Mid-Latitude (30°–60° N) climatic warming inferred by combining borehole temperatures with surface air temperatures

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Abstract. We construct a mid-latitude (30°–60° N) reduced temperature-depth profile from a global borehole temperature database compiled for climate reconstruction. This reduced temperature profile is interpreted in terms of past surface ground temperature change and indicates warming on the order of 1°C over the past 100 to 200 years. The combination of an initial temperature (the primary free parameter) with the last 140 years of gridded surface air temperature (SAT) data yields a synthetic temperature profile that is an excellent fit to observations, accounting for 99% of the observed variance and a RMS misfit of only 12 mK. The good correlation suggests that this reduced temperature profile shares much information with the mean SAT record over large areas and long time-scales. Our analysis indicates $0.7° \pm 0.1°$C of ground warming between pre-industrial time and the 1961-1990 mean SAT.

Introduction

How much warmer is the surface of the Earth at the end of the 20th Century than it was in preindustrial times? Recent estimates vary from 0.3 to 0.9 K [*Overpeck et al.,* 1997; *Jones et al.,* 1998; *Mann et al.,* 1999; *Huang et al.,* 2000; *Jones et al.,* 2000]. The answer has been elusive because extensive instrumental records of temperature change extend only to about 1850 [*Jones et al.,* 2000], and estimates of surface temperature in the critical 18th Century are based either on proxy methods with an imperfect temperature calibration [*Ellsaesser et al.,* 1986; *Jones et al.,* 1998] or on direct temperature measurements in boreholes with poor time resolution [*Clow,* 1992].

Analysis of borehole temperatures for climate change information is relatively new [*Lachenbruch and Marshall,* 1986; *Harris and Chapman,* 1997; *Huang et al.,* 2000]. Because variations in surface ground temperature (SGT) impart curvature to a mostly linear temperature structure in the subsurface and because transient climatic signals are much shorter lived than background heat flow variations, it is possible to use borehole temperature profiles to extract and interpret the record of SGT variations in the past. Time before present and subsurface depth are linked through thermal diffusivity such that temperature profiles measured to a depth of a few hundred meters contain information about SGT over the past several centuries. In contrast to traditional proxy methods in which the link between the measured data and temperature needs to be established,

temperature-depth profiles bear a direct relationship to continuous SGT forcing.

A popular approach for constructing SGT histories has been to use Bayesian inverse theory [*Shen and Beck,* 1991; *Wang,* 1992; *Huang et al.,* 2000]. A principal advantage of these inversion techniques is the ability to suppress noise, which, if left unchecked, could produce wild fluctuations in SGT histories [*Shen et al.,* 1995]. However, because of the typically large number of free parameters, it is often difficult to assess the quality of solutions. The loss of high frequency information with time in the past also makes direct comparisons between SGT histories and surface air temperature (SAT) records challenging [*Harris and Gosnold,* 1999]. Futhermore, SGT solutions based solely on temperature-depth measurements cannot retrieve the most recent temperature change information if borehole temperatures were only measured below a depth of 40 or 50 m. We address some of these shortcomings by 1) showing that noise can be suppressed by a simple averaging of reduced temperature profiles, and 2) combining borehole transient temperature profiles with conventional meteorological data in an integrated analysis. Both of these considerations greatly reduce the number of free parameters in the climate change reconstruction.
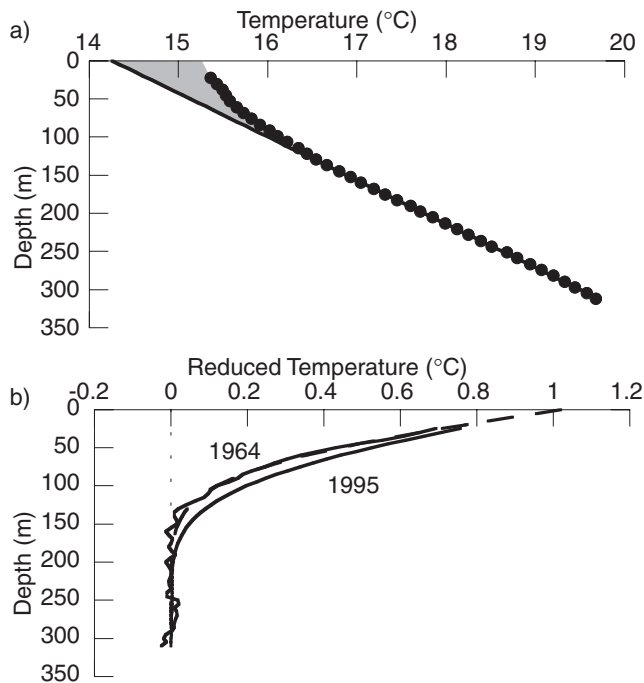
Temperature-Depth Data

Recently, a global database of borehole temperature profiles has been assembled for the purpose of reconstructing SGT histories [*Huang and Pollack,* 1998]. We have processed these data to facilitate comparisons with climate change inferred from meteorological records and to test a series of climate change scenarios. We isolate transient borehole temperature anomalies that may be attributed to climate change by removing the background thermal regime (Figure 1). The background temperature field is estimated in terms of two free parameters, the thermal gradient and surface temperature computed using data below 160 m, a depth sufficient to avoid more recent climate change effects but that retains enough data in the deeper subsurface to obtain robust estimates of these parameters. This process does not modify curvature in the temperature-depth profile.

Because of the effects of thermal diffusion, it is not appropriate to average individual reduced temperature profiles logged at different times. This compilation of temperature profiles span 27 years (1958–1995); profiles measured in 1958 contain different information than those logged in 1995. Thus we have forward continued all reduced temperature profiles to a common year of 1995 by assuming that the surface temperature is constant between the date of logging and 1995 and diffusing the reduced temperature profile for-

Figure 1. Processing borehole temperature-depth data to isolate climate-change transients. Example log is borehole US-VA6-60 measured in 1964. a) Circles depict temperature measurements. Solid line shows background thermal field. The shaded area represents anomalous temperature resulting from surface ground temperature variations to 1964. b) Reduced temperature profile computed by removing the background thermal field (Solid line labeled 1964). Dashed line shows a best fitting step function to estimate surface temperature for 1964. Solid line labeled 1995 is the forward continued reduced temperature profile assuming a constant surface temperature between 1964 and 1995.

ward in time. This process produces a reduced temperature profile (marked 1995, Figure 1) with diminished high frequency noise, anomalous reduced temperatures extending a little deeper in the subsurface, and a somewhat greater magnitude of the anomalous reduced temperatures at intermediate depths.

A composite of mid-latitude Northern Hemisphere reduced temperature profiles, based on 439 logs forward continued to 1995, is shown in Figure 2. The variability reflects natural climatic variability as well as site specific effects. Lack of any discernable trend in the reduced temperature profiles below 200 m justifies the choice of 160 m to compute a background thermal field. An average thermal anomaly for these temperature logs has been computed by first taking an average reduced temperature for each $5 \times 5°$ grid, and then averaging all grids containing data. The mean anomaly has an amplitude of 0.5°C at 30 m and a depth extent of approximately 190 m (Figure 2). Positive anomalous temperatures are direct thermal evidence of surface warming from some long-term mean value. Simple last event models that reproduce this anomaly include a step change of surface temperature of $0.7 \pm 0.1°$C in 1885 or a ramp increase of $0.8 \pm 0.1°$C starting in 1800.

Integrated Analysis

How much signal does the average Northern Hemisphere reduced temperature profile share with the Northern Hemi-

sphere SAT record? We answer this question by computing a synthetic transient temperature profile [*Lachenbruch et al.,* 1988 *Harris and Chapman,* 1998] from gridded meteorological data [*Jones et al.,* 2000] using $5 \times 5°$ grid cells collocated with the boreholes (Figure 2). The SAT time series (Figure 3a) is expressed as a sequence of N annual step functions of known amplitude and time prior to 1995. Because the SAT data are limited to the last 140 years whereas the reduced temperature profile indicates a sensitivity to at least the last 300 years, we parameterize the time before the start of the SAT record in terms of a constant temperature termed the pre-observational mean (POM) temperature. In the comparison of model prediction versus observation, this is the only free parameter.

The best model (Figure 3) jointly satisfying SAT and SGT constraints corresponds to a POM of 0.71°C below the 1961-1990 mean SAT value. The combination of this POM with the last 140 years of SAT data yields a synthetic profile that is an excellent fit to observations, with a RMS misfit of only 12 mK. The sharp trough in the misfit diagram indicates just how sensitive this fit is to the POM. A variation of $\pm 0.1°$C in the POM doubles the misfit error. Much of the misfit is produced in upper 65 m where the reduced temperature profile is less than the synthetic transient temperature and may be due to our conservative assumption of no SGT change between the year a borehole was logged and 1995. In fact, since 1980, only four years, (1982, 1984, 1985, and 1993), have been cooler than the 1961-1990 average.

Sensitivity to the SAT time series is demonstrated by comparing the fit between the reduced temperature profile and the POM-SAT model for other forcing functions. For example, a null SAT information hypothesis [*Harris and Gosnold,* 1999] would be constituted by an optimized step function, where the step is constrained to occur at the time of the beginning of the SAT record. Such a forcing function produces a RMS misfit of 29 mK, more than double that when using the information contained in the SAT time
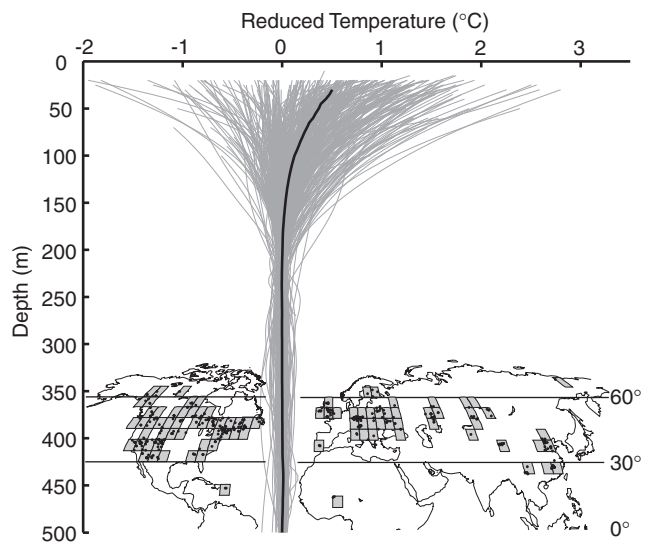
Figure 2. Northern Hemisphere reduced temperature profiles for 1995. Lines represent 439 profiles whose locations are shown in the inset. Bold line shows average reduced temperature profile. The mean SAT record is based on data from the shaded $5 \times 5°$ grid cells.
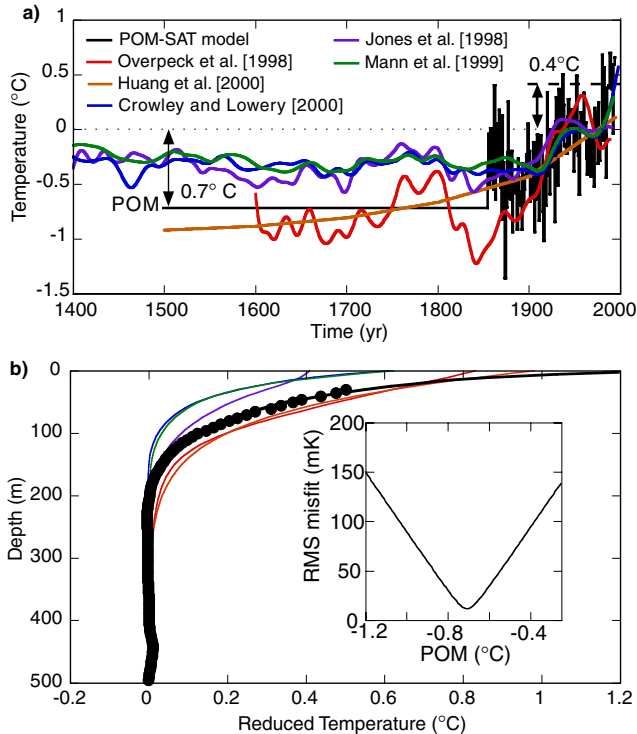
Figure 3. Climate reconstructions and their geothermal consequences. (a) Mean surface air temperatures (SAT) from 1856 to 1999 [*Jones et al., 2000*] with the pre-observational mean temperature (POM) prior to 1856. Climatic models are plotted relative to the 1961-1990 mean temperature. (b) Comparison of Northern Hemisphere reduced temperature profile and synthetic transients computed from proxy reconstructions. POM-SAT model shows fit to data by using the SAT data as a forcing function. Each synthetic profile is shown relative to the 1500– 1700 mean temperature, which was used to initialize the models.

series. This comparison indicates that ground and air temperatures are correlated [*Baker and Ruschy,* 1993; *Putnam and Chapman,* 1996] and that the hemispheric reduced temperature profile is sensitive to both the POM and details of the SAT time series [*Harris and Chapman,* 1997; *Harris and Gosnold,* 1999].

Since borehole temperatures to depths of 500 m are sensitive to temperatures over the last millennium, the borehole temperature anomaly also affords the opportunity of testing multi-century surface temperature reconstructions [*Overpeck et al.,* 1997; *Jones et al.,* 1998; *Mann et al.,* 1999; *Huang et al.,* 2000; *Crowley and Lowery,* 2000] (Figure 3a). One measure of warming since preindustrial time is the difference between the 1500-1700 mean temperature and the 1961-1990 mean commonly used as a modern reference temperature (Table 1). These differences for six reconstructions vary between 0.9° and 0.3°C and, with the exception of the Arctic reconstruction [*Overpeck et al.,* 1997] demonstrate that ground temperatures indicate greater warming than proxy reconstructions.

The extent to which various surface temperature histories for the Northern Hemisphere are consistent with the geothermal record of climate change can be illustrated by using the proxy and other reconstructions as forcing functions and calculating the subsurface thermal response (Figure 3b). Synthetic temperature profiles for each proxy re-

construction are calculated relative to respective 1500-1700 AD mean temperatures. All time series have been similarly filtered through the Earth heat conduction filter to facilitate a visual comparison.

The ground response to the arctic reconstruction and the hemispheric proxy reconstructions [*Mann et al.,* 1999; *Crowley and Lowery,* 2000] bracket the Northern Hemisphere reduced temperature profile. This variation may be a latitudinal effect because the hemispheric reconstructions rely to a greater extent on proxy records from the tropics that may attenuate the warming signal [*Mann et al.,* in press]. On the other hand, the ramp reconstruction of *Huang et al.* [2000] yields a similar total amplitude of warming as our SGT history. But the combination of the last 140 years of SAT data and a single POM used in our model seems to provide a better fit to the data than does their model of monotonically increasing century-long ramps determined from a more complex inversion procedure.

Discussion and Conclusions

This study suggests that borehole temperature profiles contain a valuable signal for measuring the magnitude and timing of surface warming since preindustrial time. This approach allows a quantitative comparison between the signals of ground warming and proxy reconstructions at appropriate frequencies and temporal scales, necessary if we are to understand and learn from their differences. These tests have assumed a constant offset between proxy surface temperatures and surface ground temperatures. Potential candidates for a time-varying offset include: 1) an imperfect or changing calibration between proxy records and air temperatures at long periods [*Ellsaesser,* 1986], 2) changing patterns of snow cover [*Groisman et al.,* 1994], and 3) changing patterns of land-use and land-cover [*Lewis,* 1998; *Skinner and Majorowicz,* 1999]. Furthermore, borehole temperature profiles respond to the continuous variation of surface ground temperature throughout the year whereas various proxies are weighted towards a seasonal temperature such as growing season for tree ring proxies and snow season for ice cores.

We have shown that the average reduced temperature profile is sensitive to, and compares well with, the Northern Hemisphere SAT record from a comparable latitude band. Our analysis indicates $0.7 \pm 0.1°$C of ground warming between preindustrial time and the interval 1961-1990. SAT data show another $0.4°$C of most recent warming (Figure 3). Thus the total surface warming in the Northern Hemisphere from preindustrial time to the end of the 20th century may

Table 1. Estimated Warming Magnitudes.

Time Series	$\Delta T, °C$[a]
Overpeck et al. [1997]	0.9[b]
Huang et al. [2000]	0.9
POM-SAT model	0.7
Jones et al. [1998]	0.4
Mann et al. [1999]	0.3
Crowely and Lowery [2000]	0.3

[a]ΔT = 1960-1991 mean temperature - 1500-1700 mean temperature.
[b]ΔT = 1960-1991 mean temperature - 1500-1600 mean temperature.

be as much as 1.1°C, although it will take some time to see if the extreme warming in the 1990s is sustained.

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