Use of Atmospheric CO2-Sensitive Trees May Influence Dendroclimatic Reconstructions

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Abstract

We examined recent radial growth increases in western juniper trees using an 11-site chronology dating from AD 1000–2006. By various measures, radial growth during the late 20th/early 21st centuries was exceptional, with increases occurring absent of regional climatic change. We found that 54% of annual radial growth variability was explained by June Palmer Drought Severity Index (PDSI) values, but the inclusion of atmospheric CO2 values accounted for a 14% increase in explanatory power. We reconstructed June PDSI both including and excluding CO2, and found that PDSI values were overestimated at the end of the record with CO2 omitted from the model. We conclude that: 1) western juniper radial growth was associated with rising CO2 during the late 20th/early 21st centuries; and, the use of CO2-sensitive trees such as western juniper for dendroclimatic reconstructions may influence the results if the impacts of CO2 fertilization are omitted.

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1. Introduction

[2] Tree rings serve as proxy indicators of past climate, but can record the influence of non-climatic factors as well. Within the last few decades a series of publications examined the causes for mid- to late-20th century radial growth increases in trees sampled in widely dispersed geographic locations in both the Northern and Southern Hemisphere mid-latitudes. Growth increases have been attributed to warmer temperatures in locations where the growing season has been extended [*Singh and Yadav*, 2000; *D'Arrigo et al.*, 2001; *Büntgen et al.*, 2005] or winters modified [*Gou et al.*, 2007]. More favorable moisture conditions [*Huang and Zhang*, 2007], and atmospheric CO_2 fertilization [*LaMarche et al.*, 1984; *Graybill and Idso*, 1993; *Knapp et al.*, 2001; *Bunn et al.*, 2003; *Soulé and Knapp*, 2006; *Voelker et al.*, 2006] have also been attributed to growth increases.

[3] Studies examining the potential role of increasing CO_2 on radial tree growth under natural conditions have provided contrasting results based on tree age [*Hättenschwiler et al.*, 1997; *Voelker et al.*, 2006], tree morphology [*Graybill and Idso*, 1993; *Bunn et al.*, 2003], and site conditions [*Soulé and Knapp*, 2006]. These responses suggest the possibility of a non-climatic radial growth enhancement in trees used for dendroclimatic reconstructions and raise a critical question whether the potential (positive) impacts of CO_2 fertilization have been adequately separated from that of climatic change. For example, the inclusion of bristlecone and foxtail pine chronologies (*Pinus aristata, P. longaeva, P. balfouriana*) for Northern Hemisphere surface temperature reconstructions generated considerable discussion because of a possible CO_2 fertilization effect on radial growth [e.g., *Graybill and Idso*, 1993; *Mann et al.*, 1998, 1999; *McIntyre and McKitrick*, 2005a, 2005b; *Wahl and Ammann*, 2007].

[4] An observed effect of CO_2 fertilization is increased water-use efficiency (WUE), which is the ratio of dry biomass produced per water transpired [*Eamus*, 1991]. WUE increases can occur through increased photosynthesis, reduced stomatal conductance, or a combination of these changes [*Eamus*, 1991]. Tree species growing in semi-arid locations have experienced radial growth responses consistent with CO_2 fertilization [*Knapp et al.*, 2001; *Soulé and Knapp*, 2006] in that: 1) growth has exceeded what would be predicted by climate alone; and 2) the greatest *relative* increases have occurred during the driest years. These findings are consistent with controlled studies [*Pospisilova and Catsky*, 1999; *Poorter and Perez-Soba*, 2001] and the meta-analysis of *Huang et al.* [2007, p. 266] who concluded that "warm, moderately drought-stressed ecosystems... might be the most CO_2-responsive ecosystems."

[5] We use a millennium-length western juniper (*Juniperus occidentalis* var. *occidentalis* Hook.) chronology from semi-arid sites in the interior Pacific Northwest to show that climatic reconstructions from CO_2-sensitive trees (i.e., species significantly affected by increased CO_2) may be affected if the impacts of CO_2 fertilization are not directly modeled. We illustrate some of the potential complexities of working with tree-ring data for climate reconstructions that in turn infer climatic change, particularly post-1950 when CO_2 concentrations increased 22% by 2006 [*Etheridge et al.*, 1998; *Keeling and Whorf*, 2005]. While much of the debate has been focused on reconstructions of temperature, our work provides an analogous example because western juniper growth is principally moisture-driven as opposed to being temperature-driven.

2. Tree-Ring Data

[6] We obtained four chronologies [*NOAA*, 2007a] and developed seven others from locales identified as having minimal anthropogenic influences excluding CO_2 [*Knapp et al.*, 2001] (Figure S1 and Table S1 of the auxiliary material[1]).

The samples represented a mix of whole-bark and strip-bark trees and all chronology samples with interior dates of 1907 or younger were removed to avoid potential age-related bias. We standardized all chronologies conservatively using negative exponential or linear regression of a negative slope to preserve climatic variability. The beginning dates for the chronologies meeting the 0.85 criteria for signal strength [*Wigley et al.*, 1984] ranged from 530 to 1809. We began our analysis at year 1000, with chronology depth increasing over time with 27%, 55%, and 100% of sites beginning in 1000, 1668, and 1809, respectively. Eight of the chronologies extended through either 1996 or 1998, with two additional chronologies extending through 2006, and one chronology ending in 1982. The data set consisted of chronologies that correlated between 0.72–0.91 ($P < 0.001$) (Table S1) with the average of all of the chronologies using a common period of 1809–1982. Growth data from the years 1000–1565 were only available from three sites (TAB, FRE, and HOR). We compared the three-site average to the remaining eight-site composite over the common period of 1809–1982, and the high interseries correlation ($r_s = 0.92$, $P < 0.001$) suggests that the three-site composite fairly represents the early portion of the study period. We checked the 11-site average radial growth data for the complete (years 1000–2006) and instrumental-record (years 1907–2006) for normality using the Shapiro-Wilk test [*Shapiro and Wilk*, 1965] and found them to be non-normally ($P = 0.035$) and normally distributed ($P = 0.428$), respectively. Thus, we used non-parametric tests for the entire chronology period, and parametric tests for the 100-year data set.

3. Climate and Atmospheric CO_2 Data

[7] We selected monthly precipitation and temperature data obtained from *Oregon Climate Service* [2007], and Palmer Drought Severity Index (PDSI) data (obtained from *NOAA* [2007b]) for Oregon Climate Division 7 (Figure S1) from 1907–2006. As an indicator of a changed climate, we tested for differences in means between selected time periods (1907–56/76 to 1957/77–2006) for the climate variables using a 2-tailed *t*-test. We also tested for linear trends in monthly precipitation, temperature, and PDSI values from 1907–2006 using Pearson's correlation.

[8] We obtained CO_2 data for years 1010–1958 and 1959–2004 [*Etheridge et al.*, 1998; *Keeling and Whorf*, 2005]. The 1010–1958 data were available at 5-year intervals and we averaged increases/decreases between inflection points of higher/lower CO_2 values to derive annual values. We developed values for 2005 and 2006 by averaging the increase from 2000–2004 and adding this to the successive years.

4. Statistical Analyses

[9] We examined bivariate relationships between a suite of monthly, seasonal, and annual measures of temperature, precipitation, and drought severity and then created a series of multiple regression models using different combinations of explanatory variables to identify those elements of climate most strongly related to radial growth. June PDSI produced the best model. We examined the standardized residuals from the growth-climate models by creating a linear regression model with time as the explanatory variable. We created a multiple regression model that included yearly values of June PDSI and CO_2 and examined the linear trend of residuals. We determined the year when included CO_2 values became significant ($P < 0.05$) by removing the later years of data annually, beginning in 2006, and re-running the growth/climate model until $P>0.05$. We reconstructed June PDSI using radial growth, and radial growth and CO_2, as independent variables (Text S1).

[10] We calculated running 30-year and 50-year averages of standardized radial growth beginning in 2006 (e.g., 1977–2006 and 1957–2006) and extending to 1000 by using growth data back to years 971 and 951, respectively. We tested whether average radial growth in the top 30- or 50-year period was significantly greater than growth in the second to fifth highest non-overlapping 30- or 50-year periods using 1-tailed Mann-Whitney tests. The time periods selected represent the accepted length for climatic normals and the approximate length of rapidly rising CO_2 levels, respectively. To compare the persistence of abnormally high radial growth periods during the past millennium, we sorted the data and assigned a value of 1 to any year at the 85th percentile and a 0 to all other years. We then calculated 30-year running averages using the zeros and ones, and graphically displayed the resulting temporal pattern. We used a method [*Rodionov*, 2004] that identified regime shifts in radial growth from years 1000–2006 (Text S2).

5. Results and Discussion

[11] For the growth-climate model excluding CO_2 (PDSI-only) (Text S1) there is an upward trend for the standardized residuals ($R^2 = 0.30$, $P < 0.001$, Figure S2), indicating that actual radial growth exceeded predicted growth through time. During the period 1977–2006, 83% of the years were marked by positive residuals. June PDSI values from 1907 to 2006 show no trend ($P = 0.81$), and the mean from 1977–2006 (-0.49) is not different ($P = 0.62$) from the mean (-0.11) from 1907–1976. The relationship between western juniper radial growth and CO_2 levels over the period 1907–2006 is significant ($r = 0.323$, $P = 0.001$), and including CO_2 values in a multiple regression growth-climate model with June PDSI (+CO_2 model) (Text S1) improved the predictive ability of the model by 14%. No temporal trend was present in the standardized residuals ($R^2 = 0.002$, $P = 0.679$) from the +CO_2 model, indicating no systematic under- or over-prediction of annual growth during the past century (Figure S2).

[12] The +CO_2 model better accounts for the recent increase in radial growth than did the models using climate variables alone. Use of the PDSI-only regression model produced almost exclusively positive residuals since 1977 (Figure S2), and the model under-predicted actual radial growth by $>0.5\ \sigma$ in 20 of the 30 years. The +CO_2 model has a greater balance of positive (53%) and negative residuals over the same period and the model under-predicted only 10 of the 30 years by $> 0.5\ \sigma$. Until 1968, the +CO_2 model almost always (i.e., 97%) produced a residual value that exceeded (i.e., more positive or less negative) the PDSI-only model. From 1968 onward this relationship reversed, particularly so during the last three decades (Figure S2). When the residuals from the +CO_2 model are subtracted

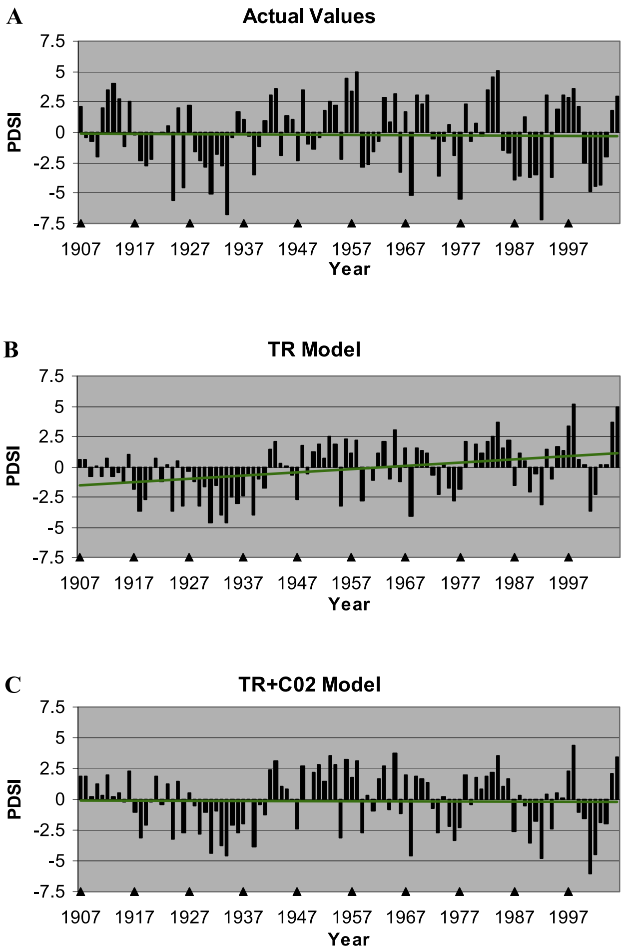

Figure 1. (a) Actual June PDSI values from Oregon Climatic Division 7 from 1907–2006 and PDSI values reconstructed using the (b) TR and (c) TR+CO_2 models with associated trend lines. The linear trend for the PDSI only model is significant ($P < 0.001$), the linear trends for actual June PDSI values ($P = 0.812$) and the TR+CO_2 model ($P = 0.855$) are not.

from the PDSI-only model a gradual upward trend exists for the 1907 to 1949 period ($R^2 = 0.34$, $P < 0.001$, 0.009 standardized residuals/year; Figure S3). From 1950–2006, however, the upward trend is greater ($R^2 = 0.91$, $P < 0.001$, 0.032 standardized residuals/year; Figure S3).

[13] Reconstructed June PDSI values better replicate actual PDSI values using both tree-ring and CO_2 data (TR+CO_2 model) as opposed to using tree-ring data only (TR model) (Text S1). Comparing trend lines between the two reconstructed models and actual June PDSI values during the past century (Figures 1a–1c) illustrates that while the TR+CO_2 model values are non-trending and consistent with actual PDSI values, the TR model produces a significant upward trend. Where a CO_2 effect is operative, but omitted from the reconstruction models, the TR model overestimates (underestimates) positively correlated climatic parameters at the end (beginning) of the record (Figure 1b), with the underestimation occurring for the majority of the reconstructed period (Figure 2a).

[14] CO_2 was largely stable from 1000 through the mid-1800s and remained a non-factor in the TR+CO_2 model until that time. Thereafter, the model included the positive and accelerating influence of CO_2. We found that the inclusion of CO_2 as a variable in the development of growth/climate models became statistically valid ($P < 0.05$) from 1979 onward. Because CO_2 is an insignificant predictor when paired with June PDSI in our regression models developed using western juniper tree-ring data prior to 1979, climatic reconstructions based on pre-1980 data would not be significantly influenced by rising CO_2 levels. Climatic reconstructions from other CO_2-responsive species should be similarly unaffected by rising CO_2 if developed using data that exclude some portion of the last five decades when CO_2 has increased rapidly.

[15] Several measures suggest that elevated radial growth rates during the late-20th/early 21st centuries are unusual within the past millennium. First, radial growth was 27% above the long-term average (1000–2006) during the period 1977–2006. Second, two significant regime shifts toward higher radial growth occurred from 1948–2006, and combined included the longest sustained major growth regime (i.e., radial growth > 0.5 σ above-average) in the record. This period is over twice the duration of the other major sustained growth regimes that occurred from 1104–1129 and 1596–1612 (Figure 2a). The beginning of the 1948–2006 radial growth regime shifts coincided with a cold Pacific Decadal Oscillation (PDO) phase onset characterized by generally wetter conditions in the Pacific Northwest [*Joint Institute for Study of the Atmosphere Ocean*, 2007]. However, elevated radial growth continued through 2006 and occurred despite the return to a warm-phase PDO (i.e., drier in the PNW) that began in 1977 and continued through 2006 [*Joint Institute for Study of the Atmosphere Ocean*, 2007], suggesting that PDO conditions cannot explain the

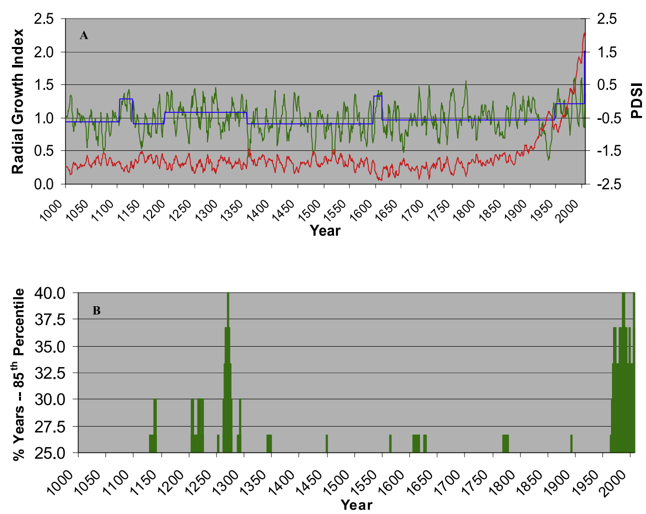

Figure 2. (a) Five-year running means of radial growth (green) and differences (red) between reconstructed PDSI values (the TR model minus the TR+CO_2 model) during AD 1000–2006. Radial growth regimes are shown in blue. (b) Percentage of years in which radial growth was at the 85th percentile based on running 30-year averages, AD 1000–2006.

long-term trends. Third, when radial growth index values are grouped by years at the 85th percentile, the late 20th/early 21st century period is exceptional (Figure 2b). From 1963 through 2006, 25% of the years had an index value at the 85th percentile of all years. In contrast, the next longest period with continuous high growth was 1204–1225. Fourth, the two highest 30- and 50-year periods of radial growth since 1000 end in 2006 and 1999, respectively, and include the single greatest growth year (1998). While neither period is different ($P < 0.05$) from the several next highest 30- and 50-year periods (Table S2), these growth rates during the past half-century occurred without a change in climatic conditions that would benefit western juniper (Tables S3 and S4). No significant differences in June PDSI values exist when comparing the years 1907–1956/1976 with the most recent 50- and 30-year periods (1957/1977–2006), June PDSI exhibited no long-term trends (Table S3), and the only temperature variable significantly related to radial growth, June temperature, had a negative impact ($r = -0.25$, $P < 0.01$) and was not retained in any multiple regression model using a significance of $P < 0.05$ (Table S3). Based on this combination of factors, radial growth during the late 20th/early 21st century may have been unlike any other period during the last millennium.

[16] While western juniper radial growth rates remain predominately controlled by soil moisture conditions (indicated by June PDSI values), the strong correlation to rising CO_2 and growth responses consistent with a CO_2 signature [*Knapp et al.*, 2001; *Soulé and Knapp*, 2006] suggest that CO_2 fertilization has significantly influenced radial growth in the late 20th/early 21st centuries. Further, few viable alternative explanations appear to exist: western juniper responds negatively to temperature, negating any linkages to regional warming; the majority of our chronologies were developed from sites with minimal human impacts [*Knapp et al.*, 2001]; and increased radial growth cannot be attributed to nitrogen fertilization, as the 11 chronology sites do not fall under any of the criteria used to identify ecosystems [*Fenn et al.*, 2003] significantly impacted by N-deposition. That said, we recognize the possibility that fine-scale environmental changes undetected by our analysis also may influence radial growth.

6. Conclusions

[17] Elevated CO_2 positively impacts radial growth rates of western juniper within the natural range of this tree species and may complicate the use of tree-ring data from other CO_2-sensitive species to infer climatic trends. If CO_2 fertilization is the driving force behind late 20th/early 21st century growth rate increases, then any non-trending climate variables positively correlated with radial growth have the potential to become over-predicted at some point in the last several decades. Given the expansive range of species like ponderosa pine (*Pinus ponderosa)* [*Soulé and Knapp*, 2006], and the importance of other semiarid tree species in the development of proxy-based reconstructions of past climates, the issue of using CO_2-sensitive trees for climatic reconstructions is potentially far-reaching in climate science. The development of climate-growth models for use in reconstructions could avoid the potential problems associated with CO_2 enrichment by: 1) using only pre-CO_2 effect data; 2) insuring that the tree species have not been sensitive to rising CO_2; or 3) developing multivariate models including CO_2 as an independent variable when statistically valid.

References

Bunn, A. G., R. L. Lawrence, G. J. Bellante, L. A. Waggoner, and L. J. Graumlich (2003), Spatial variation in distribution and growth patterns of old growth strip-bark pines, *Arct. Antarct. Alp. Res.*, *35*, 323–330.

Büntgen, U., J. Esper, D. C. Frank, K. Nicolussi, and M. A. Schmidhalter (2005), A 1052-year tree-ring proxy of Alpine summer temperatures, *Clim. Dyn.*, *25*, 141–153.

D'Arrigo, R. D., G. Jacoby, D. Frank, N. Pederson, E. Cook, B. Buckley, B. Nachin, R. Mijiddorj, and C. Dugarjav (2001), Two millennia of Mongolian temperature variability, *Geophys. Res. Lett.*, *28*, 543–546.

Eamus, D. (1991), The interaction of rising CO_2 and temperatures with water use efficiency, *Plant Cell Environ.*, *14*, 843–852.

Etheridge, D. M., et al. (1998), Historical CO_2 records from the Law Dome DE08, DE08-2, and DSS ice cores, http://cdiac.ornl.gov/trends/co2/lawdome.html, Carbon Dioxide Inf. Anal. Cent., Oak Ridge Natl. Lab., Oak Ridge, Tenn.

Fenn, M. E., et al. (2003), Ecological effects of nitrogen deposition in the western United States, *BioScience*, *53*, 404–420.

Gou, X., F. Chen, G. Jacoby, E. Cook, M. Yan, J. Peng, and Y. Zhang (2007), Rapid tree growth with respect to the last 400 years in response to climate warming, northeastern Tibetan Plateau, *Int. J. Climatol.*, *27*, 1497–1503.

Graybill, D. A., and S. B. Idso (1993), Detecting the aerial fertilization effect of atmospheric CO_2 enrichment in tree-ring chronologies, *Global Biogeochem. Cycles*, *7*, 81–95.

Hättenschwiler, S., F. Miglietta, A. Raschi, and C. Körner (1997), Thirty years of in situ tree growth under elevated CO2: A model for future forest responses?, *Global Change Biol.*, *3*, 464–471.

Huang, J.-G., and Q.-B. Zhang (2007), Tree rings and climate for the last 680 years in Wulan area of northeastern Qinghai-Tibetan Plateau, *Clim. Change*, *80*, 369–377.

Huang, J.-G., Y. Bergeron, B. Denneler, F. Berninger, and J. Tardiff (2007), Response of forest trees to increased atmospheric CO_2, *Crit. Rev. Plant Sci.*, *26*, 265–283.

Joint Institute for Study of the Atmosphere and Ocean (2007), The Pacific Decadal Oscillation (PDO) Index, http://jisao.washington.edu/pdo/, Joint Inst. for Stud. of the Atmos. and Ocean, Seattle, Wash.

Keeling, C. D., and T. P. Whorf (2005), Atmospheric CO_2 records from sites in the SIO air sampling network, http://cdiac.ornl.gov/trends/co2/sio-keel.html, Carbon Dioxide Inf. Anal. Cent., Oak Ridge Natl. Lab., Oak Ridge, Tenn.

Knapp, P. A., P. T. Soulé, and H. D. Grissino-Mayer (2001), Detecting potential regional effects of increased atmospheric CO_2 on growth rates of western juniper, *Global Change Biol.*, *7*, 903–917.

LaMarche, V. C., Jr., D. A. Graybill, H. C. Fritts, and M. R. Rose (1984), Increasing atmospheric carbon dioxide: Tree ring evidence for growth enhancement in natural vegetation, *Science*, *225*, 1019–1021.

Mann, M. E., R. S. Bradley, and M. K. Hughes (1998), Global-scale temperature patterns and climate forcing over the past six centuries, *Nature*, *392*, 779–787.

Mann, M. E., R. S. Bradley, and M. K. Hughes (1999), Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations, *Geophys. Res. Lett.*, *26*, 759–762.

McIntyre, S., and R. McKitrick (2005a), Hockey sticks, principal components, and spurious significance, *Geophys. Res. Lett.*, *32*, L03710, doi:10.1029/2004GL021750.

McIntyre, S., and R. McKitrick (2005b), Reply to comment by Huybers on "Hockey sticks, principal components, and spurious significance", *Geophys. Res. Lett.*, *32*, L20713, doi:10.1029/2005GL023586.

NOAA (2007a), International Tree-Ring Data Bank, http://hurricane.ncdc.noaa.gov/pls/paleo/fm_createpages.treering, Natl. Clim. Data Cent., Asheville, N. C.

NOAA (2007b), PDSI data, http://www.ncdc.noaa.gov/paleo/pdsidata.html, Natl. Clim. Data, Asheville, N. C.

Oregon Climate Service (2007), Zone 7—Climate data archives, http://www.ocs.oregonstate.edu/index.html, Oregon State Univ., Corvallis, Oreg.

Poorter, H., and M. Perez-Soba (2001), The growth responses of plants to elevated CO2 under non-optimal environmental conditions, *Oecologia*, *129*, 1–20.

Pospisilova, J., and J. Catsky (1999), Development of water stress under increased atmospheric CO_2 concentration, *Biol. Plant.*, *42*, 1–24.

Rodionov, S. N. (2004), A sequential algorithm for testing climate regime shifts, *Geophys. Res. Lett.*, *31*, L09204, doi:10.1029/2004GL019448.

Shapiro, S., and M. Wilk (1965), An analysis of variance for normality (complete samples), *Biometrika*, *52*, 591–611.
Singh, J., and R. R. Yadav (2000), Tree-ring indications of recent glacier fluctuations in Gangotri, western Himalaya, India, *Curr. Sci.*, *79*, 1598–1601.
Soulé, P. T., and P. A. Knapp (2006), Radial growth rate increases in naturally-occurring ponderosa pine trees: A late 20th century CO_2 fertilization effect?, *New Phytol.*, *171*, 379–390.
Voelker, S. L., R. M. Muzika, R. P. Guyette, and M. C. Stambaugh (2006), Historical CO_2 growth enhancement declines with age in *Quercus* and *Pinus*, *Ecol. Monogr.*, *76*, 549–564.
Wahl, E. R., and C. M. Ammann (2007), Robustness of the Mann, Bradley, Hughes reconstruction of Northern Hemisphere surface temperatures: Examination of criticisms based on the nature and processing of proxy climate evidence, *Clim. Change*, *85*, 33–69.
Wigley, T. M. L., K. R. Briffa, and P. D. Jones (1984), On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology, *J. Clim. Appl. Meteorol.*, *23*, 201–213.

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