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# A late Quaternary climate reconstruction based on borehole heat flux data, borehole temperature data, and the instrumental record

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[1] We present a suite of new 20,000 year reconstructions that integrate three types of geothermal information: a global database of terrestrial heat flux measurements, another database of temperature versus depth observations, and the 20th century instrumental record of temperature, all referenced to the 1961–1990 mean of the instrumental record. These reconstructions show the warming from the last glacial maximum, the occurrence of a mid-Holocene warm episode, a Medieval Warm Period (MWP), a Little Ice Age (LIA), and the rapid warming of the 20th century. The reconstructions show the temperatures of the mid-Holocene warm episode some 1–2 K above the reference level, the maximum of the MWP at or slightly below the reference level, the minimum of the LIA about 1 K below the reference level, and end-of-20th century temperatures about 0.5 K above the reference level.

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## 1. Introduction

[2] The reconstruction of past climate provides a useful context for discussions of contemporary climate change. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change [*Intergovernmental Panel on Climate Change*, 2007, chapter 6] addresses this topic at time scales ranging from geologic to millennial, with special emphasis on the reconstruction of temperature variability over the past 2,000 years. Millennial climate reconstructions typically use annually resolved climate proxies such as tree-ring width and density, ice core isotopics, and historical records, but also make use of less well resolved observations such as glacier lengths, subsurface temperatures measured in boreholes, and plankton and pollen distributions in lacustrine and marine sediments. We have contributed to the development of the paleoclimate record as reconstructed from geothermal data in many publications [e.g., *Shen and Beck*, 1991; *Huang et al.*, 2000; *Huang*, 2004; *Pollack and Smerdon*, 2004] including the discussion by *Intergovernmental Panel on Climate Change* [2007]. The principles of the geothermal approach to climate reconstruction can be found in a review by *Pollack and Huang* [2000].

[3] Climate reconstructions from geothermal data are not without limitations. Downward propagating thermal signals undergo period-dependent attenuation and spreading with depth; these characteristics of thermal diffusion together translate into increasing difficulty in detecting and assessing the magnitude of past climatic perturbations, and a progressive loss of temporal detail in reconstructing them [*Clow*, 1992]. Effectively, reconstructions of surface temperature history become more generalized with increasing time before the present day.

[4] The reconstruction of climate over the past one to two millennia has not been free of contention, because of its relevance to assessing the significance of 20th century global warming. An early reconstruction that drew considerable attention was that of *Mann et al.* [1999], which was prominently displayed in IPCC's Third Assessment Report [*Intergovernmental Panel on Climate Change*, 2001]. The contentiousness followed from the statement by *Mann et al.* [1999] and by *Intergovernmental Panel on Climate Change* [2001] that the temperatures in the last decade of the 20th century exceeded any earlier temperatures in the entire thousand-year period of the reconstruction, including the so-called Medieval Warm Period (MWP; ~1000–1200 AD). In the ensuing debate one of our publications [*Huang et al.*, 1997] (hereafter called HPS97) was occasionally offered as evidence that the MWP was in fact warmer than late 20th century [e.g., *Deming*, 2004]. Yet in our later publications on climate reconstruction [e.g., *Huang et al.*, 2000] (hereafter referred to as HPS00), and in publications by others addressing the climate history of the last two millennia [e.g., *National Research Council*, 2006; *Intergovernmental Panel on Climate Change*, 2007] there are no references to the results of HPS97.

[5] The initial purpose of the present paper is to clarify and resolve this apparent change of perspective in our work between HPS97 and HPS00. Although science certainly allows for abandoning earlier results in favor of later results, in our case there is a different explanation. The fundamental difference between HPS97 and HPS00 is that they do not analyze the same data. Below we describe their respective datasets, and show why the results of HPS97 cannot be used for comparing MWP warmth to the 20th century. We then proceed to integrate the two datasets into a new reconstruction, one based on the combination of the climate information carried by the independent data sources of these two previous studies, as well as the 20th century instrumental record.

## 2. HPS97: A Reconstruction Based on the Variation of Heat Flux With Depth

[6] HPS97 stands apart from all other climatic analyses of subsurface geothermal observations. It is not a 'standard'

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borehole paper in which temperature vs. depth profiles have been inverted to yield a ground surface temperature history (as in HPS 2000). The title of HPS97 “Late Quaternary temperature changes seen in world-wide continental heat flow measurements” is specific: the paper uses as ‘data’ many published determinations of the terrestrial heat flux, i.e. measurements of the heat flowing out from Earth’s interior. These determinations reside in a database assembled by the International Heat Flow Commission (IHFC), a formal commission of the International Association of Seismology and Physics of Earth’s Interior. The database in its most elemental form is a listing of latitude, longitude, and a value of the heat flux (milliwatts per square meter, $mWm^{-2}$) at that location.

[7] The database contains more than 24,000 entries, of which a little more than half come from measurements in boreholes on the continents. While it is true that these data were derived from temperature measurements in boreholes, the database does not include the actual temperature vs. depth measurements. For some entries (more than 6,000), there was additional information about the depth range over which the heat flux determination was made. Because we and others [e.g., *Beck*, 1977] suspected that reported heat flux data were not totally free of climatic perturbations, we decided to interrogate them to see if they contained a coherent climate signal, which would appear as small variations in the heat flux over different depth ranges (the heat flux is proportional to the temperature gradient). The interrogation involved binning and averaging the heat flux measurements in 50 m depth intervals, and inverting the resulting heat flux versus depth profile to obtain the 20,000 year surface temperature histories shown in HPS97.

[8] One very important aspect of data selection relevant to the debate about whether the MWP was warmer than 20th century temperatures, is mentioned explicitly in HPS97 in the section on Data:

> “We excluded data with representative depths less than 100 m . . . [because] . . .the uppermost 100 meters is the depth range most susceptible to non-climatic perturbations. . .; moreover, subsurface temperature measurements in this range yield information principally about the most recent century”.

[9] The consequence of excluding the upper 100 meters is that the 20,000 year reconstructions in HPS97 contain virtually no information about the 20th century. As the authors of HPS97 we can be criticized for not stating explicitly in the abstract and figure caption that the ‘present’ (the zero on the time axis) really represents something like the end of the 19th century, rather than the end of the 20th century. At the time we published that paper our focus was on trying to extract a broad-brush representation of Late Quaternary surface temperature variability that might be overprinted on the ensemble of world-wide continental heat flux measurements. We did not anticipate that a comparison of late 20th century and Medieval Warm Period temperatures would later become a contentious issue.

## 3. HPS00: A Reconstruction Based on Temperature Versus Depth Profiles in Boreholes

[10] We now turn briefly to the reconstructions given by HPS00, and subsequently by *National Research Council* [2006] and *Intergovernmental Panel on Climate Change* [2007]. In HPS00 we used present-day temperatures in 616 boreholes from all continents except Antarctica to reconstruct century-long trends in temperatures over the past 500 years at global, hemispheric and continental scales. The reconstructions in HPS00 use primary temperature data from another database containing high quality borehole temperature versus depth (T-z) profiles compiled for the explicit purpose of climate reconstruction [*Huang et al.*, 1999]. The entries in this T-z database meet several quality control criteria not imposed on entries to the earlier heat flow database. The temporal length of a reconstruction derived through inversion of a borehole temperature profile is limited in part by the depth of the borehole temperature profile and the noise level of the borehole data. Given that most of the temperature profiles in this T-z database are shallower than 400 m, HPS00 focused on reconstructions representing only the past five centuries. The results in HPS00 confirm the unusual warming of the twentieth century revealed by the instrumental record and other climate proxies.

[11] There are important differences that need to be understood between the 20,000 year reconstructions of HPS97 and the more recent five-century borehole reconstructions typified by HPS00. HPS97 is a broad-brush look at the entire Late Quaternary (exclusive of the 20th century as noted above), using a large but noisy, low temporal resolution dataset of heat flux measurements aggregated in 50-meter depth intervals. The HPS00 reconstructions use a smaller but higher quality and more homogeneous dataset of several hundred borehole temperature versus depth (T-z) profiles comprising actual temperature measurements at 10 meter intervals. The selection process for these T-z profiles has been conducted under strict quality control criteria, ensuring a much less noisy dataset than that used in HPS97. In a sense these studies are complementary, with HPS97 taking a long low-resolution view, and HPS00 making a more focused and sharper assessment of the past five centuries.

## 4. Integrated Reconstruction

[12] We now proceed to develop a reconstruction that integrates the climate information preserved in both the borehole temperature database and the heat flow database, as well as the instrumental record of temperature for the 20th century. We generate a representative temperature-depth profile from the surface down to 2000 m depth at 10 m depth intervals, by adding a transient anomaly signal to a steady-state temperature profile established by the basal heat flux augmented by modest radiogenic heat production within the 2000 m column.

[13] The statistics of the heat flow database indicate that the mean heat flux of the dataset is in the range of 60–64 $mWm^{-2}$, slightly below the worldwide continental heat flux mean of 65 $mWm^{-2}$ [*Pollack et al.*, 1993]. In the reconstructions that follow we explore the consequences of different estimates of the steady state heat flux, because the magnitude of the climate transient is related to the difference between the observed heat flux and the estimate of the steady state; lower (higher) values of the steady heat flux yield smaller (larger) climate anomalies. For thermal con-

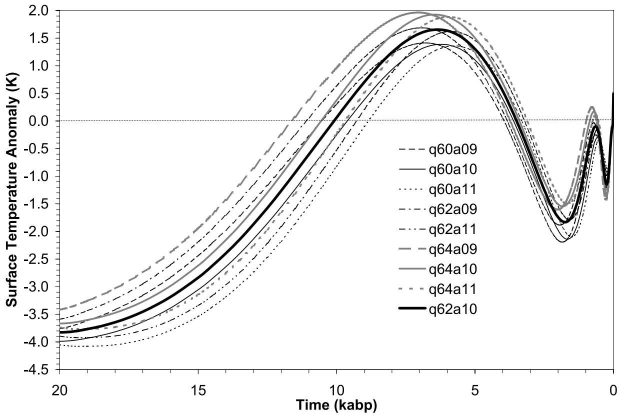

**Figure 1.** Suite of reconstructions of surface temperature history over the past 20,000 years. Nine curves correspond to three values of thermal diffusivity (0.9, 1.0, 1.1 × $10^{-6}$ $m^2s^{-1}$, denoted in the legend as a09, a10 and a11, respectively), each paired with three values of steady state heat flux (60, 62, 64 $mWm^{-2}$, denoted in the legend as q60, q62 and q64, respectively). Bold curve (q62a10) represents a reconstruction using mid-range values of diffusivity and heat flux. The reference level is the mean of the instrumental record in the interval AD 1961–1990.

ductivity and radiogenic heat production we use typical values of 2.5 $Wm^{-1}K^{-1}$ and 1.5 $\mu Wm^{-3}$, respectively.

[14] The transient anomaly to a depth of 300 m is generated with a forward model that drives the surface with the 20th century instrumental record (land only) and the 16th through 19th century temperature trends from HPS00. The initial condition for the forward model calculation is the steady-state temperature profile pinned to a zero surface temperature. The variance-adjusted version of the global land only surface air temperature anomaly time series we used was retrieved from the University of East Anglia Climate Research Unit web site on November 1, 2007 (CRU, http://www.cru.uea.ac.uk/cru/data/temperature/crutem3vgl.txt, 2007), with the zero reference level set at the 1961–1990 global mean. The century long trends from HPS00 were based on 616 borehole temperature profiles from six continents. As the T-z database has grown, updated century long trends have been estimated by others [e.g., *Pollack and Smerdon*, 2004; *Huang*, 2004], but for the purposes of this paper the small differences are inconsequential.

[15] We then extend this temperature-depth profile downward from 300 m to 2000 m, making use of the heat flux vs. depth data of HPS97. The steps to convert heat flux over a depth interval to temperature change over that interval involves integration of Fourier's equation of heat conduction

$$T(z) = T(300) + \int_{300}^{z} \frac{q(z)}{k} dz$$

where *T(300)* is the temperature at 300 m depth; *q(z)* is the empirically determined variation of heat flux with depth *z* as reported in HPS97, and *k* is thermal conductivity. The heat flux through a depth interval comprises the heat flux entering from below augmented by any radiogenic heat production within the depth interval, as well as any climatic perturbation propagating downward from the surface. Both the basal heat flux and the radiogenic increment change only on geologic time scales, whereas the climatic perturbation varies on millennial and shorter time scales. Accordingly, the climatic perturbation is considered a transient superimposed on a much more slowly changing 'steady state'.

[16] We then invert this composite 2,000 meter temperature versus depth profile, synthesized from the instrumental record, the century-long temperature trends of HPS00, and the integrated heat flux versus depth data from HPS97, to yield a reconstruction of the surface temperature history over the past 20,000 years. We employ the Bayesian functional space inversion scheme developed by *Shen and Beck* [1991], incorporating a conservative null hypothesis as the *a priori* estimate of the surface temperature history.

[17] The pace of transient signal propagation in the subsurface is controlled by the thermal diffusivity. We explore the dependence of the reconstructions on thermal diffusivity, by considering deviations from a nominal value in the range 1.0 ± 0.1 × $10^{-6}$ $m^2$ $s^{-1}$. To account for an observed excursion of the heat flux at a certain depth, a lower (higher) thermal diffusivity requires a longer (shorter) time for a surface event to propagate to that depth, and therefore the surface event must have occurred less (more) recently, compared to the time required at the nominal value.

[18] We show the results of the inversions of the integrated T-z profile at two time scales: Figure 1 shows the reconstructions of surface temperature history over the entire 20,000 year interval, and Figure 2 shows the reconstructions over only the past 2,000 years on an expanded time scale. The several curves represent the range of variability due to the range of steady-state heat flux and thermal diffusivity values described above. The range of reconstructions is effectively bounded by two limiting cases: a higher steady state heat flux paired with lower thermal diffusivity, and a lower steady heat flux with a higher diffusivity. The former leads to a larger amplitude reconstruction with prominent events further back in time, whereas the latter produces lesser amplitude events that occurred more recently. The bold curve in Figures 1 and 2

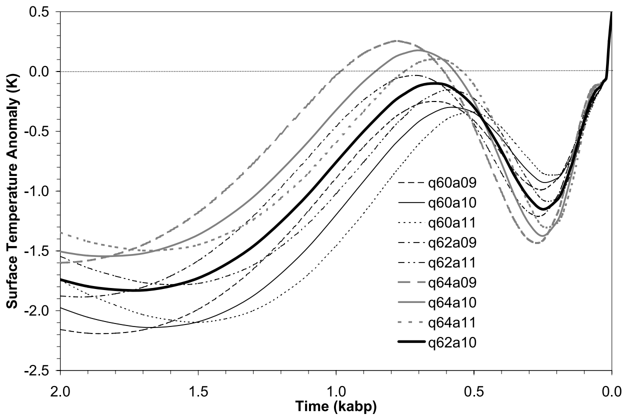

**Figure 2.** Same suite of reconstructions as in Figure 1, but displayed over only the past 2,000 years on an expanded timescale. Labeling of curves as in Figure 1.

represents a reconstruction using mid-range values of heat flux and diffusivity.

[19] In Figure 1 one sees a long mid-Holocene warm episode. The warmest interval of time (average temperature anomalies >1 K relative to the AD 1961–1990 mean reference level) in the entire set of reconstructions is about three to four thousand years in duration, and peaks some 6,000–7,000 years BP. Because of the progressive inability of the geothermal record to resolve relatively rapid events in the more distant past, there is no apparent signature of the Younger Dryas temperature excursion (12,700–11,500 years BP) in the reconstruction.

[20] All reconstructions show a temperature some 3.5 to 4 K below the reference level near the end of the Last Glacial Maximum (LGM), but one must recognize that this probably represents little more than the very long term average temperature over a succession of many glacial and interglacial periods. It is consistent with the estimate presented in IPCC (2007) of 4–7 K of warming since the LGM. Following the reconstructions in Figure 1 forward in time from the mid-Holocene warm interval, one observes a cooling to a broad minimum of about 1.5 to 2 K around 1800 years BP, a feature well-documented in subsurface temperatures in Greenland [*Dahl-Jensen et al.*, 1998], but as the global heat flux data indicate, apparently much more widespread.

[21] Figure 2 displays the array of reconstructions on an expanded time scale extending over the past 2000 years (AD 1 to 2000). The broad cool minimum around 1800 years BP (AD 200) was followed by a warming that peaked around 600–800 years BP (AD 1200–1400; the Medieval Warm Period), a subsequent cooling to a minimum around 200–300 years BP (AD 1700–1800; the Little Ice Age, LIA), followed by rapid and substantial warming in the past few centuries. The reconstructed peak temperatures in the MWP appear comparable to the AD 1961–1990 mean reference level, with the bold mid-range curve slightly below. None of the reconstructions show MWP peak temperatures as high as late 20th century temperatures, consistent with the conclusions of both *National Research Council* [2006] and *Intergovernmental Panel on Climate Change* [2007] about the warmth of the MWP. The LIA temperature minimum shows an amplitude about 1.2 K below the MWP maximum, and about 1.7 K below present-day temperatures.

[22] We call attention to the greater amplitude and narrower temporal extent of the LIA cooling shown in Figures 1 and 2, as compared to the HPS00 reconstruction. The comments made earlier in comparing HPS97 and HPS00 remain relevant in the context of understanding the differences between the present 20,000 year reconstruction and HPS00. Differences between these arise because the reconstruction we present here in Figures 1 and 2 involves inversion of a much larger but noisier dataset and represents a much longer time period. Those conditions require different parameterizations, different smoothing parameters, and different noise suppression techniques than those employed in the shorter HPS00 reconstruction. In a generalized least squares formulation, in which the optimal solution is obtained by minimizing over the entire (un-segmented) data and model misfits, it is impossible to replicate a reconstruction parameterized differently and optimized over a very small segment of the reconstruction interval. The present reconstruction is our optimal estimate of the surface temperature history over 20,000 years; it in no way invalidates or replaces HPS00 as our best representation of the most recent five centuries alone.

[23] The climatic excursions described above – a late Pleistocene warming leading to a mid-Holocene warm episode, a MWP and a LIA – are consistent with the broad outlines of late Quaternary climate histories suggested by other proxies. The timing of some features seen in our reconstructions differs modestly from chronologies inferred from other proxies. Such differences can arise because of the intrinsic regional and temporal variability of climatic excursions, the differences in geographic sampling of various proxies, and the limitations on temporal resolution inherent in geothermal reconstructions. For example, in Greenland the thermal expressions of the LIA and the mid-Holocene warm period seen in the subsurface temperatures of the GRIP and Dye-3 boreholes, separated by just 800 km, show significant variability in depth of occurrence (timing) and amplitude [*Dahl-Jensen et al.*, 1998].

[24] The *Intergovernmental Panel on Climate Change* [2007] discussion of the MWP notes “that medieval warmth was heterogeneous in terms of precise timing and regional expression.” *Lamb* [1977a, 1977b] also commented on the spatial and temporal variability in medieval warmth; in Greenland the warmest conditions occurred between AD 950–1100, but throughout most of Europe between AD 1150–1300. Heat flux data from Europe contribute significantly to our reconstruction, and thus may explain why the reconstruction shows the peak of the MWP between AD 1200–1400. And finally, the ability of the geothermal data to resolve two separate warm episodes (AD 1000–1100 and AD 1350–1450, IPCC 2007 p.468) is limited, and the reconstructions simply indicate that the broad time interval encompassing both was on average relatively warm.

## 5. Summary and Conclusions

[25] The 20,000 year reconstructions presented in HPS97 utilized observations contained in a database of terrestrial heat flux measurements. Data from the depth range 0–100 meters, the depth range where most of the information about 20th century climate change resides, were excluded from the reconstruction because of noise considerations. Thus the reconstructions derived from that dataset cannot be used to compare the Medieval Warm Period to changes taking place in the 20th century.

[26] A 500 year reconstruction (HPS00) derived from a different database, one containing actual temperature observations at different depths below the surface, shows a warming of about 1 K from the cool temperatures of the Little Ice Age in the 16th and 17th centuries. More than half of the warming has occurred in the 20th century alone. This result has played a prominent role in discussions of past climate appearing, for example, by *National Research Council* [2006] and *Intergovernmental Panel on Climate Change* [2007].

[27] We present a suite of new 20,000 year reconstructions that integrate the information in the heat flux database, the T-z database, and the 20th century instrumental record of temperature, all referenced to the 1961–1990 mean of the

instrumental record. These reconstructions resolve the warming from the last glacial maximum, the occurrence of mid-Holocene warm period, a MWP and LIA, and the rapid warming of the 20th century, all occurring at times consistent with a broad array of paleoclimatic proxy data. The reconstructions show the temperatures of the mid-Holocene warm period some 1–2 K above the reference level, the maximum of the MWP at or slightly below the reference level, the minimum of the LIA about 1 K below the reference level, and end-of-20th century temperatures about 0.5 K above the reference level. All of these amplitude estimates are, as with the timing of these episodes, generally consistent with amplitudes estimated from other climate proxies as summarized by *Intergovernmental Panel on Climate Change* [2007].

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