

## Global surface temperatures over the past two millennia

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[1] We present reconstructions of Northern and Southern Hemisphere mean surface temperature over the past two millennia based on high-resolution 'proxy' temperature data which retain millennial-scale variability. These reconstructions indicate that late 20th century warmth is unprecedented for at least roughly the past two millennia for the Northern Hemisphere. Conclusions for the Southern Hemisphere and global mean temperature are limited by the sparseness of available proxy data in the Southern Hemisphere at present. **INDEX TERMS:** 1620 Global Change: Climate dynamics (3309); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4221 Oceanography: General: Dendrochronology; 4215 Oceanography: General: Climate and interannual variability (3309). **Citation:** Mann, M. E., and P. D. Jones, Global surface temperatures over the past two millennia, *Geophys. Res. Lett.*, 30(15), 1820, doi:10.1029/2003GL017814, 2003.

### 1. Introduction

[2] It is important to place modern climate warming in a longer-term context. A number of previous studies have thus focused on climate change of the past few centuries to millennium, based both on modeling experiments employing estimated climate forcings [e.g., Crowley, 2000; Gerber *et al.*, 2003] and empirical reconstructions based on climate proxy data. The requirements for the latter such reconstructions are (a) high (annual to decadal) resolution and exact dating, so that proxy records may be calibrated against instrumental data, (b) reliability of the low-frequency information so that millennial-scale variability can be faithfully reconstructed, and (c) adequate spatial distribution of data so that the regionally-variable nature of past climate variability [e.g., Bradley and Jones, 1993] is appropriately taken into account in reconstructing a large-scale (e.g., hemispheric) mean. It is also important to keep in mind the seasonality of proxy indicators in forming a climate reconstruction [see Jones *et al.*, 1998; 2001; Mann, 2002; Mann *et al.*, 2003].

[3] Several recent studies emphasize spatial reconstruction of climate fields, typically based on multivariate climate field reconstruction (CFR) techniques [e.g., Mann *et al.*, 1998; 1999; Luterbacher *et al.*, 2002; Evans *et al.*, 2002]. Such spatial reconstructions of past surface temperature can be averaged to yield hemispheric mean temperature estimates [Mann *et al.*, 1998; Briffa *et al.*, 2001]. Other hemispheric mean temperature reconstructions have employed a more

elementary approach, in which various temperature proxy records are composited (perhaps after applying some weighting factor) and then simply scaled against the available overlapping instrumental record to yield a hemispheric reconstruction [Bradley and Jones, 1993; Overpeck *et al.*, 1997; Jones *et al.*, 1998; Crowley and Lowery, 2000]. The similarity of these latter reconstructions to those determined based on more elaborate approaches [e.g., Folland *et al.*, 2001; Mann, 2002] suggests that the more elementary approach can yield a reliable reconstruction. Previous work has emphasized the Northern Hemisphere, and the past 1000 years for which adequate proxy data have been available for hemispheric mean temperature reconstructions. Preliminary reconstructions of Southern Hemisphere temperatures in past centuries have also been attempted [Jones *et al.*, 1998; 2001; Mann *et al.*, 2000].

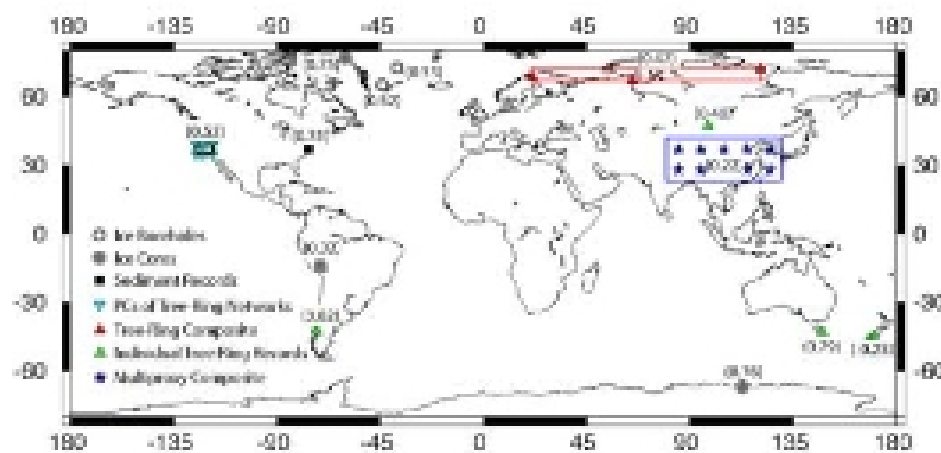
[4] During the past few years, a number of additional long, high-resolution (annual or decadal) temperature proxy reconstructions (or extensions of previous, shorter records) with reliable millennial-scale variability have been produced. These new records allow an extension of proxy-based hemispheric mean temperature reconstructions for both hemispheres. Such extensions are the focus of this study.

### 2. Data

[5] For the Northern Hemisphere (NH), we make use of temperature reconstructions from 8 distinct regions (based on 23 individual proxy records). Each employs either indicators (e.g., sediments and ice cores) with no known limitations in resolving millennial-scale variability, or tree-ring records in which various 'conservative' standardization methods have been used, which, though not all identical, share the common aim of seeking to preserve millennial-scale temperature variability. Since some of the proxy indicators may contain non-temperature influences, the variable reliability of the temperature signal in different proxy estimates is dealt with in our methodology (section 3). The available dataset, though modest in size, samples a range of seasons, tropical through polar latitudes, both major continents, and marine as well as terrestrial environments in the Northern Hemisphere (Figure 1). The data set includes:

[6] (1) multiproxy composite reconstruction of annual mean temperatures over eastern Asia back to 1 AD based on a composite of 11 historical, lake sediment, tree-ring, and ice core proxy records from China, Japan, the Tibetan Plateau, and Taiwan [Yang *et al.*, 2002].

[7] (2) conservatively standardized tree-ring temperature reconstruction from Mongolia (annual mean temperatures back to AD 264 [D'Arrigo *et al.*, 2001]).



**Figure 1.** Locations of temperature proxy records used in this study. Correlations (decadal timescale over 1901–80) with local instrumental temperature grid-box data are indicated in parentheses next to the associated symbol/s.

[8] (3) northern Eurasia tree-ring temperature reconstruction (warm-season temperature back to AD [Briffa and Osborn, 1999]; the record is a composite of 3 ring-width chronologies processed using Regional Curve Standardization (RCS) [see Briffa *et al.*, 2001, and references therein] spanning the Eurasian treeline, and includes the two longest series used by Esper *et al.*, 2002 in their reconstruction of extratropical Northern Hemisphere summer temperature).

[9] (4) western North American tree-ring temperature reconstruction, (warm season temperature [Mann *et al.*, 1999]; we employ an extension of the first principal component of the western North American tree-ring data based on 6 ultra-long lived, temperature-sensitive Western North American tree ring records available back to AD 200—the resulting series is virtually indistinguishable from the corresponding Principal Component (PC) series used by Mann *et al.*, [1999] based on 27 available chronologies during the AD 1000–1980 overlap interval).

[10] (5) A decadal-resolution reconstruction of coastal eastern North American (spring) temperatures back to 200 BC based on Mg/Ca paleothermometry from fossil shells in the Chesapeake Bay [Cronin *et al.*, 2003].

[11] (6) Stacked ice core oxygen isotope record from west Greenland back to AD 553 [putative annual temperature; Fisher *et al.*, 1996].

[12] Finally, though they provide more limited (multi-decadal) temporal resolution for calibration against the instrumental record, we also perform analyses which additionally include ice borehole (annual) temperature reconstructions [Dahl-Jensen *et al.*, 1998] from:

[13] (7) Southern Greenland (Dye3).

[14] (8) Central Greenland (GRIP).

[15] Fewer long series are available for the Southern Hemisphere (SH), where we make use of temperature reconstructions from 5 distinct regions. As for the Northern Hemisphere, the proxy data set spans tropical, subtropical, and polar regions of the Southern Hemisphere. The data include:

[16] (1) conservatively standardized (RCS) tree-ring warm-season temperature reconstructions for Tasmania back to 1600 BC [Cook *et al.*, 2000];

[17] (2) southern South America tree-ring reconstruction back to AD 869 (warm season; [Lara and Villalba, 1993] conservatively re-standardized based on 500 year spline by P. Jones, unpublished).

[18] (3) ‘RCS’-based tree-ring temperature reconstruction [warm-season; Cook *et al.*, 2002] for southern New Zealand back to AD 900.

[19] (4) ice core oxygen isotope temperature estimates for Law Dome, Antarctica, back to 100 BC (putative annual temperature [T. Van Ommen *et al.*, in prep]).

[20] (5) ice core oxygen temperature estimates for Quelccaya, Peru back to AD 470 (putative annual temperature [Thompson, 1992]).

### 3. Methods

[21] Composites were performed separately for both hemispheres, based on the available regional temperature records (8 for the NH, 5 for the SH). Each regional temperature record was standardized by removal of the long-term mean and division by the standard deviation after decadal smoothing (lowpass filtering at  $f = 0.1$  cycle/year). The latter step emphasizes the timescales (decadal and longer) on which the reconstructions are most reliable, given the possible uncertainties in annual dating for certain proxy data used (NH records #5, 7, 8 and SH record #4 and 5).

[22] A flawed recent study [Soon and Baliunas, 2003, hereafter referred to as ‘SB03’] compels us to stress two points which might seem patently obvious: (1) It is essential to assess each proxy series for sensitivity to past temperature variability and not, as in SB03, to equate hydrological influences with temperature influences; (2) It is also essential (e.g., by compositing records) to distinguish between regional anomalies, which often cancel in a hemispheric mean, and not, as in SB03, to equate (e.g., the existence of asynchronous warm anomalies in different regions with a hemispheric mean warm anomaly).

[23] Composite series were formed from weighted combinations of the individual standardized proxy series, employing weights on the individual records that account for the size of the region sampled, and the estimated reliability of the temperature signal as determined by comparison with the instrumental surface temperature record [Jones *et al.*, 1999]. Local (decadal) correlations were calculated between each proxy record and the instrumental grid-box surface temperature records for the regions they represent over the period 1901–1980 (see Figure 1). Proxy records exhibiting negative or approximately zero local correlations (SH record #2 and #3) were eliminated from further consideration in the study. Alternatively, reliability was determined from the correlation of the proxy series against the target (SH or NH) instrumental decadal hemispheric mean series. For reference, an area-weighted average of the instrumental data over the regions sampled by the proxy network (8 regions for NH and 3 for SH) yield extremely high decadal correlations with the associated full hemispheric mean instrumental series [ $r^2 = 0.73$  (0.60) for the NH (SH) during the 1901–1980 period].

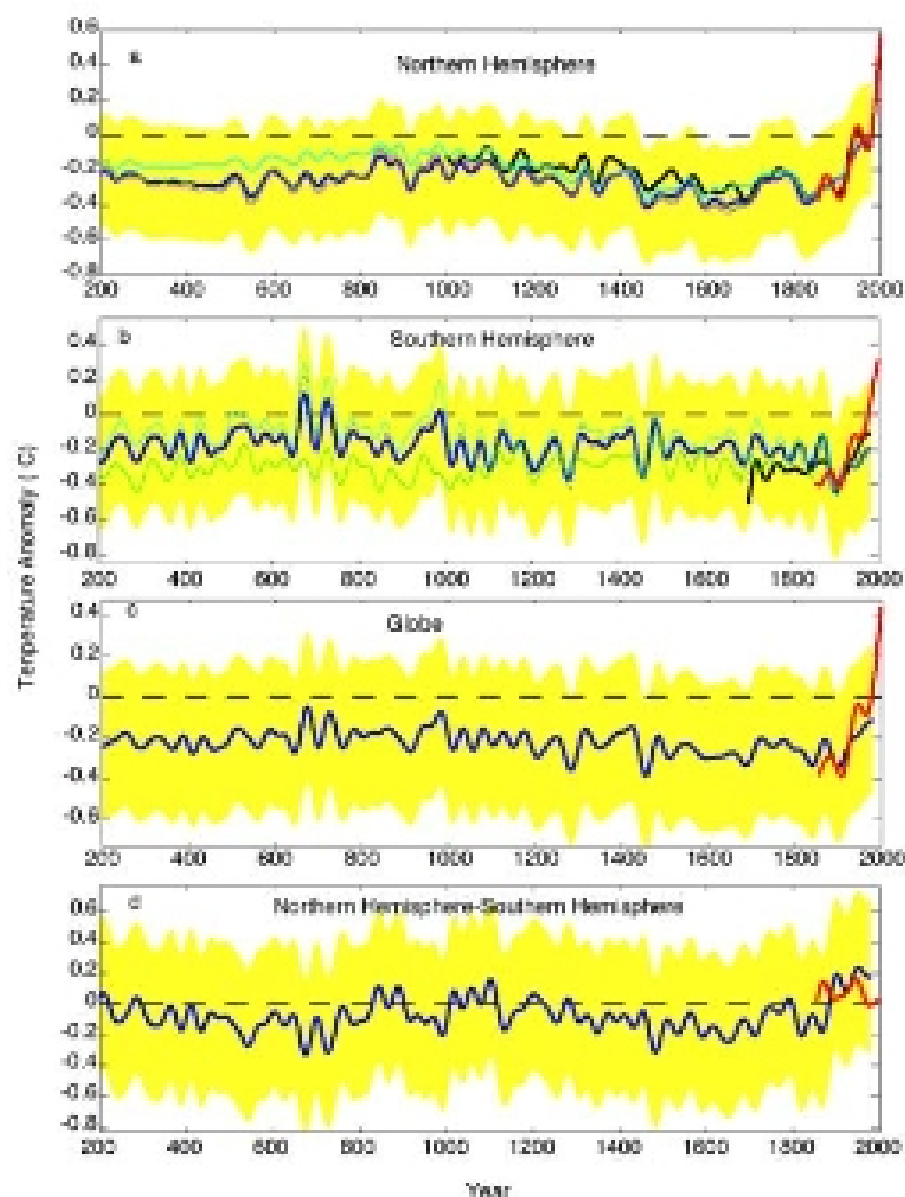
[24] The hemispheric and global composites were standardized to have the same mean and (decadal) standard deviation as the target instrumental hemispheric mean series over the period of common overlap (1856–1980). While our ‘standard’ reconstruction involved area and local-correlation weighted composites, the sensitivity to the weighting scheme was also examined. Calibration resolved variance ( $\beta$ ) [see e.g., Mann *et al.*, 1998] was conservatively

estimated from the detrended decadal data variance resolved in the instrumental record. These yield values  $\beta = 0.37$  ( $\beta = 0.29$ ) for the NH (SH). Rough uncertainty estimates in the hemispheric reconstructions were determined from the magnitude of the unresolved variance during the calibration period, taking into account enhancement of uncertainty at centennial timescales [Mann *et al.*, 1999].

[25] Unlike annually-calibrated reconstructions for which the 20th century instrumental record can be used for calibration, while independent 19th century data is withheld for cross-validation [e.g., Mann *et al.*, 1998], decadal-resolution reconstructions require the use of the extended (1856–1980) instrumental record for an appropriately constrained scaling, leaving no hemispheric-scale instrumental record available for cross-validation. However, previous, more highly (annually) resolved hemispheric temperature reconstructions available back to AD 1000 which have already been successfully cross-validated against the instrumental record [e.g., Mann *et al.*, 1999] provide a means for longer-term cross-validation. We use for cross-validation, in the case of the NH, a simple composite of three previous millennial temperature reconstructions [Jones *et al.*, 1998; Mann *et al.*, 1999; Crowley and Lowery, 2000] and for the SH case, a more tentative composite of the Mann *et al.* [2000] and Jones *et al.* [1998] SH reconstructions, which is available back to 1700. This gives a cross-validation of  $\beta = 0.77$  ( $r^2 = 0.57$ ) for the NH for the period AD 1600–1855 ( $\beta = 0.16$  for the full period from AD 1000, likely due to expanded uncertainties in the reconstructions contributing to the composite [e.g., Mann *et al.*, 1999]). As a cross-check, an NH extratropical warm-season temperature reconstruction based on entirely independent (tree ring density) data [Briffa *et al.*, 2001], yielded a highly significant correlation  $r^2 = 0.3$  with the NH reconstruction during the overlap interval (1402–1960). For the SH, the verification statistics (available for the interval 1700–1855) are lower ( $r^2 = 0.16$ ), probably due to greater uncertainty in both series being compared.

#### 4. Results and Discussion

[26] The proxy data used here reflect temperature variations over a range of seasons, and, broadly speaking, are best interpreted in terms of annual conditions (though there may be some residual seasonal emphasis). The reconstructions are presented in Figure 2. The NH reconstruction (Figure 2a) is observed to be largely insensitive to the elimination of the shorter proxy records, or to the precise nature of the weighting of records, suggesting that the result shown back to AD 200 is fairly robust. Only when indicators are not areally weighted (in which case the Greenland borehole data carry considerably greater weight) is a notably different result obtained, and even then, primarily prior to AD 800. The reconstruction is consistent with previous reconstructions (and model simulations [e.g., Mann, 2002]) of NH mean temperatures over the past millennium within estimated uncertainties. The amplitude of variability is notably less than that implied in some reconstructions emphasizing only the mid-latitude continental regions and the summer season [Esper *et al.*, 2002], underscoring the importance of taking into account seasonal and spatial sampling in comparisons of alternative reconstructions. In the nearly two millennium context afforded by the NH reconstruction presented here, the broad period from



**Figure 2.** Hemispheric temperature reconstructions ('standard reconstructions' based on area and local correlation weighting, shown as thick blue). All series are anomalies based on 1961–1990 instrumental reference period (mean shown by dashed line), and smoothed with a 40 year lowpass filter. Smoothed instrumental series are shown by thick red curve (the constraint employed by the filter preserves the late 20th century trend). 95% confidence intervals for the standard reconstructions are shown by yellow shading. (a) NH reconstruction based on 6 indicators available back to AD 200. Also shown are NH reconstructions based on areal and hemispheric correlation weighting (green), areal weighting only (magenta), local-correlation weighting only (cyan) [blue dotted curve shows standard reconstruction based on all 8 indicators available back to AD 553]. Shown for comparison is millennial composite of previous shorter reconstructions discussed in text (thick black). (b) SH reconstruction based on 2 indicators back to AD 200 (thick blue) and 3 indicators back to AD 470 (blue dotted). Other weighting schemes shown using color convention of (a). Shown for comparison is multi-century composite of previous reconstructions discussed in text (thick black). (c) global mean (average of NH and SH) surface temperature reconstruction, and (d) interhemispheric temperature contrast (Northern minus Southern Hemisphere mean).

approximately AD 800–1400 is observed to be moderately warmer than multi-century periods both preceding and following it. This warmth is, however, dwarfed by late 20th century warmth which is observed to be unprecedented at least as far back as AD 200. The coldest periods are the 6th, 15th, 17th, and 19th centuries.