the warmest month (mean of 18.5°C) and January the coldest (mean of −8.5°C). Precipitation is well distributed throughout the year, with a predominance of summer rains; May is the wettest month (34 mm total on average), and February the driest (12 mm total on average). Collinearity between pairs of monthly predictors is often significant, with peaks of 0.37 for temperature in adjacent months, 0.28 for precipitation in adjacent months, and −0.38 for temperature and precipitation during the same month. Because its computation emphasizes temporal persistence of moisture conditions, PDSI is highly correlated (≥0.89) from one month to the next.

Evolutionary (ERFs) and moving (MRFs) response functions are based on progressively changing the period of years used for calibration. An evolutionary response function uses a progressively longer number of years to compute the response coefficients. It allows for forward or backward evolution by maintaining a fixed beginning or ending year, respectively. A moving response function employs a fixed number of years progressively slid across time to compute the response coefficients (Biondi, 1997). While the combination of evolutionary and moving response functions is useful to uncover subtle changes in climate/tree growth relationships, moving response functions provide more robust information than evolutionary response functions because statistical significance is evaluated using a constant sample size. To provide a large enough number of degrees of freedom, I considered only periods ≥60 yr. Evolutionary and moving response functions produce a temporal set of coefficients for each monthly predictor, and coefficients not significant at the 95% confidence level are changed to zero. Significance is tested using a bootstrap procedure (see Appendix), and the statistical issue of multiplicity was not considered in this analysis. The coefficient matrix, one row per year and one column per predictor, is charted using a pseudo-color plot (MathWorks, 1995).

**Results and Discussion**

Even though the Douglas-fir chronology extends back to A.D. 1135 (Biondi et al., 1999), the period prior to 1895 is not considered in this paper in order to match the length of the climate record. Each annual tree-ring index is based on 27 core samples from 14 trees, and chronology statistics are listed in Table 1. A first-order autoregressive model was selected for prewhitening the Douglas-fir chronology (Fig. 1). The chronology is well correlated with tree-ring records over a large portion of the western United States, corresponding to the central Rocky Mountain region (Fig. 2). Temporally stable and unstable climate signals are uncovered by comparing results for multiple calibration intervals (Fig. 3). The strongest, and temporally stable, cli-
mastic signal is a negative response to July temperature. It is also possible to identify a weaker, positive April–June precipitation signal, which is more pronounced and temporally consistent for the month of May. The combination of negative response to summer temperature and positive response to late spring/early summer precipitation indicates that Douglas-fir growth at this arid site is mostly a proxy for moisture stress during the growing season, presumably because of lack of soil, 50 to 60% slope, and scarce precipitation (Biondi, 1997).

There is a tendency for the moisture stress signal to become earlier during the course of the 20th century (Fig. 3). Over time, significance shifts slightly from June to May to April precipitation, and a negative response to April temperature appears in the last decades. Those shifts may be associated with increased temperatures in early spring. Of all monthly variables considered, only March temperature shows a significant linear trend from 1895 to 1995, estimated at 1.6°C/100 yr. Since March is the last cold-season month, with mean temperature of −0.24°C, a slight increase in temperature would influence snowmelt patterns, for instance by causing earlier release of water accumulated as snowpack, thereby reducing moisture availability for tree growth at the beginning of the season. The variability of April mean temperature, which has never fallen below 0°C from 1895 to 1995, could then become more closely associated with the variability of tree growth by controlling soil water balance at the start of tree growth. The combination of stronger negative response to April temperature and stronger positive response to April precipitation indicates higher dependence of tree growth on soil moisture in recent decades. The possible appearance of a positive December precipitation signal (Fig. 3) is consistent with the stronger role of water supply in controlling tree growth variability.

If the Palmer Drought Severity Index is used as predictor, the hypothesis that summer moisture stress affects tree growth is supported by positive regression estimates (Fig. 4). It is also evident, as shown by both evolutionary and moving response functions, that the strength of that association increases in recent decades. When the calibration interval ends in the 1970s or later, May and June PDSI are significant predictors of tree growth, whereas they are nonsignificant during earlier times. Similarly, higher regression estimates are obtained for May and June PDSI when the calibration interval begins later than 1920 (Fig. 4). Because the minimum length of the calibration interval is 60 yr, and significance is tested nonparametrically, such differences cannot be caused by differences in degrees of freedom, as can be directly confirmed by the moving response functions. Most likely, the additional moisture stress discussed in the previous paragraph is responsible for the enhanced response to May–June PDSI.

The divisional climatic data used in this study are generally of excellent quality. However, the reduced number of meteorological stations going back in time required a complex series of adjustments to generate pre-1931 data in 11 western states, including Idaho (Karl et al., 1983). It is difficult to test the temporal stability and accuracy of the climate data, because no "absolutely true" record exists. Data from individual stations may also be affected by multiple sources of error, and procedures used for quality control depend on the number of existing stations and on the overall precision of the measurements. From the point of view of paleoclimatic reconstruction, regression models estimated using different time periods may not be as sensitive as response functions to changes in climate/tree-growth relationships, or to changes in data quality. To test if the Douglas-fir tree-ring record would indeed produce a temporally stable reconstruction of July temperature, and an unstable one for June PDSI, I then estimated those bivariate regression models for two 50-yr time periods, 1896–1945 and 1946–1995 (Table 2). The difference between regression coefficients was evaluated using an F-test procedure (Sokal and Rohlf, 1981: 505), and the null hypothesis could not be rejected for either July temperature or June PDSI. In other words, the choice of time interval had no significant influence on the climate reconstruction.

An enhanced tree response to summer moisture stress would be particularly relevant for predicting the impact of future climate variability on vegetation. Simulation studies have shown that drought frequency in the U.S.A. is likely to increase as temperatures rise under enhanced greenhouse forcing (Hansen et al., 1991; Rind et al., 1992), even though the spatial extent of increased drought is not regionally uniform (Gregory et al., 1997). As public and private management agencies strive to develop robust indicators of changing ecological state at multiple temporal scales, tree-ring records hold great promise because they provide long, continuous, and absolutely dated information.

### TABLE 2

Summary of dendroclimatic regression models estimated for two different time periods

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>T7 = July mean temperature, °C</td>
<td>F-value = 8.571** R² = 13%</td>
<td>F-value = 9.180** R² = 14%</td>
</tr>
<tr>
<td>PDS6 = June Palmer Drought Severity Index</td>
<td>F-value = 13.601*** R² = 20%</td>
<td>F-value = 10.087** R² = 16%</td>
</tr>
</tbody>
</table>

* T7 = July mean temperature, °C; PDS6 = June Palmer Drought Severity Index; MRI = mean ring index used as predictand in response functions; ** = P-value <0.001; *** = P-value <0.01; * = P-value <0.05; m = P-value >0.05; R² = adjusted R².
Paleoclimate reconstruction, however, is based on the "uniformitarian principle" (Fritts, 1976), which may not necessarily hold when anthropogenic influences become significant (Briffa et al., 1998a, 1998b). The present study expands the range of information on altered climate-tree growth relationships during the 20th century by uncovering an enhanced response to summer moisture stress in the interior Northwest. However, it does not uncover any evidence to question the va-
lidity of paleoclimatic reconstructions based on linear regression models.

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References Cited


FIGURE 3. Backward and forward evolutionary response functions (BERF and FERF, respectively), and moving response functions (MRF) of the Douglas-fir tree-ring chronology. Predictors are monthly Palmer Drought Severity Index (PDSI) from the previous September (SEP) to the current October (Oct). BERF were plotted against the beginning calibration year, 1896 to 1936; FERF and MRF were plotted against the last year of the period, 1955 to 1995.

FIGURE 4. Backward and forward evolutionary response functions (BERF and FERF, respectively), and moving response functions (MRF) of the Douglas-fir tree-ring chronology. Predictors are monthly Palmer Drought Severity Index (PDSI) from the previous September (SEP) to the current October (Oct). BERF were plotted against the beginning calibration year, 1896 to 1936; FERF and MRF were plotted against the last year of the period, 1955 to 1995.


**Appendix**

In matrix notation,

\[ I = Xb + e \]

represents the statistical relationship between the \( n \times 1 \) vector \( I \) of tree-ring values, the \( n \times q \) matrix \( X \) of monthly climate predictors, and the \( q \times 1 \) vector \( b \) of regression parameters; \( e \) is the \( n \times 1 \) vector of error terms, which are assumed to be independent and with the same variance \( \sigma^2 \) (Jolliffe, 1986). Because multicollinearity produces estimates of \( b \) that are unstable, the original variables are orthogonalized into their principal components, and the model becomes

\[ I = XAA'b + e = Zk + e \]

with \( A \) being a \( q \times q \) matrix whose columns are the eigenvectors of \( X'X \); \( Z = XA \) is the matrix of principal component scores; \( k = A'b \) is a vector of new regression parameters, and is also the linear combination of the eigenvector matrix with the original parameters (therefore, \( b = Ak \), and this allows the computation of regression parameters for the original predictors). When a collinearity exists, it produces a principal component with very small variance, hence it is quite useful to retain in the regression only the components with relatively large eigenvalues. In this study, principal components were selected according to the PVP criterion (Guiot, 1990). The model then becomes

\[ I = Zmkm + e \]

where \( Z_m \) is the \( n \times m \) matrix obtained after discarding \( (q - m) \) principal components, and \( e \) incorporates both random disturbances and the discarded components. Ordinary least squares is used to estimate \( k_m \), and an estimate of \( b \) can be obtained after setting the last \( (q - m) \) elements of \( k \) equal to zero. Significance of estimated regression parameters can be tested using a bootstrap procedure (Guiot, 1991). In this study, 100 random samples were drawn with replacement from the calibration period to obtain 100 sets of response function estimates: mean regression coefficients are deemed significant if they are at least twice their standard deviation.