Northern Hemisphere Temperatures During the Past Millennium: Inferences, Uncertainties, and Limitations

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Abstract. Building on recent studies, we attempt hemispheric temperature reconstructions with proxy data networks for the past millennium. We focus not just on the reconstructions, but the uncertainties therein, and important caveats. Though expanded uncertainties prevent decisive conclusions for the period prior to AD 1400, our results suggest that the latter 20th century is anomalous in the context of at least the past millennium. The 1990s was the warmest decade, and 1998 the warmest year, at moderately high levels of confidence. The 20th century warming counters a millennial-scale cooling trend which is consistent with long-term astronomical forcing.

Introduction

Estimates of climate variability during past centuries must rely upon indirect "proxy" indicators–natural archives that record past climate variations. Trends over several centuries are evident in the recession of glaciers [Grove and Switsur, 1994], and the sub-surface information from boreholes [Pollack et al, 1998]. Annual climate estimates, however, require proxies such as tree rings, varved sediments, ice cores, and corals (combined with any available instrumental or historical records), which record seasonal/annual variations. Studies based on such "multiproxy" data networks [e.g., Bradley and Jones, 1993; Hughes and Diaz, 1994; Mann et al, 1995] have allowed the 20th century climate to be placed in a longer-term perspective, thus allowing for improved estimates of the influence of climate forcings [Lean et al, 1995; Crowley and Kim, 1996; Overpeck et al, 1997], and validation of the low-frequency behavior exhibited by climate models [e.g., Jones et al, 1998].

Recently, Mann et al [1998–henceforth "MBH98"] reconstructed yearly global surface temperature patterns back in time through the calibration of multiproxy networks against the modern temperature record. Skillful reconstruction of Northern Hemisphere mean annual surface temperature ("NH") was possible back to AD 1400, as the pattern of

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surface temperature most readily calibrated by the available multiproxy network corresponds largely to synchronous large-scale temperature variation. It has been speculated that temperatures were warmer even further back, ~1000 years ago–a period described by Lamb [1965] as the Medieval Warm Epoch (though Lamb, examining evidence mostly from western Europe, never suggested this was a global phenomenon). We here apply the methodology detailed by MBH98 to the sparser proxy data network available prior to AD 1400, to critically revisit this issue, extending NH reconstructions as far back as is currently feasible. We also reevaluate earlier estimates of uncertainties in the NH series.

Data and Method

The multiproxy data network and instrumental temperature data used to calibrate it are discussed in detail by MBH98 (see supplementary information therein). Before AD 1400, only 12 indicators of the more than 100 described by MBH98 are available. This includes the first 3 principal components (PCs) of the (28) dendroclimatic series available back to AD 1000 in the International Tree Ring Data Bank ("ITRDB")–all from North America. The 12 indicators (14 counting two nearby ice core sites) are summarized in Table 1.

The calibration procedure (see MBH98) invokes the assumptions (1) that a linear relationship exists between proxy climate indicators and and some combination of large-scale temperature patterns, and (2) that patterns of surface temperature in the past can be suitably described in terms of some linear combination of the dominant present-day surface temperature patterns. MBH98 performed extensive cross-validation experiments to verify the reliability of the reconstruction using global temperature data from 1854-1901 withheld from (1902-1980) calibration, and, further back, by the small number of instrumental temperature series available back through the mid-18th century.

In using the sparser dataset available over the entire millennium (Table 1), only a relatively small number of indicators are available in regions (e.g., western North America) where the primary pattern of hemispheric mean temperature variation has significant amplitude (see Fig. 2 in MBH98), and where regional variations appear to be closely tied to global-scale temperature variations in model-based experiments [Bradley, 1996]. These few indicators thus take on a particularly important role (in fact, as discussed below, one such indicator– PC #1 of the ITRDB data–is found to be essential), in contrast with the post AD 1400 reconstructions of MBH98 for which indicators are available in several key regions [e.g., the North American northern treeline ("NT") dendroclimatic chronologies of Jacoby and D'Arrigo, 1989].

Due to the leverage of ITRDB PC #1 in the millennial reconstruction, any non-climatic influence must first be removed before it can meaningfully be used in the reconstructions. Spurious increases in variance back in time associated with decreasing sample sizes [see e.g. Jones et al, 1998] are not an issue with this series, owing to the high degree of replication in the underlying chronologies back to AD 1000. A number of the highest elevation chronologies in the western U.S. do appear, however, to have exhibited long-term growth increases that are more dramatic than can be explained by instrumental temperature trends in these regions. Graybill and Idso [1993] suggest that such high-elevation, CO_2-limited trees, in moisture-stressed environments, should exhibit a growth response to increasing CO_2 levels. Though ITRDB PC #1 shows significant loadings among many of the 28 constituent series, the largest are indeed found on high-elevation western U.S. sites. The ITRDB PC#1 is shown along with that of the composite NT series, during their 1400-1980 period of overlap (Figure 1). The low-frequency coherence of the ITRDB PC#1 series and composite NT series during the initial four centuries of overlap (1400-1800)is fairly remarkable, considering that the two series record variations in entirely different environments and regions. In the 19th century, however, the series diverge. As there is no *a priori* reason to expect the CO_2 effect discussed above to apply to the NT series, and, furthermore, that series has been verified through cross-comparison with a variety of proxy series in nearby regions [Overpeck et al, 1997], it is plausible that the divergence of the two series, is related to a CO_2 influence on the ITRDB PC #1 series. The residual is indeed coherent with rising atmospheric CO_2 (Figure 1b), until it levels off in the 20th century, which we speculate may represent a saturation effect whereby a new limiting factor is established at high CO_2 levels. For our purposes, however, it suffices that we consider the residual to be non-climatic in nature, and consider the ITRDB PC #1 series "corrected"' by removing from it this residual, forcing it to align with the NT series at low frequencies throughout their mutual interval of overlap. This correction is independently justified by the fact that temperatures averaged over the NT region and western U.S. region dominating ITRDB PC #1 exhibit very similar low-frequency trends this century (not shown).

Verification and Consistency Checks

The calibration/verification statistics for reconstructions based on the 12 indicators available back to AD 1000, are, as expected, somewhat degraded relative to those for the post AD 1400 period. The calibration and verification resolved variance (39% and 34% respectively) are consistent with each other, but lower than for reconstructions back to AD 1400 (42% and 51% respectively–see MBH98). Results further back than a millennium, based on even sparser data (see Table 1) are yet further degraded. With only a single eigenvector of the instrumental temperature data (#1– see Figure 2 in MBH98) skillfully resolved by the network available back to AD 1000, the total *spatial* variance calibrated is far more modest than that for the NH mean ($\approx$ 5% in calibration and verification). Thus, the NH series, but not the spatial details, are most meaningful in the millennial reconstructions.

Further consistency checks are required. The most basic involves checking the potential resolvability of long-term variations by the underlying data used. An indicator of climate variability should exhibit, at a minimum, the red noise spectrum the climate itself is known to exhibit [see Mann and Lees, 1996 and references therein]. A significant deficit of power relative to the median red noise level thus indicates a possible loss of true climatic variance, with a deficit of zero frequency power indicative of less trend than expected from noise alone, and the likelihood that the longest ("secular") timescales under investigation are not adequately resolved. Only 5 of the indicators (including the ITRDB PC #1, Polar Urals, Fennoscandia, and both Quelccaya series) are observed to have at least median red noise power at zero frequency for the pre-calibration (AD 1000-1901) period. It is furthermore found that only one of these series–PC #1 of the ITRDB data–exhibits a significant correlation with the time history of the dominant temperature pattern of the 1902-1980 calibration period. Positive calibration/variance scores for the NH series cannot be obtained if this indicator is removed from the network of 12 (in contrast with post-AD 1400 reconstructions for which a variety of indicators are available which correlate against the instrumental record). Though, as discussed earlier, ITRDB PC#1 represents a vital region for resolving hemispheric temperature trends, the assumption that this relationship holds up over time nonetheless demands circumspection. Clearly, a more widespread network of quality millennial proxy climate indicators will be required for more confident inferences.

A further consistency check involves examining the calibration residuals. In Figure 2 we show the power spectrum of the residuals of the NH calibration from 1902-1980 for both the calibrations based on all indicators in the network available back to 1820 (see MBH98), and the calibrations based on the 12 indicators available back to AD 1000. Not only (as indicated earlier) is the calibrated variance lower for the millennial reconstruction, but there is evidence of possible bias. While the residuals for the post-AD 1820 reconstructions are consistent with white noise (at no frequency does the spectrum of the residuals breach the 95% significance level for white noise–this holds in fact back to AD 1600), a roughly five-fold increase in unresolved variance is observed at secular frequencies (>99% significant) for the millennial reconstruction. In contrast to MBH98 where uncertainties were self-consistently estimated based on the observation of Gaussian residuals, we here take account of the spectrum of unresolved variance, separately treating unresolved components of variance in the secular (longer than the 79 year calibration interval in this case) and higher-frequency bands. To be conservative, we take into account the slight, though statistically insignificant inflation of unresolved secular variance for the post-AD 1600 reconstructions. This procedure yields composite uncertainties that are moderately larger than those estimated by MBH98, though none of the primary conclusions therein are altered.

Temperature Reconstruction

The reconstructed NH series and estimated uncertainties are shown in Figure 3, along with its associated power spectrum. The substantial secular spectral peak is highly significant relative to red noise, associated with a long-term cooling trend in the NH series prior to industrialization ($\delta T = -0.02^o$C/century). This cooling is possibly related to astronomical forcing, which is thought to have driven long-term temperatures downward since the mid-Holocene at a rate within the range of -0.01 to -0.04^{o}C/century [see Berger, 1988]. In addition, significant century-scale variability may be associated with solar irradiance variations [see Lean et al, 1995; MBH98], and a robust spectral peak centered at 50-70 year period seems to correspond to a multidecadal climate signal discussed by Mann et al [1995].

The 20th century (1900-1998) (anomaly of $\overline{T} = 0.07^o$C relative to the 1902-1980 calibration period mean) is nominally the warmest of the millennium (11-12th: -0.04; 13th: -0.09, 14th: -0.07; 15th: -0.19; 16th: -0.14; 17th: -0.18; 18th : -0.14; 19th:-0.21). Expanded uncertainties in centennial means prior to AD 1600, and warmer conditions during the earlier centuries of the millennium, however, preclude a definitive statement prior to AD 1400–the 11th and 12th centuries are within a (centennial) standard error of the 20th century. The late 11th, late 12th, and late 14th centuries rival *mean* 20th century temperature levels (see Figure 3a). Our reconstruction thus supports the notion of relatively warm hemispheric conditions earlier in the millennium, while cooling following the 14th century could be viewed as the initial onset of the Little Ice Age *sensu lato*. Considerable spatial variability is evident however [see Hughes and Diaz, 1994] and, as in in Lamb's [1965] original concept of a Medieval Warm Epoch, there are episodes of cooler as well as warmer conditions punctuating this period. Even the warmer intervals in our reconstruction pale, however, in comparison with *modern* (mid-to-late 20th century) temperatures. For the NH series, both the past year (1998) and past decade (1989-1998) are well documented as the warmest in the 20th century instrumental record. Furthermore, the past decade ($\overline{T} = 0.45^o$C) is nearly two (decadal) standard errors warmer than the next warmest decade prior to the 20th century (1166-1175: $\overline{T}$=0.11), and 1998 ($T = 0.78^o$C) more than two standard errors warmer than the next warmest year (1249 with an anomaly $T = 0.27^o$C; 1253 and 1366 with $T \approx 0.25^o$C are the only other two years approaching typical modern warmth), supporting the conclusion that both the past decade and past year are likely the warmest for the Northern Hemisphere *this millennium*. The recent warming is especially striking if viewed as defying a long-term cooling trend associated with astronomical forcing.

Conclusions

Although NH reconstructions prior to about AD 1400 exhibit expanded uncertainties, several important conclusions are possible, notwithstanding certain caveats. While warmth early in the millennium approaches *mean* 20th century levels, the late 20th century still appears anomalous: the 1990s are likely the warmest decade, and 1998 the warmest year, in at least a millennium. More widespread high-resolution data which can resolve millennial-scale variability are needed before more confident conclusions can be reached with regard to the spatial and temporal details of climate change in the past millennium and beyond.

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Table 1. 12 Proxy Indicators Available Back to AD 1000. Description ("SERIES"–see MBH98 for details regarding data and reference), location ("LOC"–region or lat/lon coordinates, start year ("y_0") AD, and type ("TYPE") of series is indicated. These data (and the NH series discussed in the text) are available over the internet through the World Data Center-A for Paleoclimatology (http://www.ngdc.noaa.gov/paleo/paleo.html).

SERIES	LOC	y_0	TYPE
ITRDB (PC #1)	N. Amer	1000	T. Ring width
ITRDB (PC #2)	N. Amer	1000	T. Ring width
ITRDB (PC #3)	N. Amer	1000	T. Ring width
Fennoscandia	68N 23E	500	T. Ring density
Polar Urals	67N 65E	914	T. Ring density
Tasmania	43S 148E	900	T. Ring width
N. Patagonia	38S 68W	869	T. Ring width
Morocco	33N 5W	984	T. Ring width
France	44N 7E	988	T. Ring width
Greenland stacked core	77N 60W	553	ice core $\delta^{18}O$
Quelccaya (2)	14S 71W	488	ice core $\delta^{18}O$
Quelccaya (2)	14S 71W	488	ice accum.

Figure 1. Comparison of ITRDB PC#1 and NT series. (a) composite NT series vs. ITRDB PC #1 series during AD 1400-1980 overlap. Thick curves indicate smoothed (75 year low-passed) versions of the series. The smoothed "corrected" ITRDB PC #1 series (see below) is shown for comparison, (b) Residual between the smoothed NT and ITRDB series, and its secular trend (retaining timescales longer than 150 years). Relative variations in atmospheric CO_2 since AD 1700 are shown for comparison.

Figure 2. Spectrum of NH series calibration residuals from 1902-1980 for post-AD 1820 (solid) and AD 1000 (dotted) reconstructions (scaled by their mean white noise levels). Median and 90%,95%,and 99% significance levels (dashed lines) are shown.

Figure 3. Millennial temperature reconstruction. (a) NH reconstruction (solid) and raw data (dotted) from AD 1000-1998. Smoothed version of NH series(thick solid), linear trend from AD 1000-1850 (dot-dashed) and two standard error limits (shaded) are also shown. (b) Power spectrum of the NH series based on full (AD 1000-1980) and pre-calibration (AD 1000-1901) intervals. Robustly estimated median and 90%, 95%, and 99% significance levels relative to red noise are shown [see Mann and Lees, 1996].

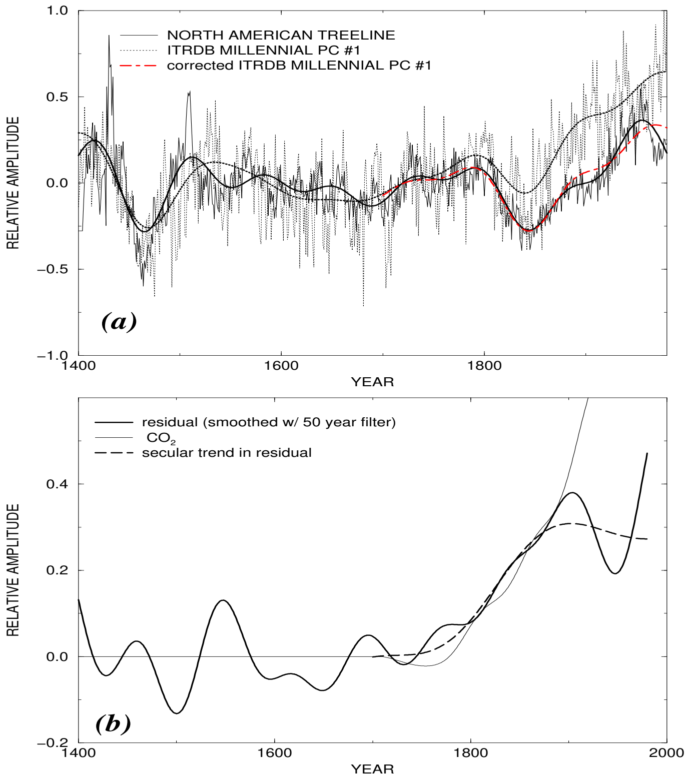
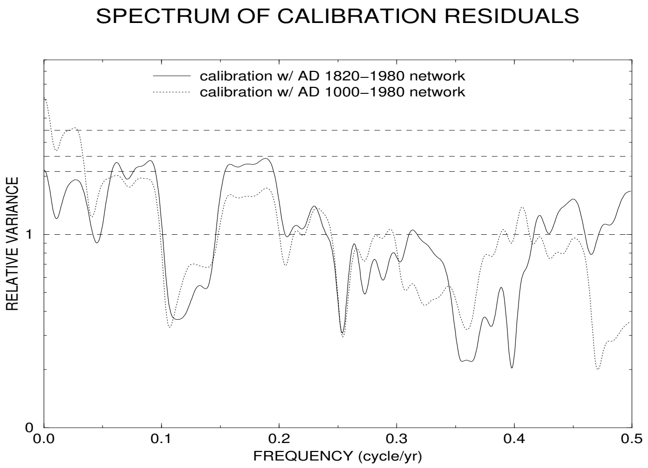
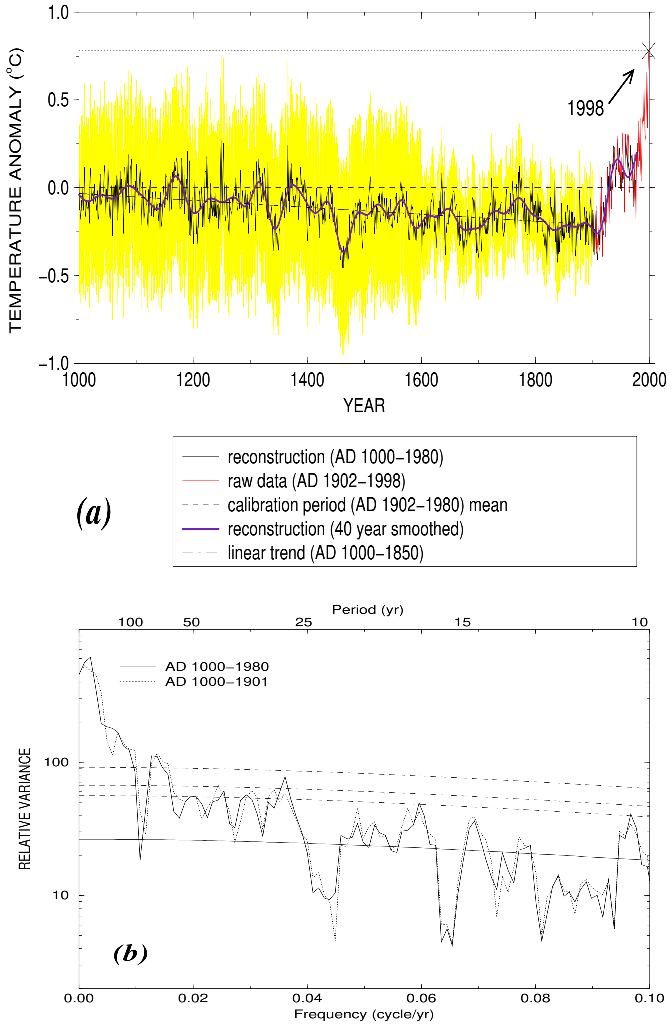


Figure 1



SPECTRUM OF CALIBRATION RESIDUALS
calibration w/ AD 1820−1980 network
calibration w/ AD 1000−1980 network
RELATIVE VARIANCE
1
0
0.0
0.1
0.2
0.3
0.4
0.5
FREQUENCY (cycle/yr)

Figure 2



TEMPERATURE ANOMALY (°C)
1.0
0.5
0.0
−0.5
−1.0
1998
1000
1200
1400
1600
1800
2000
YEAR
reconstruction (AD 1000−1980)
raw data (AD 1902−1998)
calibration period (AD 1902−1980) mean
reconstruction (40 year smoothed)
linear trend (AD 1000−1850)
(a)
Period (yr)
100
50
25
15
10
AD 1000−1980
AD 1000−1901
RELATIVE VARIANCE
100
10
(b)
0.00
0.02
0.04
0.06
0.08
0.10
Frequency (cycle/yr)

Figure 3