Borehole temperatures and tree rings: Seasonality and estimates of extratropical Northern Hemispheric warming

Robert N. Harris[1] and David S. Chapman

Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah, USA

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[1] We construct an extratropical reduced temperature–depth profile for land areas north of 20°N latitude from the global borehole temperature database compiled for climate reconstruction. The mean reduced temperature profile compares well with a time series constructed from an initial baseline temperature (0.6° ± 0.1°C) and the last 140 years of gridded annual surface air temperature data diffused into the ground. This analysis yields a root-mean-square misfit of only 15 mK and indicates warming of 1.1°C over the past 500 years. In contrast, a tree ring analysis from the same area (Briffa et al., 2001) indicates considerably less warming over the same time period. The recognition that tree rings correlate most strongly with warm season temperatures (April–September), while boreholes reflect annual temperatures, offers an explanation for the discrepancy in warming estimates. This analysis yields a reconstruction of surface temperature over the past 500 years that is consistent with both the borehole and tree ring analysis and also provides an estimate of long-term cold season temperature. We estimate that continental extratropical Northern Hemisphere annual and cold season (October–March) temperatures have warmed by 0.2° ± 0.1°C and 0.3° ± 0.3°C, respectively, between 1500 and 1856, prior to the start of the instrumental surface air temperature record.

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1. Introduction

[2] Tree ring records of climate change are an important component of multiproxy records used to reconstruct climate [*Jones et al.*, 1988; *Mann et al.*, 1999; *Briffa et al.*, 2001; *Crowley and Lowery*, 2000; *Esper et al.*, 2001; *Jones and Mann*, 2004; *Moberg et al.*, 2005]. Tree rings provide powerful tools for temperature reconstruction because they are widespread, extend estimates of climatic variability well beyond the instrumental period, are well dated, and capture high-frequency events. However, two disadvantages of tree rings are that they predominantly reflect warm season temperatures when the trees are actively laying down wood [*Briffa et al.*, 2002; *Jones et al.*, 2003] and, because of detrending practices, it is difficult to obtain low-frequency variations in temperature [*Cook et al.*, 1995, 2004]. The former is a problem because as shown by the period of instrumental recording, most of the annual warming has occurred during the cold season [*Jones and Moberg*, 2003]. The latter problem has been overcome in part through the use of age band decomposition [*Briffa et al.*, 2001] and regional band decomposition [*Esper et al.*, 2001], but there is still considerable uncertainty regarding temperature variations at the centennial scale [*Briffa and Osborn*, 2002].

[3] Borehole temperature-depth profiles are also used to reconstruct ground surface temperature (GST) histories [*Lachenbruch and Marshall*, 1986; *Huang et al.*, 2000; *Harris and Chapman*, 2001; *Beltrami*, 2002] and contain information complementary to reconstructions based on tree rings [*Beltrami et al.*, 1995; *Huang*, 2004; *Moberg et al.*, 2005]. Variations in GST diffuse into the subsurface, imparting curvature to a mostly linear temperature-depth structure. Thermal diffusivity ($\sim 1 \times 10^{-6}$ m^2 s^{-1} for rocks) relates temperature perturbations as a function of depth to GST variations as a function of time before present. Because thermal diffusion in the Earth is relatively slow, temperature profiles measured to depths of a few hundred meters contain information about GST over the past several centuries. Over large space scales and timescales, variations in GST are directly related to variations in surface air temperature (SAT), without the need for an empirical calibration inherent to proxy methods [*Harris and Chapman*, 2001; *Baker and Ruschy*, 1993]. Borehole temperature records of climatic change provide a complementary data set to the tree ring record because they are sensitive to the full calendar year of temperature variability and preferentially retain low-frequency GST variations. Thus additional information about preinstrumental surface temperatures can be gleaned from borehole temperature reconstructions.

[1]Now at College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.

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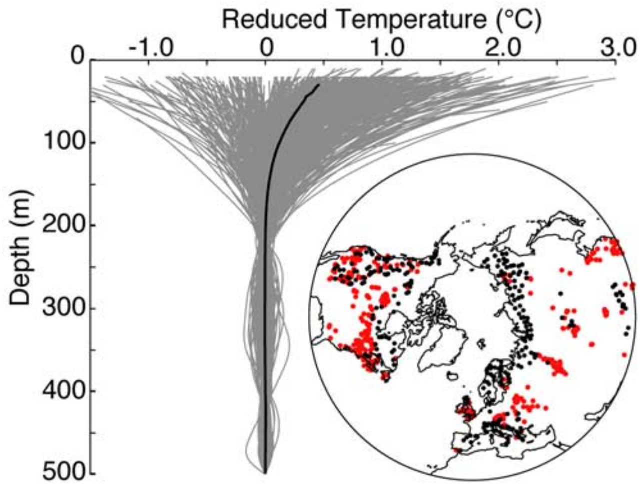

Figure 1. Extratropical Northern Hemisphere reduced temperature profiles. Individual lines represent profiles for 687 boreholes whose locations are shown in the inset. Thick black line shows average reduced temperature profile. The inset shows the location of tree ring [*Briffa et al.*, 2001] and borehole [*Huang and Pollack*, 1998] sites used for temperature reconstructions. Tree ring sites are shown in black, and borehole sites are shown in red.

[4] Many multiproxy climate reconstructions and those solely using tree ring records [*Jones et al.*, 1988; *Mann et al.*, 1999; *Briffa et al.*, 2001; *Crowley and Lowery*, 2000], however, generally show less warming over the last 500 years than those based on temperature-depth profiles [*Huang et al.*, 2000; *Harris and Chapman*, 2001; *Osborn and Briffa*, 2002; *Harris and Chapman*, 2002; *Beltrami*, 2002]. Borehole analyses have been argued to overestimate the amount of warming due to seasonal biases, including the insulating effects of snow [*Mann and Schmidt*, 2003] and land use changes coupled with warm season radiation [*Lewis and Wang*, 1998; *Majorowicz et al.*, 2002]. Although the snow effect on ground temperature is complex [*Smerdon et al.*, 2004; *Bartlett et al.*, 2004], snow cover could decrease the magnitude of warming inferred from temperature-depth profiles because it attenuates cold season warming, thereby enhancing rather than decreasing the discrepancy in warming estimates between borehole temperatures and multiproxy reconstructions. In any event, the effect of snow cover on ground temperature appears to be small [*Chapman et al.*, 2004; *Gonzalez-Rouco et al.*, 2003]. Land use change arguments depend on complex radiation scenarios that preferentially affect GST but not SAT. Conversely, several strands of evidence suggest that multiproxy reconstructions have underestimated the magnitude of warming. Standardization procedures in tree ring analysis that remove long-term growth trends may also be removing long-term climatic trends [*Cook et al.*, 1995], and regression-based mulitproxy reconstructions may be underestimating climatic variability due to poor noise suppression and inadequate spatial coverage [*von Storch et al.*, 2004]. Finally, issues associated with the differing geographic distribution of data have been suggested. *Mann et al.* [2003] argued that the analyses of the Northern Hemisphere borehole temperatures had been improperly aggregated, but *Pollack and Smerdon* [2004] showed that the *Mann et al.* [2003] aggregation was flawed. The subsequent correction [*Rutherford and Mann*, 2004] increases the estimated warming magnitude and is similar to estimates by *Harris and Chapman* [2001] and *Pollack and Smerdon* [2004]. The causes of the discrepancy between warming estimates based on tree rings and those based on borehole temperatures have remained elusive.

[5] In this paper we explore the effects of seasonality in tree ring series and boreholes as a possible source of the discrepancy in warming estimates, using the tree ring reconstruction of *Briffa et al.* [2001] and the borehole data set compiled by *Huang and Pollack* [1998]. These data sets have good geographic coverage and significant overlap (Figure 1). In North America and Europe, there is good overlap of the areas covered by these two data sets, while in Asia many tree ring sites are north of borehole sites. Nevertheless, both of these data sets reflect Northern Hemisphere extratropical continental temperatures. An additional advantage of the *Briffa et al.* [2001] tree ring reconstruction is that it has been analyzed to capture low-frequency events and therefore should be more comparable to the borehole data set.

[6] We first demonstrate that the Northern Hemisphere extratropical reduced temperature–depth profile is more consistent with the annual SAT record of temperature change than either the warm or cold season records. We then demonstrate that the discrepancy between the tree ring series and the reduced temperature–depth profile is quantitatively consistent with cold season warming, as indicated by the SAT record over the common period of overlap. Finally, we extend our analysis over the past 500 years to estimate Northern Hemisphere extratropical continental annual and cold season warming and discuss its implications.

2. Analysis

[7] We process the temperature-depth data to facilitate quantitative hemispheric reconstructions of GST change with SAT and tree ring records of climate change [*Harris and Chapman*, 2001, 2005]. The background temperature field is parameterized in terms of the long-term thermal gradient and surface temperature intercept and is removed to isolate a reduced temperature field that includes the transient component of each temperature-depth profile. These background parameters are estimated using data below 160 m, a depth sufficient to avoid more recent climate change effects yet shallow enough to provide a significant depth interval that yields robust estimates of these parameters. This compilation of temperature profiles represents data collected over a 47-year period (1958–2001). Profiles logged in 1958 contain a slightly different surface temperature history than those logged in 2001. To obtain a conservative and consistent average reduced temperature anomaly, profiles are forward continued in time using a Laplace transform, assuming a constant GST between the year the borehole was logged and 2001. This analysis produces a reduced temperature profile with anomalous temperatures slightly deeper in the subsurface, having slightly greater magnitudes at intermediate depths, and that are somewhat smoothed relative to the original profile. Profiles forward continued with a linear trend based on

Table 1. Estimates of Northern Hemisphere Extratropical Continental Surface Warming

Method	Time Period	ΔT, °C	Source
Ramp fit to T(z)[a]	1840 to present	0.8	this paper
Multiramp fit to T(z)	1500 to present	1.0	*Huang et al.* [2000]
Initial temperature and SAT fit to T(z)[b]	1500 to present	1.1	this paper
SAT annual trend	1856–2001	0.8	*Jones and Moberg* [2003]
SAT warm season	1856–2001	0.5	*Jones and Moberg* [2003]
SAT cold season	1856–2001	1.1	*Jones and Moberg* [2003]
Missing warming	1856–2001	0.3	this paper
TR warm season[c]	1500–1856	0.1	*Briffa et al.* [2001]
Cold season trend based on T(z) and TR	1500–1856	0.3	this paper
Annual trend based on T(z) and TR	1500–1856	0.2	this paper

[a]T(z) denotes borehole reduced temperature–depth data.
[b]SAT denotes surface air temperature.
[c]TR denotes tree ring temperature series.

the SAT time series between the year of logging and 2001 show slightly more warming [*Harris and Chapman*, 2001].

[8] The composite of reduced temperature profiles shows generally positive anomalous temperatures indicative of long-term warming (Figure 1). The variability in reduced temperature profiles reflects natural climatic variability and site-specific effects. An average reduced temperature profile for these logs is computed by averaging individual reduced temperature profiles for each 5° × 5° grid cell containing temperature logs, weighting each grid cell by its area, and then averaging all grid cells together. The mean reduced temperature profile has an amplitude of 0.5°C at 30 m that extrapolates to an amplitude of 0.8°C at the surface. This profile represents a diffused consequence of temperature change at the Earth's surface over the past century or so. A simple last event model that reproduces this anomaly is a linear increase (i.e., ramp) of 0.8°C starting in 1840 (Table 1).

[9] Annual, warm season (April–September), and cold season (October–March) extratropical continental SATs [*Jones and Moberg*, 2003] are plotted in the inset of Figure 2. Linear trends to these time series show that winter temperatures have warmed twice as fast as summer temperatures (Table 1). Note that the magnitude of warming of the annual SAT trend (0.8°C/145 yr) is the same magnitude independently predicted by the reduced temperature profile. Because of diffusion the difference between starting the trend in 1840 and 1856, when the SAT record starts, is negligible.

[10] One can quantitatively test whether any SAT time series is consistent with borehole temperature profiles by diffusing the SAT signal into the ground to produce a synthetic temperature-depth profile [*Harris and Chapman*, 1998, 2001]. Each SAT time series is initialized such that the initial temperature (horizontal lines in Figure 2, inset) joins the linear fit to the SAT time series. This construction limits the variability in the synthetic temperature profile to the time period of the SAT time series and allows a straightforward comparison to the reduced temperature profile. The transient temperatures produced by each time series show that the annual time series best fits the reduced temperature profile, both in depth and magnitude (Table 2). This result supports our contention that the reduced temperature profile contains a faithful, albeit diffused, record of annual surface temperature change. In contrast, the warm and cold season SAT records underpredict and overpredict the magnitude and timing of warming, respectively, and do not support the assertion that borehole temperatures are strongly affected by a warm season bias as argued by *Mann and Schmidt* [2003].

[11] In the foregoing analysis no free parameters were used. If we relax this constraint, the initial baseline temperature that minimizes the misfit between the SAT record and the average reduced temperature profile is 0.6° ± 0.1°C below the 1961–1990 mean SAT and produces an excellent fit to the profile accounting for 99% of the observed variance and a RMS misfit between observed and synthetic reduced temperatures of only 15 mK. The total warming found by this technique is approximately 1.1°C over the past 500 years (Table 1), in good agreement with warming inferred through a multitrend analysis [*Huang et al.*, 2000]. The good fit of the annual SAT time series to the reduced temperature profile affirms the use of temperature-depth profiles to reconstruct GST histories.

[12] We now compare the extratropical Northern Hemisphere tree ring record [*Briffa et al.*, 2001] with the reduced temperature profile (Figure 3). *Briffa et al.* [2002] show that this tree ring series has greatest correlation with warm season months (April–September) and calibrate it such that the tree ring series represents warm season temperatures. We hypothesize that the discrepancy between the tree ring record of *Briffa et al.* [2001] and the borehole temperature record is due to cold season warming not captured by the tree rings.

[13] We test our hypothesis by constructing a pseudo tree ring model (TR1) consisting of an initial temperature, corresponding to the mean tree ring temperature over the period 1400–1856 (0.36°C below the 1961–1990 mean) and the tree ring temperature series over the period 1856–1960. The tree ring record is extended to 2001 using the warm season months from the SAT record. This construction isolates temperature variability to the time period corresponding to the instrumental SAT record that we use to test our results. Time series TR1 (Figure 3a) is diffused into the ground and compared against the reduced temperature profile (Figure 3b). With this construction we plot the reduced and synthetic temperature profiles relative to the temperature used to initialize the synthetic, so that the difference between the profiles corresponds to the time period over which there are SAT values. The reduced temperature profile indicates greater warming than the subsurface response to TR1. We test if the difference between these profiles represents the difference between annual warming (the borehole temperature profile) and

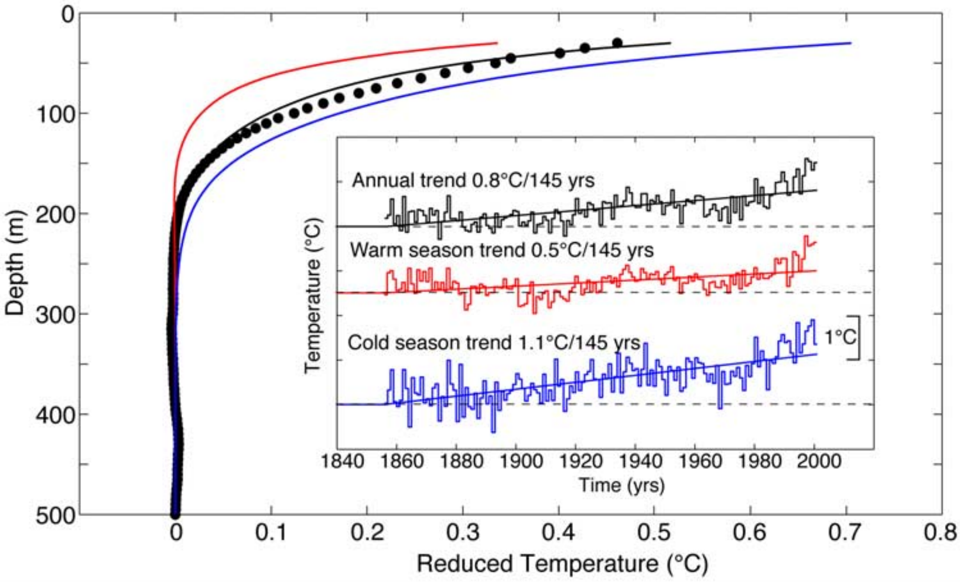

Figure 2. Comparison of the extratropical Northern Hemisphere reduced temperature and surface air temperature (SAT) records [*Jones and Moberg*, 2003]. Circles show the reduced temperature profile, and lines show, for comparison purposes, the synthetic temperature profiles constructed from the diffused air temperature records for the annual time series (black), warm season (April–September) time series (red), and cold season (October–March) time series (blue). The annual SAT time series most closely matches the reduced temperature profile. The inset shows annual, warm season, and cold season temperature records plotted relative to the beginning of its linear fit. The horizontal line associated with each record shows the temperature used to initialize the time series.

warm season warming (the tree ring record) by fitting the discrepancy with a linear trend (Figure 3c). The best fitting linear trend, constrained to begin in 1856, the start of the observational record, has an amplitude of 0.3°C (Figure 3c), the same amplitude as the difference between SAT annual and warm season trends (Table 1). This test indicates that the discrepancy in reconstructions is due to cold season warming and suggests a method for estimating cold season warming prior to the instrumental record.

[14] We compute the difference in warming estimates over the time period (1500–2001) for which both the tree ring and borehole temperature signals have sensitivity. A new pseudo tree ring model (TR2) is constructed with an initialization corresponding to the mean tree ring temperature during 1400–1500 (0.25°C below the 1960–1991 mean) and the temperature values during 1500–2001, and diffused into the subsurface. This synthetic temperature profile is plotted relative to its initialization temperature. The subsurface response to TR2 (Figure 3d) shows more variation than TR1 (Figure 3b), with slightly more negative temperatures between depths of 300 and 100 m associated with the lower temperatures between approximately 1570 and 1800, relative to the initialization used in TR1. Subsequent to about 1800 the TR2 synthetic shows slightly greater warming because of its lower initialization temperature. The reduced temperature profile and the synthetic produced from the annual SAT record are plotted relative to the best fitting initial temperature (0.6°C below the 1961–1990 mean temperature). This construction ties each synthetic temperature profile to its 1961–1990 mean temperature. We estimate the difference between annual and warm season warming by modeling the misfit profile (Figure 3e) in terms of two linear trends whose time boundary is fixed at 1856, the start of the SAT record. The first linear trend covers the period from 1500 to 1856 and has an amplitude of 0.2°C. The second linear trend is constrained to recover the computed difference between annual and warm season warming inferred from the analysis above and has an amplitude of 0.3°C over the period 1856–2001.

3. Results

[15] Using the tree ring series [*Briffa et al.*, 2001] to represent warm season temperatures (W) and the linear trends just calculated to represent the difference between annual and warm season trends (ΔT), we calculate estimates of cold season warming ($C = W + 2\Delta T$) and annual warming ($A = (W + C)/2$) (Figure 4). Our analysis indicates that the cold season has been warming since about the middle of the last millennium and more rapidly since about 1850, consistent with the SAT record. This estimate of cold season

Table 2. Comparison of Reduced Temperature Profile With Warm Season, Cold Season, and Annual Surface Air Temperatures

SAT Time Series	Initial Temperature,[a] °C	RMS,[b] mK
Warm season (Apr–Sep)	−0.31	71.7
Cold season (Oct–Mar)	−0.80	57.4
Annual	−0.55	20.5

[a]Initial temperature is based on beginning of linear fit to time series and is relative to 1961–1990 mean SAT.

[b]RMS is root-mean-square misfit and is calculated to a depth of two thermal lengths (270 m).

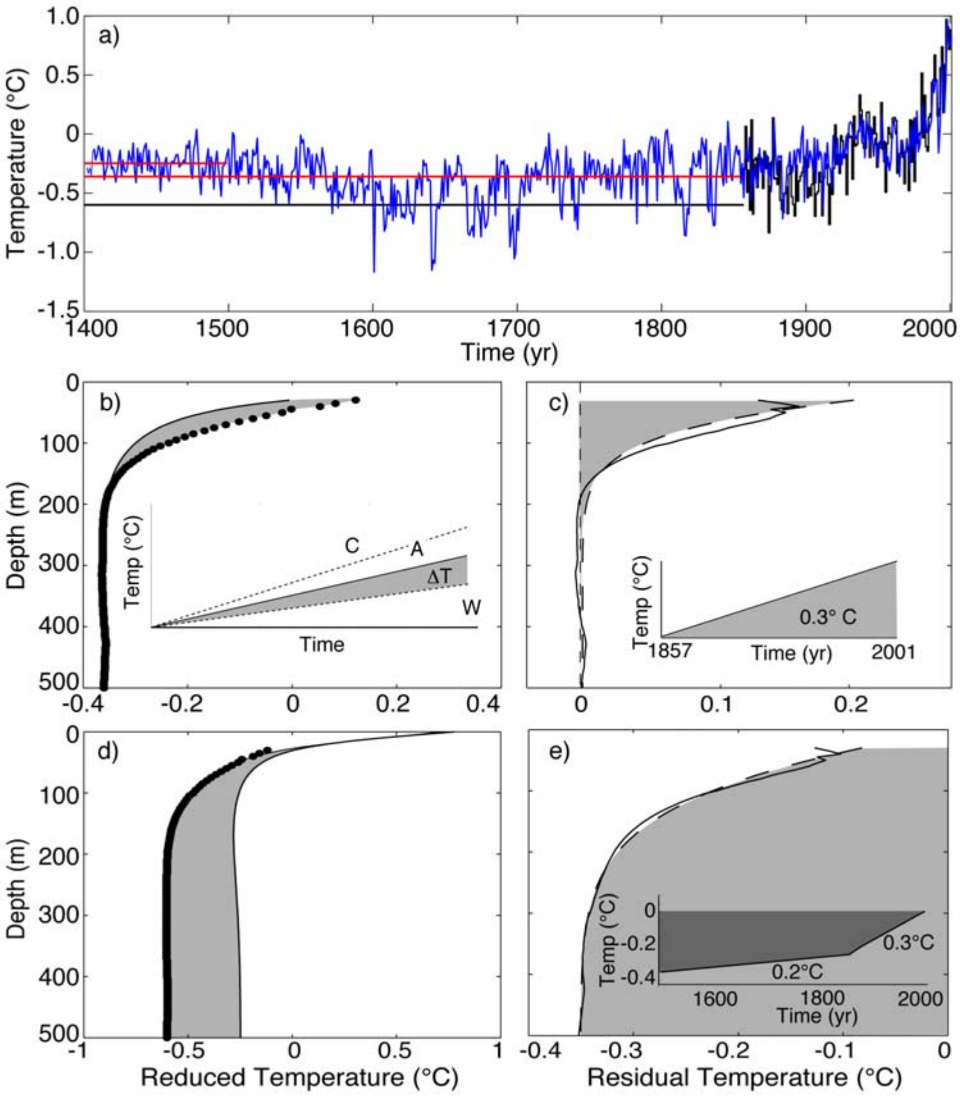

Figure 3. Analysis of temperature reconstructions using a combined analysis of surface air temperatures (SATs), tree rings, and borehole temperatures. (a) SATs (black line) [*Jones and Moberg*, 2003], tree ring reconstruction (blue line) [*Briffa et al.*, 2001], and two initial temperatures based on the mean of tree ring values for the period (red horizontal lines). Horizontal black line shows best fitting initial temperature when comparing SAT record and average reduced temperature profile. (b) Average reduced temperature profile (circles) and modeled subsurface response to initial temperature (tree ring mean value during 1400–1856, bottom red line in Figure 3a) and tree ring record (1856–2001). Reduced temperatures and model are plotted relative to the initial temperature. Shaded area shows discrepancy between borehole and tree ring reconstruction. The inset shows a cartoon of cold season (C), warm season (W), and annual (A) warming trends, where shaded area shows discrepancy between warm season and annual warming (ΔT). (c) Difference between average reduced temperature profile and tree ring model from Figure 3b (solid line). Dashed line shows best fitting ramp function (inset) with amplitude of 0.3°C starting in 1856. (d) Average reduced temperature profiles (circles) and modeled subsurface response to initial temperature (tree ring mean value during 1400–1500, top red line in Figure 3a) and tree ring record (1500–2001). Shaded area shows discrepancy between borehole and tree ring reconstruction. (e) Difference between average reduced temperature profile and model (solid line). Dashed line shows best fitting ramp functions to difference profile. Best fitting ramp functions with amplitudes are shown in the inset.

warming most likely represents a maximum since warm season low frequencies not captured by the tree ring series, but captured by the reduced temperature profile, will be partitioned into cold season warming. However, this partitioning does not affect our estimate of annual temperatures, and this series represents our best estimate of Northern Hemispheric extratropical continental temperatures consistent with both the tree ring and the borehole temperature records. Our estimate of more rapid cold season warming prior to the onset of widespread instrumental

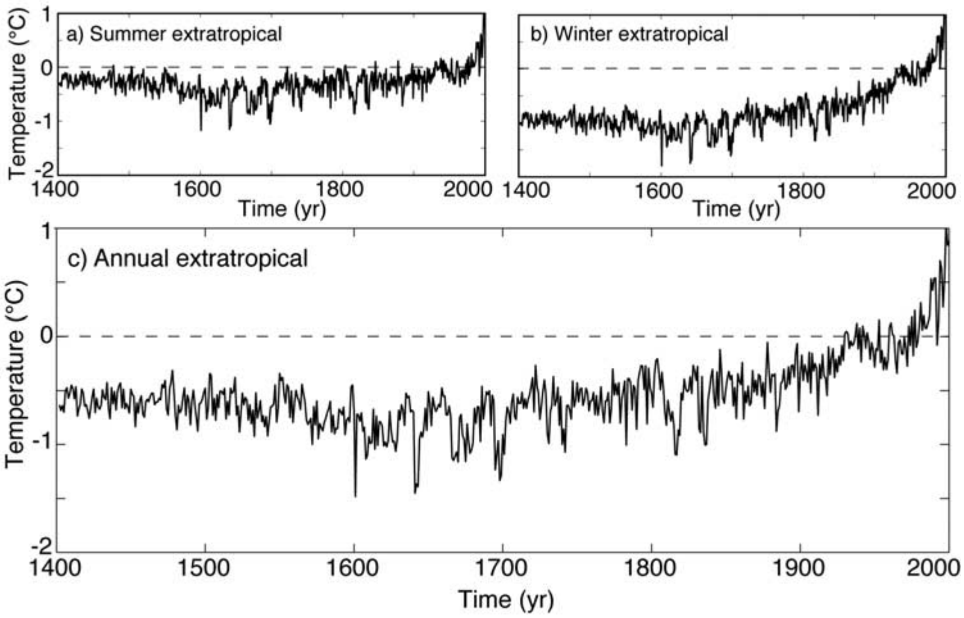

Figure 4. Seasonal and annual temperature variations over the past 500 years consistent with both tree rings and borehole temperatures. (a) Continental extratropical warm season from tree ring analysis [*Briffa et al.*, 2001]. (b) Continental extratropical cold season from combined analysis of tree ring and borehole temperature records. (c) Preferred continental extratropical annual temperatures.

records is consistent with 200-year cold season reconstructions for China and Europe [*Jones et al.*, 2003] and 500-year multiproxy reconstructions for Europe [*Luterbacher et al.*, 2004].

[16] Stratospherically dynamic models indicate that prior to the onset of global anthropogenic warming, variations in total solar irradiance [*Lean*, 2000] produce the greatest external forcing [*Shindell et al.*, 2001] and explain much of the low-frequency variability in Northern Hemisphere temperatures [*Crowley*, 2000; *Shindell et al.*, 2003]. Prolonged periods of reduced solar activity (e.g., the Maunder Minimum) are associated with pronounced cooling over midlatitude to high-latitude continental interiors [*Shindell et al.*, 2003]. Enhanced solar irradiance increases midlatitude sea level pressure, generating enhanced westerly advection of relatively warm oceanic air over the continents and of cooler air from continental interiors to their eastern coasts [*Shindell et al.*, 2003]. This effect is most pronounced in the cold season. The recovered cold season warming trend is consistent with increasing solar irradiance at the end of the 17th century and through the first half of the 18th century that may have induced a shift toward a high Arctic Oscillation index [*Cook et al.*, 2002].

[17] We have advanced the idea that part of the discrepancy between warming estimates derived from borehole temperatures and tree rings may be due to the seasonality of tree rings. This idea stems from the excellent agreement between the mean reduced temperature profile and the annual SAT series, the good correlation between the tree ring series of *Briffa et al.* [2001] and the warm season SAT series, and the assumption that these signals are mostly stationary in time. Other sources of this discrepancy may stem from standardization techniques implicit in tree ring analysis [*Cook et al.*, 1995] and from poor noise suppression and inadequate spatial representation of regression-based multiproxy reconstructions [*von Storch et al.*, 2004]. In a recent study, *Moberg et al.* [2005] showed that when climatic indicators containing high- and low-frequency information are combined in a way to preserve the best temporal characteristics of each, estimates of warming compare well with those estimated from borehole temperature data.

4. Conclusions

[18] We have advanced a technique for producing a Northern Hemisphere reconstruction consistent with the seasonality of tree ring derived temperature and temperature-depth profiles. This technique also yields a cold season temperature reconstruction that suggests Northern Hemispheric temperatures are more sensitive to external forcing in the cold season. We estimate annual and cold season warming of 0.2° ± 0.1°C and 0.4° ± 0.3°C, respectively, between 1500 and 1856. Subsequent to 1856 the SAT record indicates annual warming and cold season warming of 0.82° and 1.13°C, respectively [*Jones and Moberg*, 2003]. This reconstruction indicates that the late 20th century is warmer relative to the past 500 years than previously thought and suggests that the climate has greater sensitivity to external forcings. These results are consistent with previous findings of recent global warming and its causes in that since the onset of the industrial revolution, temperatures appear to be rising at an unprecedented rate [*Briffa et al.*, 2004; *Jones and Mann*, 2004].

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D. S. Chapman, Department of Geology and Geophysics, University of Utah, Salt Lake City, UT 84102, USA.

R. N. Harris, College of Oceanic and Atmospheric Sciences, Oregon State University, 104 COAS Admin Building, Corvallis, OR 97331-5503, USA. (rharris@coas.oregonstate.edu)