

Merging information from different resources for new insights into climate change in the past and future

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[1] An understanding of climate history prior to industrialization is crucial to understanding the nature of the 20th century warming and to predicting the climate change in the near future. This study integrates the complementary information preserved in the global database of borehole temperatures [Huang *et al.*, 2000], the 20th century meteorological record [Jones *et al.*, 1999], and an annually resolved multi proxy model [Mann *et al.*, 1999] for a more complete picture of the Northern Hemisphere temperature change over the past five centuries. The integrated reconstruction shows that the 20th century warming is a continuation to a long-term warming started before the onset of industrialization. However, the warming appears to have been accelerated towards the present day. Analysis of the reconstructed temperature and radiative forcing series [Crowley, 2000] offers an independent estimate of the transient climate-forcing response rate of 0.4–0.7 K per Wm^{-2} and predicts a temperature increase of 1.0–1.7 K in 50 years. **INDEX TERMS:** 1600 Global Change; 1620 Global Change: Climate dynamics (3309); 1645 Global Change: Solid Earth; 5418 Planetology: Solid Surface Planets: Heat flow. **Citation:** Huang, S. (2004), Merging information from different resources for new insights into climate change in the past and future, *Geophys. Res. Lett.*, 31, L13205, doi:10.1029/2004GL019781.

1. Introduction

[2] Because of the short duration of the worldwide instrumental record, an understanding of climate history in the pre-industrial era relies principally on climate proxies. Each disciplinary approach to a paleoclimate reconstruction has its own strengths and limitations in representing past climate variability. For example, tree-ring analyses, which play a crucial role in conventional proxy-based climate reconstructions [Jones *et al.*, 1998; Mann *et al.*, 1999; Briffa *et al.*, 2001; Crowley and Lowery, 2000; Briffa and Osborn, 2002; Esper *et al.*, 2002; Mann and Jones, 2003], can do an excellent job in recovering inter-annual and decadal variability, but it is usually more difficult to determine a long term trend, obstructed by the detrending treatment of the growth effect of aging. By contrast, a paleoclimate reconstruction derived from borehole temperatures is characterized by a progressive inability to resolve climatic excursions in the more remote past. The resolving power of a borehole-based reconstruction is not only restricted by the diffusive nature of heat transfer, but also dependent on the level of non-climatic perturbations and the

numerical technique applied in the reconstruction [see Pollack and Huang, 2000].

[3] Along with a growing awareness of the limitations of individual proxies, there is an increasing appreciation of the need for inter-comparison and inter-validation of reconstructions derived from different disciplinary approaches [Beltrami *et al.*, 1995; Overpeck, 2000; Broecker, 2001; Jones *et al.*, 2001]. Here I present a reconstruction of the Northern Hemisphere surface temperature history over the past five centuries through integrated analysis of 696 borehole temperature profiles, the 20th century meteorological record [Jones *et al.*, 1999], and an annually resolved multi-proxy reconstruction [Mann *et al.*, 1999].

2. Borehole Data and Borehole Based Reconstruction

[4] With support from the international heat flow community, a global database of borehole temperature logs has been constructed as an archive of geothermal signals of climate change [Huang and Pollack, 1998]. Currently the database contains 861 borehole temperature profiles, of which 696 are located in the Northern Hemisphere (Figure 1). The geographic coverage is densest in North America and Europe, with substantial datasets from Asia.

[5] I take a standardized borehole data inversion approach [Huang *et al.*, 1996, 2000], which is independent of any other proxy or meteorological records, to derive long-term climate information from each of the 696 borehole data sets. The individual borehole-based reconstructions are then assembled for a Northern Hemisphere representation via various averaging schemes (Table 1).

[6] From a Northern Hemisphere perspective, the 696 boreholes suggest a cumulative change of around 0.9°C over the period from 1500 to 1980, with a progressively accelerated warming trend toward the present day. After an over 50% increase in the number of participating sites, this hemisphere-wide borehole-based reconstruction remains consistent with that derived earlier from a smaller



Figure 1. Location of the participating borehole sites (solid triangles) and the $5^\circ \times 5^\circ$ grids (shaded squares) covered by the annually resolved multi-proxy reconstruction of Mann *et al.* [1999].

Table 1. Averages of the Century-Long Rates of Temperature Change Over the Last Five Centuries From the 696 Individual Borehole-Based Reconstructions in the Northern Hemisphere

| Method | Number of Data Points | Estimate of Century-Long Rate (K/100a) | | | | | 1500–1980 Cumulative Change (K) |
|--|-----------------------|--|--------------|--------------|--------------|--------------|---------------------------------|
| | | 16th Century | 17th Century | 18th Century | 19th Century | 20th Century | |
| Simple arithmetic average | 696 | 0.018 | 0.063 | 0.135 | 0.238 | 0.588 | 0.924 |
| 1° × 1° gridded without area weighting | 328 | 0.046 | 0.079 | 0.130 | 0.208 | 0.556 | 0.908 |
| 1° × 1° gridded with area weighting | 328 | 0.057 | 0.088 | 0.135 | 0.210 | 0.560 | 0.938 |
| 2° × 2° gridded without area weighting | 230 | 0.071 | 0.095 | 0.134 | 0.202 | 0.536 | 0.931 |
| 2° × 2° gridded with area weighting | 230 | 0.081 | 0.102 | 0.138 | 0.204 | 0.545 | 0.961 |
| 5° × 5° gridded without area weighting | 117 | 0.037 | 0.072 | 0.131 | 0.223 | 0.510 | 0.871 |
| 5° × 5° gridded with area weighting | 117 | 0.047 | 0.081 | 0.139 | 0.231 | 0.525 | 0.918 |
| 10° × 10° gridded without area weighting | 62 | 0.081 | 0.095 | 0.126 | 0.191 | 0.451 | 0.854 |
| 10° × 10° gridded with area weighting | 62 | 0.098 | 0.108 | 0.136 | 0.202 | 0.474 | 0.923 |

data set of 453 boreholes [Huang *et al.*, 2000]. The independent borehole-based reconstruction, regardless of averaging methods, is also remarkably consistent with the 20th century meteorological record.

3. Extended Surface Temperature History and Subsurface Temperature Anomaly

[7] Given that the 20th century surface air temperature (SAT) record is the most reliable and the 5° × 5° area weighting scheme is the most commonly used method to suppress geographical bias among the climate research community, I extend the SAT record with the 5° × 5° area weighted 16th–19th century-long trends derived from the 696 boreholes (Figure 2). The annual SAT record is joined with the borehole-based reconstruction at the extrapolated temperature at 1900. The temperature history is shown up to 1980 in part because the multi-proxy reconstruction to be integrated in this study ends at 1980. The reference zero line is the 1961–1980 mean of the surface air temperature. I then calculate the borehole temperature anomaly based on this borehole-extended five-century surface temperature history for a representative Northern Hemisphere subsurface temperature signal.

[8] Temperature changes at the surface impose a downward-propagating transient anomaly on the subsurface temperature field [Pollack and Huang, 2000]. A one-dimensional conductive model is employed in the calculation of the subsurface temperature anomaly. The temperature at 1500 is taken as the initial steady state; and the thermal conductivity and diffusivity of the rocks are respectively assumed to be 2.5 W m⁻¹ K⁻¹ and 1.0 mm² s⁻¹. A positive subsurface temperature anomaly corresponding to the extended surface temperature history is discernible down to a depth of around 300 m (Figure 3). This subsurface temperature signal is comparable to the ones determined independently by two other research groups [Harris and Chapman, 2001; Beltrami, 2002] from a smaller data set.

4. Subsurface Temperature Signal and Conventional Proxy Model Integrated Reconstruction

[9] The multi-proxy reconstruction [Mann *et al.*, 1999] is based on a combined terrestrial (tree ring, ice core and historical documentary indicator) and marine (coral) multi-

proxy climate network with a fairly broad geographical coverage in North America and Europe, but very little coverage in Asia (Figure 1). It is so far the most well cited reconstruction among the scientific community and general public [Intergovernmental Panel on Climate Change (IPCC), 2001]. However, Zorita *et al.* [2003] show that the technique of the multi-proxy reconstruction can capture annual climate variability reasonably well, whereas it suffers from difficulties in reproducing the low-frequency behavior of the global temperature evolution even under favorable conditions. In contrast, both long-term (last millennium [Gonzalez-Rouco *et al.*, 2003]) and short-term (from 1951 to 1998 [Mann and Schmidt, 2003; Chapman *et al.*, 2004]) model simulations confirm that subsurface temperature can track surface air temperature very well at decadal and longer time scales.

[10] With annual climate variability captured in high temporal resolution proxies and long-term information preserved in subsurface temperatures, it is desirable to develop a technique to integrate them for a more complete picture of the past climate change. This is achieved through a Bayesian inversion [Shen and Beck, 1991] of the Northern Hemisphere subsurface temperature signal joined by the

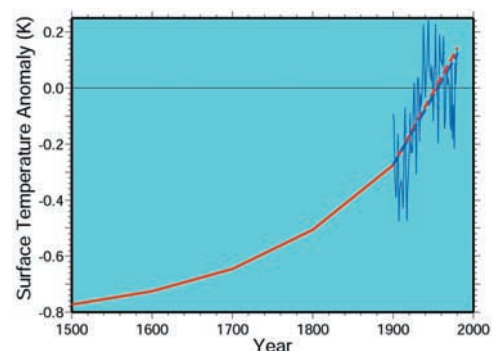


Figure 2. Extended surface temperature history combining the 1900–1980 surface air temperature (SAT) record (blue, [Jones *et al.*, 1999]) and the borehole-based estimates of the century-long trends from the 16th to the 19th centuries (red). The SAT trend and the borehole-based estimate for the 20th century are shown in dashed lines for comparison. Temperature anomaly is shown with reference to the 1961–1980 mean.

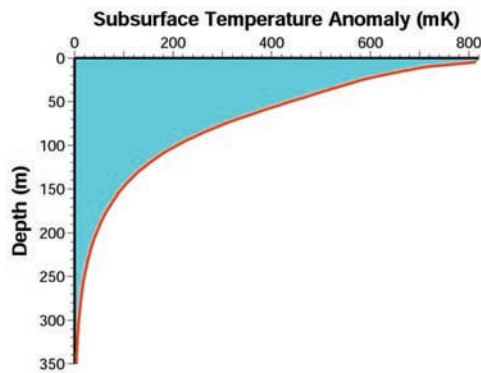


Figure 3. Subsurface temperature anomaly corresponding to the extended surface temperature history shown in Figure 2.

annually resolved multi-proxy reconstruction as the a priori model.

[11] The functional space Bayesian inversion method [Shen and Beck, 1991] allows for explicit incorporation of an a priori model, i.e., a hypothesis of the climate history in examination. Traditionally, as a conservative and independent approach to climate reconstruction with a Bayesian method, borehole temperature inversion employs a null hypothesis as the a priori model. For the integrated reconstruction of Northern Hemisphere surface temperature history over the past five centuries, I parameterized the temporal domain at an annual interval to enable the incorporation of the annual multiproxy temperature reconstruction as an a priori model.

[12] The integrated reconstruction (Figure 4 (right)) shows that the late 16th century to the earlier 17th century was the coldest and the 20th century the warmest over the past five centuries. Despite some fluctuations at annual to decadal scales, the general trend over the past five centuries

is a progressive warming. The integrated reconstruction suggests that the 20th century warming is a continuation to a long-term warming started before the onset of industrialization. However, the warming appears to have been accelerated since industrialization. This integrated reconstruction is significantly different from the a priori model, which shows a long-term cooling followed by an abrupt 20th warming (Figure 4 (left)).

[13] It is worth pointing out that the integrated reconstruction is not a simple superposition of the high frequencies of the multi-proxy reconstruction on the lower frequencies of the borehole reconstruction. The integrated reconstruction consolidates information given in the subsurface temperature data and in the a priori model. For the 20th century where the a priori multi-proxy model is well trained by meteorological record, little alteration is made through the inversion. At very long periods, the subsurface data provide information that is weak or absent in the multi-proxy reconstruction, whereas at very short periods the multi-proxy record provides information that the borehole data cannot contest. At intermediate periods both the a priori model and subsurface data provide important constraints.

5. Discussion

[14] The key differentiator of this integrated reconstruction is that it allows for a merging of the complementary climate information preserved in borehole temperatures, the 20th century meteorological record, and the conventional proxies used in the a priori model. The integration of these three bodies of information greatly improves the relationship between the reconstructed temperatures and a radiative forcing history.

[15] Various forcing factors, both natural and anthropogenic, are known to affect Earth's climate. Crowley [2000] assembled a radiative forcing history comprising the effects of solar irradiance, anthropogenic aerosols, greenhouse

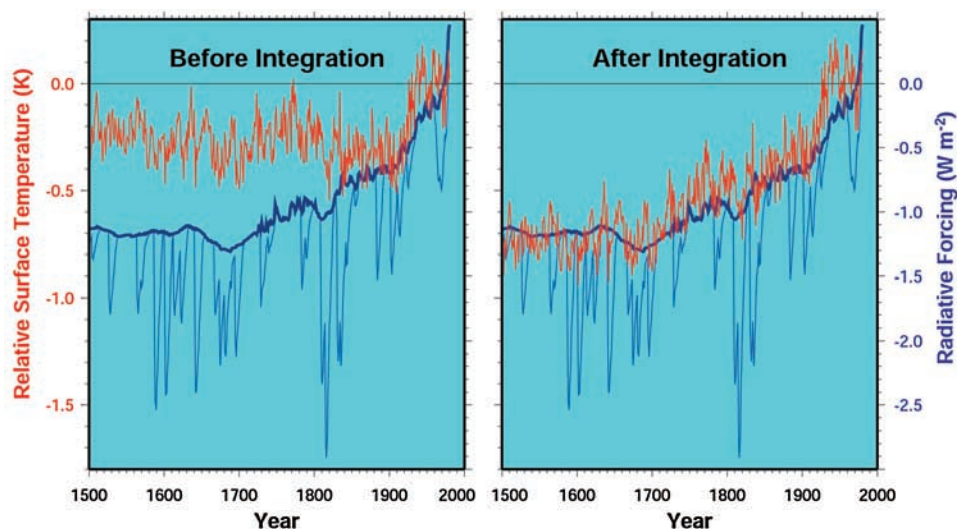


Figure 4. Comparison of the surface temperature anomaly (red) versus radiative forcing (blue) before and after the integrated reconstruction. The radiative forcing series shown in thin curve comprises the effects of solar irradiance, anthropogenic aerosols, greenhouse gases, and volcanism; the thick curve is volcanism excluded. Both radiative forcing series are based on Crowley [2000]. Surface temperature anomaly is shown with reference to the 1961–1980 mean. Radiative forcing is relative to the 1961–1980 mean of the volcanism excluded forcing series.

gases, and volcanism. In both scenarios of radiative forcing with and without volcanism, the integrated reconstruction is much better related to radiative forcing than does the a priori model. Nonetheless, the integrated reconstruction is most closely related to the forcing series without volcanism. This tends to support the need for a re-evaluation of the transient forcing effect of the climate system following episodic volcano eruptions [Ammann *et al.*, 2003]. Andronova and Schlesinger [2000] also found that better agreement between simulated and observed temperatures is obtained when the volcanic forcing is excluded.

[16] The improvement in the comparability between climate reconstruction and the radiative forcing series is a validation of the climate information integration strategy. The good agreement between the integrated reconstruction and the forcing model confirms that there are both natural and anthropogenic factors in the recent warming. It also allows for an independent estimate of the rate of climate-forcing response.

[17] Assuming the temperature anomaly to be a linear function of radiative forcing, the slope of the linear regression provides an estimate of the rate of transient response of temperature to overall radiative forcing over the time interval of observation. Because the radiative forcing of volcanism is negative, the slope of around $0.7 \text{ K per Wm}^{-2}$ of forcing without volcanism sets an upper bound of the transient climate response rate. The volcanic forcing component shown in Figure 4 is associated with only a muted response in temperature. Accordingly, I take the slope of $0.4 \text{ K per Wm}^{-2}$ derived from forcing with volcanism as a lower bound. The range of the transient climate response rate is therefore empirically estimated as $0.4\text{--}0.7 \text{ K per Wm}^{-2}$, which is substantially greater than what is suggested by the original multi-proxy model.

[18] An important objective of paleoclimate studies is to improve our ability to predict future climate. If we assume an IPCC middle-of-the-road forcing scenario, there will be a radiative forcing increment of about 2.5 W m^{-2} above present day level in Year 2050. If the mean transient climate response rate of $0.4\text{--}0.7 \text{ K per Wm}^{-2}$ is unchanged over the coming decades, a warming of 1.0 to 1.8 K will take place over that time interval.

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