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Forward modeling of regional scale tree-ring patterns in the southeastern United States and the recent influence of summer drought

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[1] We use a mechanistic model of tree-ring formation to simulate regional patterns of climate-tree growth relationships in the southeastern United States. Modeled chronologies are consistent with actual tree-ring data, demonstrating that our simulations have skill in reproducing broad-scale patterns of the proxy's response to climate variability. The model predicts that a decrease in summer precipitation, associated with a weakening Bermuda High, has become an additional control on tree ring growth during recent decades. A nonlinear response of tree growth to climate variability has implications for the calibration of tree-ring records for paleoclimate reconstructions and the prediction of ecosystem responses to climate change. **Citation:** Anchukaitis, K. J., M. N. Evans, A. Kaplan, E. A. Vaganov, M. K. Hughes, H. D. Grissino-Mayer, and M. A. Cane (2006), Forward modeling of regional scale tree-ring patterns in the southeastern United States and the recent influence of summer drought, *Geophys. Res. Lett.*, *33*, L04705, doi:10.1029/2005GL025050.

1. Introduction

[2] The use of tree rings in paleoclimatology typically assumes that annual tree-ring growth can be reasonably approximated by a linear function of local or regional precipitation and temperature with a set of coefficients that are temporally invariant. Tree-ring records, however, are the result of multivariate, often nonlinear biological and physical processes [*Fritts*, 1976; *Vaganov et al.*, 2006]. Apparent temporal nonstationarity in the biological response of trees to climate might be a function of changes in climate itself [*Vaganov et al.*, 1999; *Aykroyd et al.*, 2001], although caution is necessary since this could also arise stochastically [*Gershunov et al.*, 2001]. Tree-ring records from individual sites may also reflect the influence of unobserved localized and non-climatic influences [*Fritts*, 1976; *Trotter et al.*, 2002]. Consequently, linear empirical–statistical analyses alone cannot be used to prove a physical or biological mechanism for variability or change in the climate-tree growth relationship.

[3] A tractable forward model that resolves the critical processes linking climate variables to proxy formation permits us to identify and account for such processes in developing better estimates of past climate. Here, we investigate the ability of the Vaganov–Shashkin model of tree-ring formation [*Vaganov et al.*, 2006] to reproduce broad-scale patterns of growth variability in the warm, mesic southeastern United States. While a hemisphere-wide evaluation of the model (M. N. Evans et al., A forward modeling approach to paleoclimatic interpretation of tree-ring data submitted to Journal of Geophysical Research, 2006, hereinafter referred to as Evans et al., submitted manuscript, 2006) has suggested that conifer tree-ring width chronologies may be successfully simulated over a range of climate regimes, the model performed most poorly in warm and wet environments, including the southeastern United States. It is in just such an environment, where changes in both precipitation and temperature may influence tree growth, that a mechanistic model might be particularly useful in understanding temporal relationships between climate and tree ring width.

2. Tree-Ring Modeling

[4] To objectively investigate whether tree-ring width chronologies across the southeastern United States can be simulated as a function of climate alone, we employed a biological model linking daily temperature, precipitation, and daylength to ring-width variations in conifers [*Vaganov et al.*, 1999, 2006]. The Vaganov–Shashkin model is based on the hypothesis that climatic influences are associated directly, but nonlinearly, with tree-ring characteristics through controls on the rates and duration of cellular processes (division, growth, and maturation) in the developing wood. Simulations possess none of the age/size-related trends present in real tree-ring data [*Fritts*, 1976; *Vaganov et al.*, 2006]. The modeled cambial growth rate is determined by comparing the daily temperature and soil moisture budget to quasi-parabolic growth functions, and using the most limiting factor [*Fritts*, 1976] to scale the component processes of tree-ring formation. Modeled tree-growth therefore behaves stoichiometrically, and potentially nonlinearly, with respect to temperature and soil moisture on a daily time scale.

[5] We use a regional, multichronology modeling approach and principal components analysis in order to robustly identify the regional growth response to climate. We simulated eight hypothetical tree-ring width chronolo-

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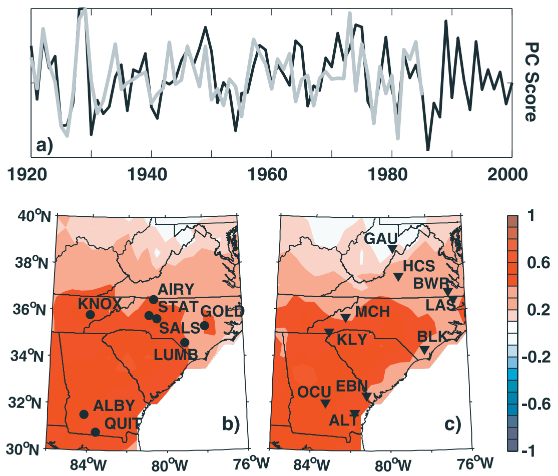

Figure 1. Intercomparison of synthetic and actual tree-ring width chronologies from the southeast United States. (a) Leading time series expansions from PCA on simulated and actual regional ring width data (black and gray lines, respectively). Correlation fields between the spring (MAM) UEA/CRU 0.5° precipitation data set [*New et al.*, 2000] and the first principal component for the (b) simulated and (c) real tree-ring width chronologies for the full period of overlap (1920–1985). Four-letter identifiers mark eight meteorological stations in Figure 1b; three-letter identifiers denote 10 ring-width chronology sites in Figure 1c) (see auxiliary material).

gies using daily meteorological data from southeast United States stations for 1920 to 2000 (Figure 1b). Missing daily temperature data were linearly interpolated and missing precipitation data were set to zero. We did not simulate those years at a given station for which more than 90 single daily values were missing. The skill of the model was evaluated against 10 actual high-quality conifer tree-ring width chronologies from the region (Figure 1a) available through the late 1970s and early 1980s [*Cook and Cole*, 1991; *Stahle and Cleaveland*, 1992] that were previously screened for their utility in paleoclimatic reconstruction [*Mann et al.*, 1998, 2000]. We used the default model parameters [*Vaganov et al.*, 2006; Evans et al., submitted manuscript, 2006], except for the soil water drainage rate, which we adjusted based on a priori field observations, comprehensive model sensitivity analyses, and from a hemisphere-wide suite of simulations using the unaltered default parameters (Evans et al., submitted manuscript, 2006).

3. Results

[6] Principal component analysis (PCA) on the complete set of eight model simulated tree-ring width chronologies produced one statistically-significant [*Preisendorfer*, 1988] component (PC), which accounted for just over 50% of the total variance. The leading PC of the set of ten actual tree-ring chronologies was also significant and accounted for 35% of the total variance. The first PCs of the simulated and regional real chronologies are significantly correlated ($r = 0.61$, $p < 0.0001$, $n = 66$ years) (Figure 1a). The first PC of both the real and simulated chronologies is most strongly correlated with regional spring precipitation (Figures 1b and 1c). This reflects the strong loadings of southern Taxodium chronologies on the first PC of the real chronologies [*Stahle and Cleaveland*, 1992], and the importance of spring precipitation in determining variations in the annual growth from year to year in the modeled ring-width chronologies. This result suggests that the model, based only on observed meteorological data, can successfully describe the primary mode of variance in the actual regional tree-ring width data set and reproduce the long-term mean climate response.

[7] No modeled change in mean climate-tree growth relationship is observed in the simulations prior to the mid 1970s. After the mid-1970s, however model-calculated relative growth rates due to soil moisture (Figure 2) become significantly lower during the summer months. Soil moisture during those months when potential plant water stress is highest begins to influence to a greater extent the year-to-year variability in growth rates, although the effect is not uniform over the study region. Differences in the correlation fields between summer (JJA) precipitation [*New et al.*, 2000] and the first principal component of the simulated chronologies before and after 1976 show an increasing sensitivity of year-to-year growth variability to summer precipitation in the Appalachian Mountains, northern Georgia, and Virginia (see auxiliary material[1]).

4. Discussion

[8] The modeled chronologies are consistent with actual tree-ring data, demonstrating that the Vaganov–Shashkin model has skill in reproducing broad-scale patterns of tree-ring formation in response to climate. This suggests that the model can be used to simulate, evaluate, and interpret climate-tree growth relationships, even in warm and mesic environments like the southeastern United States. Use of the model presents an independent, mechanistic approach to evaluating tree-ring width chronologies and their association with climate.

[9] The Vaganov–Shashkin model also predicts a trend toward increased summer drought sensitivity in the southeastern United States in recent decades, suggesting that climate variability might drive changes in regional tree growth response. The existing high-quality tree-ring chronologies from the southeastern United States were collected in the late 1970s and early 1980s, so they themselves cannot be used to validate the model-predicted increase in the importance of summer precipitation for patterns of tree-ring formation over the most recent decades. However, in 2000 two of us (KJA and HDGM) developed a *Pinus strobus* tree-ring width chronology from Deep Gap in western North Carolina (36°N, 81.5°W, 680 m), a site where the model now predicts a modest increase in the correlation between summer drought and year-to-year growth variability. This new chronology does show an increasing sensitivity to summer precipitation consistent with our modeling results (see online auxiliary material). However, this single chronology is not sufficient to validate the model prediction. If our simulations are correct, climate-sensitive conifer tree-ring width chronologies from sites in the southeastern United States recollected and updated to the present should

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL025050.

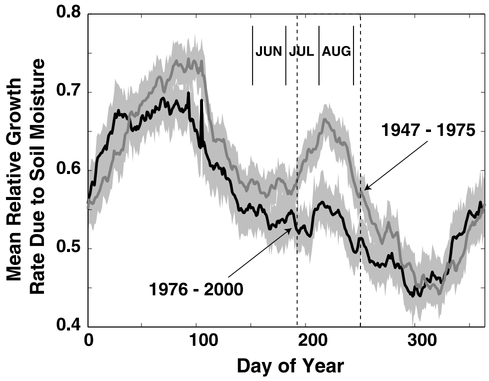

Figure 2. Modeled mean growth rates due to soil moisture for region-wide simulations for the period 1947–1975 (heavy gray line) and 1976–2000 (heavy black line). Shaded regions are 95% bootstrapped confidence intervals about the means, and demonstrate that average growth rates as a function of soil moisture are indistinguishable between the two periods except during the summer (shown by dashed box).

show nonstationary behavior with respect to summer precipitation similar to that observed in model results and at Deep Gap.

[10] Are these model results consistent with observed large-scale climate variability and forcing over the last century? Mean summer precipitation anomalies in our study area over the period 1901–1998 [*New et al.*, 2000] show a downward trend which is statistically significant at the 90% confidence level. Drought in the region has been associated with the strength and position of the Bermuda High [*Stahle and Cleaveland*, 1992; *Henderson and Vega*, 1996], and negative anomalies are seen in summer sea level pressure (SLP) over the western Atlantic during the last 25 years, consistent with other analyses of the seasonal features of the North Atlantic Oscillation (NAO) [*Portis et al.*, 2001]. Singular value decomposition (SVD) [*Bretherton et al.*, 1992] of the covariance matrix of regional summer precipitation [*New et al.*, 2000] and Northern Hemisphere SLP anomalies [*Basnett and Parker*, 1997] shows a primary mode which is responsible for approximately 49% of the total squared covariance (Figure 3), indicating that dry (wet) summers in the southeastern United States are associated with anomalously low (high) SLPA over the extratropical western North Atlantic. A weaker (stronger) Atlantic anticyclone in the summer results in weaker (stronger) circulation around the high and results in decreased (increased) moisture advection into the southeastern United States. A simple composite analysis of mean SLPA shows the same result. The SVD pattern loading in the eastern tropical Pacific (Figure 3b) is intriguing and possibly part of the observed wave structure, but in analyses not shown appears to fluctuate on a quasidecadal basis. Observed low-frequency variability in North Atlantic circulation has been linked to decadal-scale SST forcing, associated with regime shifts in the Atlantic Multidecadal Oscillation (AMO) [*Sutton and Hodson*, 2003]. However, a trend toward increased SSTs in the tropical western Pacific and Indian Oceans may be responsible for driving changes in North Atlantic circulation in recent decades [*Hoerling et al.*, 2001], which may in turn be related to anthropogenic greenhouse gas emissions [*Hoerling and Kumar*, 2003]. Indeed, climate modeling has suggested that SLP centers of action in the North Atlantic may migrate eastward under increasing atmospheric CO_2 concentrations [*Hu and Wu*, 2004], which could have a significant influence on moisture advection into the southeastern United States. Summer SLPs over the North Atlantic may also be reduced through a teleconnection to El Niño events in the preceding winter, although the effect is inconsistent [*Wang and Enfield*, 2003]. Future reductions in summer precipitation in the region have been predicted by climate models for doubled atmospheric CO_2 [*Mearns et al.*, 2003].

[11] Overall, the simulated tree-ring response fits the regional, long-term and interannual climate variations over the study period. We note that it is the nonlinear biological nature of the climate proxy used here which is responsible for the predicted and observed change in climate sensitivity. Our study emphasizes the need for caution when evaluating tree-ring based reconstructions whose very sensitivity to local-scale climate may be a function of large-scale climate variability. Other authors have identified nonstationary statistical relationships between climate and tree-ring chronologies [*Briffa et al.*, 1998a, 1998b; *Biondi*, 2000; *Jacoby et al.*, 2000] and the Vaganov–Shashkin model has previously been used to account for such changes in northern Siberia [*Vaganov et al.*, 1999]. Techniques for addressing these issues exist, including the use of multiple proxies [*Hughes*, 2002; *Mann*, 2002; *McCarroll et al.*, 2003]. Given the global historical meteorological data network, the Vaganov–Shashkin model could be used to verify tree-ring proxy responses to climatic variability in other regions over the last century.

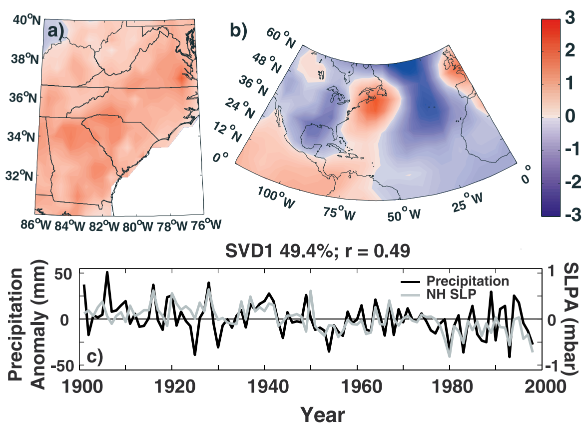

Figure 3. Leading mode of the singular value decomposition (SVD) analysis for the area-weighted covariance matrix of gridded regional summer precipitation [*New et al.*, 2000] and a gridded reconstruction of Northern Hemisphere summer sea level pressure (HadSLP1) [*Basnett and Parker*, 1997]. (a) The non-dimensional spatial precipitation pattern (49.4% of the covariance) is positive over our study region. (b) The non-dimensional SLP pattern has loadings of the same sign as the precipitation pattern over the western Atlantic Basin, and opposite signed loadings over the eastern United States. (c) The time series expansions of the first mode are significantly correlated with each other (r = 0.49, p < 0.0001, n = 98 years) and exhibit overall downward trends. The patterns and associated time series are similar for the linearly detrended data (not shown).

This model could also be used to predict forest growth responses to climate change using output from forecast GCMs. Inverse techniques incorporating process models such as the Vaganov–Shashkin model have the potential to further improve future paleoclimate reconstructions.

5. Conclusions

[12] We have found that the Vaganov–Shashkin model skillfully reproduces regional patterns of variability in tree-ring width chronologies in the southeastern United States, and can be used to study the causes of temporal non-stationarity in tree-ring growth responses to climate. The model predicts an increased sensitivity to summer precipitation in conifers in the Appalachians and portions of Georgia and Virginia as a response to decreases in precipitation. Our study suggests that in some cases nonstationarity in climate-tree growth relationships can arise from changes in climate alone. This finding has implications for retrospective studies of climate, as well as for forecasting ecological responses to future anthropogenic change.

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