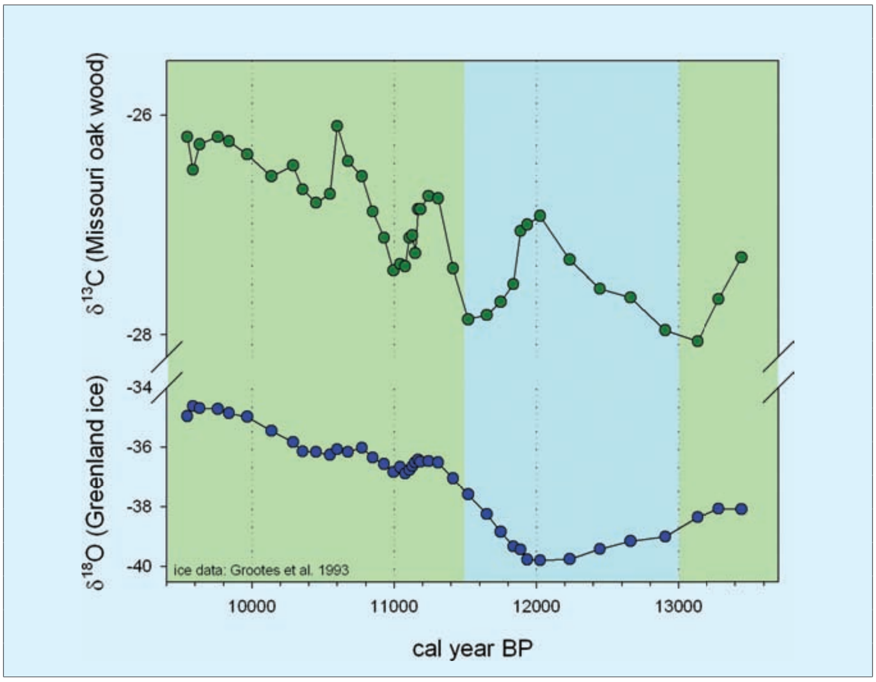

Figure 2: Stable isotope data for oak (δ^{13}C) in mid-continental North America (93°20′ W, 40°10′ N) paired with δ^{18}O from Greenland ice (GRIP and GISP2 data, Grootes et al., 1993). Paired values of δ^{13}C and δ^{18}O infer a climate link during the post glacial-Holocene transition between maritime climate of the North Atlantic and continental climate of Midwestern North America.

with temporally paired δ^{18}O values (GRIP, GISP2) during the post glacial period. This association occurs despite the complexities of possible ^{13}C signals in tree rings (Loader et al., 2003). The termination of the Younger Dryas (about 11.5 cal ka BP) in mid-continental North America oak is marked by an expected and abrupt enrichment in the climate-sensitive stable isotope δ^{13}C. This abrupt termination is synchronous with dates of Younger Dryas termination based on pollen, ice core and tree-ring studies from marine and maritime regions of the North Atlantic. Additionally, an increase in oak δ^{13}C ca. 12.0 cal ka BP is coincident with intra Younger Dryas variability, as documented by δ^{18}O from Greenland ice cores (Grootes et al., 1993). Increasing δ^{13}C in oak during the post Younger Dryas transition to the Holocene is found to be consistent (r = 0.64) with changes in Greenland δ^{18}O (GISP2).

Our preliminary results indicate that despite the low resolution of our data, climate change during the glacial-Holocene transition in mid-continental North America was approximately synchronous with that in the North Atlantic (~4,500 km northeast of the study site). In addition, serial correlation among tree growth and isotope chronologies suggests that post glacial climate variations had marked effects on the growth rates of trees. The construction of tree-ring chronologies for the Younger Dryas will eventually provide an annual-resolution climate proxy for an under-represented continental region.

Note

Radiocarbon dates are on file at commercial laboratories (Beta Analytic Inc. Miami, FL) as well as the Missouri Tree Ring Laboratory (http://www.missouri.edu/~guyetter/) where the growth data is also stored. Future ^{14}C dated 'floating' ring-width chronologies will be posted at International Tree-Ring Data Bank (http://www.ncdc.noaa.gov/paleo/treering.html).

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Consolidating high- and low-resolution information from different sources into a Northern Hemisphere climate reconstruction

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Our understanding of climate history in the pre-industrial era relies principally on climate proxies, each of which has strengths and limitations in representing past climate variability.

A paleoclimate reconstruction from borehole temperature data has its foundation in the theory of thermal diffusion and, as such, is characterized by a progressive inability to resolve climatic excursions in the more remote past. But the compensation for the loss of resolution is a better determination of the mean surface temperature in the interval of time for which the details cannot be resolved. Conversely, reconstructions from many traditional proxy approaches offer higher temporal resolution of relative changes but with greater uncertainties in the long-term trends.

It would be desirable to develop a technique to integrate complementary high- and low-resolution climate information preserved in different data sources for a more complete picture of the past climate change. Huang (2004) attempted such an integrated reconstruction of the Northern Hemisphere surface temperature history over the past five centuries through an integrated analysis of the global da-

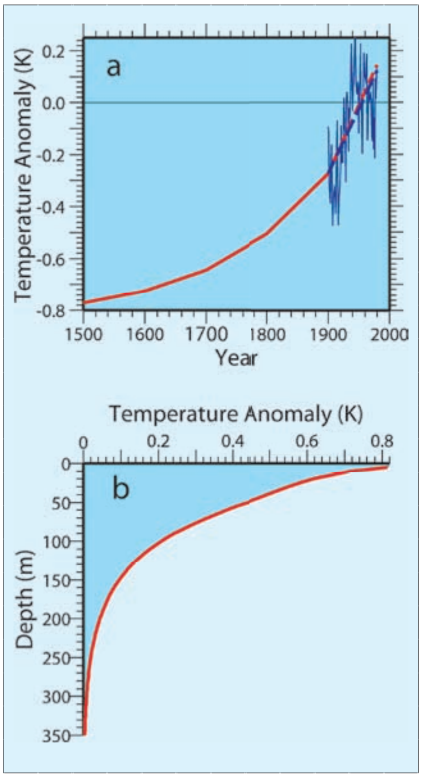

*Figure 1: **A**) Extended surface temperature history combining the 1900-1980 surface air temperature (SAT) record (blue) and the 5°×5° area weighted average of the borehole-based reconstruction over the 16th-19th century period (red). The SAT trend and the borehole-based estimate of the 20th century trend are used for extension (dashed lines). **B**) Subsurface temperature anomaly corresponding to the extended surface temperature history.*

tabase of borehole temperatures, the annually resolved multi-proxy reconstruction of Mann et al. (1999), and the 20th century meteorological record.

Methods and data

The integrated reconstruction involves several steps: reconstructing century-long trends from hundreds of borehole temperature profiles, extending the surface air temperature (SAT) record with the borehole-based reconstruction, determining a subsurface temperature anomaly with the extended temperature record, and inverting the subsurface anomaly with the Mann et al. (1999) reconstruction as the a priori model.

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. At the time of this study, the database contained 862 borehole temperature profiles, of which 697 were located in the Northern Hemisphere.

A standardized borehole data inversion technique independent of any other proxy or meteorological records is employed for the reconstruction of century-long trends (Huang et al., 2000) from each of the 697 Northern Hemisphere borehole data sets. The individual borehole-based reconstructions are then aggregated for a hemispheric representation.

From a Northern Hemisphere perspective, the 697 boreholes suggest a cumulative change of about 1°C over the past five centuries, with an accelerated warming trend towards the present day (Fig. 1a). With approx. 50% more data, this new borehole-based reconstruction is consistent with that derived earlier from a smaller data set of 453 boreholes employed by Huang et al. (2000).

The independent borehole-based estimate of 20th century warming is remarkably consistent with the meteorological record (Jones et al., 1999). Given that the 20th century meteorological record is the most reliable climate record, Huang (2004) extends the SAT record with the 5°×5° area weighted 16th-19th century-long trends derived from the 697 boreholes. This borehole-extended five-century surface temperature history is then used to calculate a representative Northern Hemisphere subsurface signal (Fig. 1b), with the temperature at year 1500 taken as the initial steady state.

The last step of the integrated analysis is to bring into a coherent reconstruction process the subsurface temperature signal and the annually resolved multi-proxy model of Mann et al. (1999). Such an integrated reconstruction is accomplished through a functional space Bayesian inversion, which allows for explicit incorporation of an a priori model, i.e., a hypothesis of the climate history under examination. For the integrated reconstruction of Northern Hemisphere surface temperature history over the past five centuries, the temporal domain is parameterized at an annual interval to enable the incorporation of the Mann et al. (1999) reconstruction as the a priori model.

Results

The integrated reconstruction (Fig. 2b) shows that the late 16th century to the early 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

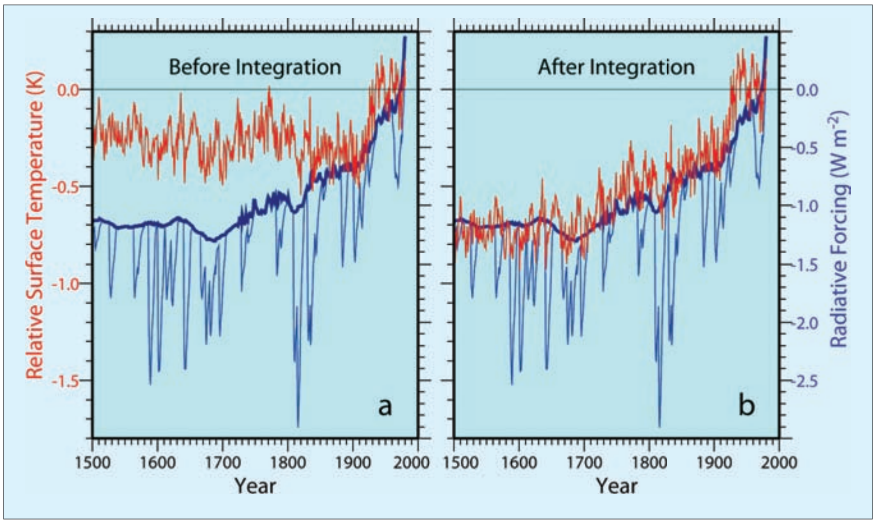

*Figure 2: Comparison of the reconstructed surface temperature anomaly (red) versus radiative forcing (blue) before (**A**) and after (**B**) the integrated reconstruction (Huang, 2004). The radiative forcing series shown by the thin curve comprises the effects of solar irradiance, anthropogenic aerosols, greenhouse gases, and volcanism; the thick curve shows 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 forcing series with volcanism excluded.*

continuation of a long-term warming. However, the warming appears to have been accelerated towards the present day.

Integration of the complementary information greatly improves the comparability of the reconstructed temperatures and the Crowley (2000) radiative forcing history (Fig. 2). Analysis of the reconstructed temperature and radiative forcing series 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 (Huang, 2004).

Discussion

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 the meteorological record, little alternation is made through the inversion. At very long periods, the subsurface temperature data provide information that is weak or absent in the multi-proxy reconstruction. At intermediate periods both the a priori model and subsurface data provide important constraints.

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 influencing the recent warming.

Acknowledgements

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Note

The time series of this integrated reconstruction can be downloaded from www.ncdc.noaa.gov/paleo/pubs/huang2004.

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www.pages-igbp.org/products/newsletters/ref2006_2.html

Can models of abrupt climate change be tested from sea level reconstructions?

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Introduction

As hypotheses concerning the origin of abrupt climate change accumulate, there is an increasing need to synthesize data and to develop methods that may help assess their strengths and inconsistencies. Understanding the mechanisms of abrupt climate change is particularly challenging because of the uncertainties in paleoclimate observations and in our knowledge of the physics of the climate system. Among the techniques that can be used to piece together the common elements of noisy observations given knowledge of a system's physics are so-called "inverse methods". In particular, stochastic inverse modeling provides a way to navigate the uncertainties in data and models, and deal with the possibility of multiple solutions (inferences). Most notably, it can re-express the problem of abrupt climate change in terms of its implications for what we should see in observations if models provide adequate representation of the processes that exist in nature. Here, we demonstrate the potential of this approach (i) by estimating the changes in global sea level implied by the combination of a Greenland ice core paleotemperature record during the last glacial period, with a highly simplified model of the buoyancy-driven ocean circulation, and (ii) by comparing these changes to reconstructions of global sea level during this period. The comparison provides a test of the consistency between the various datasets and a test of the hypothesis of a freshwater forcing of abrupt climate change.

Freshwater forcing hypothesis

The freshwater forcing hypothesis to explain abrupt climate change involves changes in the freshwater supply to the North Atlantic Ocean through instabilities of the large continental ice sheets that covered the high northern latitudes during the last glacial period. A key part of this hypothesis is the capability of the ocean meridional circulation and of the attendant poleward heat flux to suddenly switch state and hold the climate system in a new state for hundreds to thousands of years. This possibility is suggested by a hierarchy of ocean models that exhibit multiple equilibria of the meridional circulation and that demonstrate the potential of surface freshwater forcing to initiate transitions between the equilibria. Thus, a hysteresis exists within