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Late Quaternary temperature changes seen in world-wide continental heat flow measurements

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Abstract. Analysis of more than six thousand continental heat flow measurements as a function of depth has yielded a reconstruction of a global average ground surface temperature history over the last 20,000 years. The early to mid-Holocene appears as a relatively long warm interval some 0.2-0.6 K above present-day temperatures, the culmination of the warming that followed the end of the last glaciation. Temperatures were also warmer than present 500-1,000 years ago, but then cooled to a minimum some 0.2-0.7 K below present about 200 years ago. Although temperature variations in this type of reconstruction are highly smoothed, the results clearly resemble the broad outlines of late Quaternary climate changes suggested by proxies.

Introduction

Temperature changes at the Earth's surface propagate downward into the crustal rocks by thermal conduction and impart perturbations to the subsurface temperatures and heat flow. A progressive cooling at the surface will increase the upward heat flow at shallow depth, while a progressive warming will result in a diminished or even negative flow. If the surface temperature oscillates with time, oscillations in the subsurface temperature and heat flow profile will follow. Therefore, present-day rock temperatures and heat flow at shallow depths of the crust preserve a record of the past variation of surface temperature (Birch, 1948), although the resolution of past events becomes murkier with time because of the diffusive nature of heat conduction and the obscuring effects of noise (Clow, 1992; Beltrami and Mareschal, 1995).

Reconstructing this ground surface temperature history from borehole temperatures has become a major endeavor of geothermal research in recent years (For an overview see Lewis, 1992; Other works include: Cermak, 1971; Beck, 1977; Lachenbruch and Marshall, 1986; Beltrami and Mareschal, 1991; Wang, 1992; Wang and Lewis, 1992; Pollack and Chapman, 1993; Majorowicz, 1993; Deming, 1995; Harris and Chapman, 1995; Huang et al., 1996; Pollack et al, 1996; Shen et al, 1995, 1996). Here we examine a large archive of continental heat flow measurements for evidence of late Quaternary temperature variations. The approach is novel in that we attempt a global rather than local reconstruction. The attractiveness of this approach derives from the existence of the large database of terrestrial heat flow measurements (Pollack et al., 1993) compiled by the International Heat Flow Commission (IHFC) of the International Association of Seismology and Physics of the Earth's Interior. This compilation includes data from both continental and oceanic regions but only data from continents are suitable for long term climate reconstructions. Oceanic heat flow data are less useful in this context, mainly because they are determined from measurements with a probe which penetrates only a few meters into the sediments on the ocean floor, therefore precluding an analysis of heat flow versus depth over a sufficient depth range.

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Data

More than 13,000 continental data entries reside in the IHFC database, about half of which include information about the depth range over which the heat flow determination was made. For those data with such depth information, we take the mid-point of the reported depth range of temperature measurements used in the determination of the heat flow to establish a representative depth for each heat flow observation. These heat flow data were then ordered by this depth and averaged over 50 m intervals. We excluded data with representative depths less than 100 m or greater than 2000 m. The uppermost hundred meters is the depth range most susceptible to non-climatic perturbations such as advective heat transfer associated with ground water flow and terrain effects related to topography and vegetation; moreover, subsurface temperatures in this depth range yield information principally about the most recent century. Below 2,000 meters there are too few data to enable reliable estimates of heat flow over sufficiently short depth intervals. Synthetic experiments also show that climatic perturbations of realistic amplitude over the last 20,000 years are retained mainly within the upper 2,000 m. We have also excluded heat flow values in excess of 150 mW m^{-2} because advective disturbances are frequently observed in terrains with very high geothermal gradients, and we did not include data from the continental shelves because the Earth's solid crust there is not in direct contact with the atmosphere. A total of 6,144 heat flow measurements survived the exclusionary filters and qualified for analysis. The mean of these qualifying heat flow measurements is slightly less than the average continental heat flow reported by Pollack, et al. (1993) because of the exclusion of the very high heat flow values and continental shelf data, both of which comprise measurements on the high side of the continental average. The geographic distribution of the qualifying sites is shown in Figure 1. Although the majority are concentrated in the mid-latitudes of the northern hemisphere, the data set has some representation from every continent.

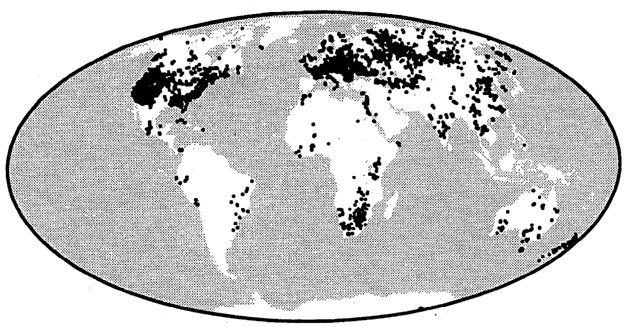

Figure 1. Map showing the location of the qualifying heat flow sites selected from the global heat flow data compilation of the International Heat Flow Commission.

The statistics of the selected heat flow data over 50 m intervals are summarized in Table 1. The standard errors of the interval means reflect principally the regional variability of the continental heat flow, and generally increase with depth as the numbers of observations comprising the successive interval means diminish. The distribution contains both short and long wave-length variations of heat flow as a function of depth. These variations show no clear relationship to the thermal conductivity or heat production of the rocks, and cannot be easily explained by other global scale perturbations, for example a depth-dependent advection signature, in the heat flow distribution. It is, however, possible that such variation could arise from climatic perturbations at the surface.

Table 1. Statistical summary of the selected heat flow measurements in 50 m intervals

Depth range (m)	Interval mean heat flow (mW m^{-2})	Standard error (mW m^{-2})	Number of measurements
100-150	61.5	0.9	1001
150-200	62.2	1.0	704
200-250	63.1	1.1	509
250-300	58.3	1.3	365
300-350	61.6	1.7	299
350-400	56.2	1.5	265
400-450	58.2	1.6	221
450-500	61.9	1.8	206
500-550	57.7	1.8	197
550-600	62.2	1.9	175
600-650	62.1	1.6	169
650-700	58.7	1.9	121
700-750	58.0	1.9	107
750-800	56.5	2.0	90
800-850	60.0	2.2	98
850-900	58.3	2.4	86
900-950	56.9	2.3	79
950-1000	53.3	2.0	73
1000-1050	57.0	2.1	96
1050-1100	59.0	2.7	61
1100-1150	60.2	2.9	73
1150-1200	61.7	2.9	69
1200-1250	58.6	2.1	78
1250-1300	57.0	1.8	82
1300-1350	55.4	1.9	77
1350-1400	58.9	1.8	88
1400-1450	57.6	1.6	97
1450-1500	56.9	1.9	85
1500-1550	58.3	1.7	98
1550-1600	56.9	1.9	70
1600-1650	58.2	2.1	68
1650-1700	59.6	2.2	62
1700-1750	54.9	2.2	53
1750-1800	58.9	2.5	58
1800-1850	59.4	2.5	56
1850-1900	57.0	2.1	42
1900-1950	58.1	2.9	29
1950-2000	61.4	2.4	37

To enable an interpretation of the variation of heat flow with depth in terms of a temporal variation of temperature at the surface, we convert the interval heat flow data into a temperature profile via integration of Fourier's equation of heat conduction (Carslaw and Jaeger, 1959), and then invert the temperature profile with a Bayesian functional space inversion scheme (Shen and Beck, 1991). In a layered crust, the variation of heat flow with depth is equivalent to the temperature profile calculated from $T_i = T_0 + \Sigma\, q_i D_i / K_i$, where T_i is the temperature at the base of the ith layer; T_0 is the temperature at the Earth's surface; q_i, K_i, and D_i are respectively the heat flow, thermal conductivity and thickness of the ith layer.

Climate Reconstruction

The inversion makes use of the one-dimensional theory of heat conduction as the link between past temperature changes at the surface and the present-day variation of heat flow with depth. Because heat conduction is a diffusive process, the Earth acts as a low pass filter, selectively attenuating shorter period fluctuations as they propagate downward. The inversion scheme, as we employ it, is framed very conservatively in terms of a null hypothesis, i.e. with an *a priori* assumption that there is no climate signal present in the interval mean heat flow as a function of depth. If the null hypothesis were true, the observed heat flow would represent only the steady-state heat flow from the Earth's interior, and should be a diminishing linear function of depth, with a slope governed by the rate of radiogenic heat generation in the crustal rocks.

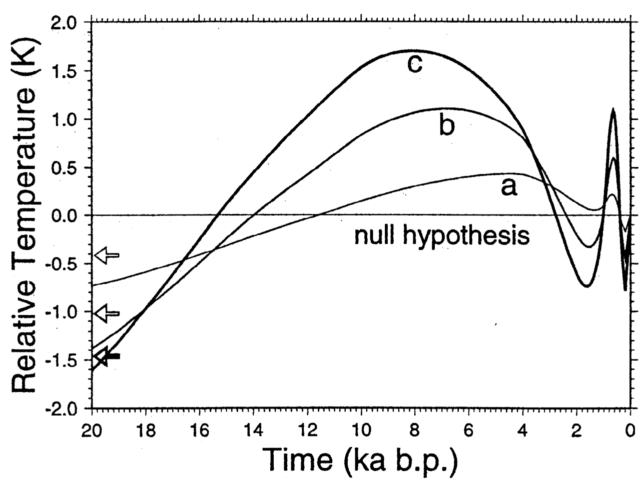

Figure 2. Surface temperature histories over the last 20,000 years shown as deviations from the present-day temperature. The null hypothesis, in which it is assumed there has been no climatic perturbation, is shown by the dashed line. The three curves labeled a, b, and c represent reconstructions resulting from progressively greater weight given to the data, which in turn allows progressively greater deviations from the null hypothesis. The arrows on the left show the apparent steady-state surface temperature prior to the interval represented.

Departures of the data from linearity would then be ascribed to random noise. But if the subsurface thermal regime exhibits a sufficiently structured non-random pattern of variation with depth, the inversion will return a ground surface temperature history that deviates from the *a priori* null hypothesis. In this circumstance the inversion separates the subsurface thermal regime into two components, a steady-state temperature distribution corresponding to the heat flowing upward from greater crustal depths, and a transient component corresponding to climatic perturbations propagating downward from the surface.

Three surface temperature history reconstructions are shown in Figure 2 (a,b,c), representing results from inversions that respectively give increasing weight on the internal structure of the observations and their correlation over a range of depth scales. In a Bayesian approach to interpretation of data, one holds data in one hand, and in the other hand a conceptual model within which the data are to be interpreted. Both model and data have associated uncertainties and inadequacies, and depending on how an investigator weights each of them, the final interpretations will differ. The inversion balances the conflict, if any, between the observations and the *a priori* model, with the balancing weighted by the investigator's assessment of the quality of the observations and the adequacy of the model. We believe three reconstructions shown in Figure 2 represent the range of permissible outcomes that can be achieved, when sufficient weight is given to the observations to permit a deviation from the null hypothesis if the data push in that direction, yet not with so much confidence in the data to require the outcome to reflect every detail of the heat flow versus depth profile. Reconstructions that deviate from the null hypothesis even less than 2a are indeed possible, but they require a more forceful adherence to the null hypothesis and a weaker assessment of the observations than we feel is merited. Similarly, reconstructions with amplitudes much greater than 2c can be achieved, but we believe such amplitudes are climatically unrealistic. Moreover, inversions that yield reconstructions beyond 2c also begin to show additional short period oscillations, an indication that noise is not being adequately suppressed (Shen et al., 1995). The *a priori* thermophysical properties utilized in these reconstructions include 2.5 W m^{-1} K^{-1} for thermal conductivity; 1.0×10^{-6} m^2 sec^{-1} for thermal diffusivity; and 1.5×10^{-6} W m^{-3} for radiogenic heat production. A variation of thermal diffusivity in the range $(0.8\text{-}1.2) \times 10^{-6}$ m^2 sec^{-1} shifts the timing of events modestly and affects the amplitudes negligibly.

These surface temperature histories shown in Figure 2 indicate a long-term warming from the colder conditions of the last glacial epoch of the late Pleistocene, peaking at temperatures above present-day in the interval 4,000-8,000 years ago. For several thousand years in the early Holocene the temperature averaged some 0.2-0.6 K above present-day. Following this warm interval a cooling ensued in which the temperature dropped to near or below present-day, reaching a minimum in the interval 1,300-1,600 years before present. A warming followed, yielding temperatures that averaged 0.1-0.5 K above present-day in the interval 500-1,000 years ago. From the peak of this warm period some 700-800 years ago, the temperature declined until about 200 years ago, reaching a minimum of about 0.2-0.7 K below present-day, at which time a warming commenced that continues to the present. The timings of the more recent climatic events are better constrained and better resolved than are the more remote ones. The range of timing and relative amplitudes of the principal events appearing in the reconstructions resemble generalized Holocene temperature histories derived from a variety of proxies (see, for example, Folland et al., 1990), and suggest that the frequently cited but still rather contentious climatic intervals such as the mid-Holocene Maximum, the Medieval Optimum, and Little Ice Age may have a residual signature in the thermal regime of the upper continental crust. We emphasize, however, that the reconstructions we derive from geothermal observations are independent of other proxy interpretations. Indeed, the *a priori* null hypothesis renders the analysis independent of any preconceptions or biases as to the nature of the actual climate history.

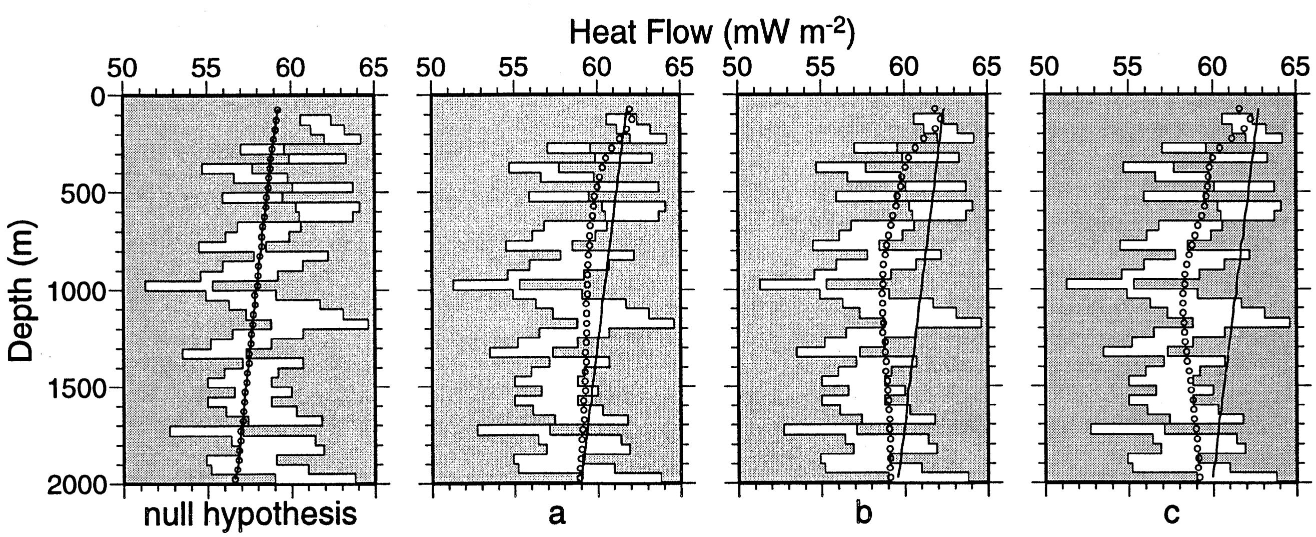

Figure 3. The calculated heat flow versus depth as compared to the 50 m interval mean heat flows given in Table 1. The four panels correspond to the four cases shown in Figure 2. The observed interval means ± standard error are represented by the open boxes, and the calculated heat flow values by the open circles. The inferred steady-state component of the heat flow is shown with solid lines. The transient component at each depth is the difference between the calculated heat flow and the steady state component.

Discussion

The surface temperature histories we show in Figure 2 are highly smoothed reconstructions, for several reasons. First, the downward propagation of a climate signal by heat conduction is a diffusion process; as with all diffusion processes, details are progressively muted with time, and short term excursions in the more remote past such as the Younger Dryas cool event around 11,000 years ago have little chance of being resolved. Second, we are attempting to recover a global climate history from worldwide observations that display regional and local variation. The regional and local climate variability, as well as observation errors, contribute to the standard errors shown in Table 1 and appear as noise in the inversion process. Such noise adversely affects the resolving power of the inversion, because in attempting to suppress the effects of the noise, one also pays the price of muting the recovered signal (Shen et al., 1995). Third, the *a priori* null hypothesis, the smoothest possible climate model, also plays an important role in smoothing the results. In a Bayesian inversion of this kind, the output model is always the one with the least "distance" from the *a priori* hypothesis, within a tolerance bound set by the data confidence level.

The data misfits corresponding to the four cases shown in Figure 2 are displayed in the four panels of Figure 3. For the null hypothesis, the calculated and steady-state heat flows coincide, as the null hypothesis assumes no transient component. For cases a, b, and c the magnitude of the transient component increases progressively. As more weight is given to the data and less to the null hypothesis, a greater portion of the heat flow variation is interpreted as a transient climatic perturbation from the surface, and a smaller data misfit results. But not all the variability in the heat flow vs. depth profile can or should be interpreted in terms of climate change in the past, and thus data misfit remains. The inversion codes identify the possible and reject the impossible transient anomalies, so as to be consistent with the theory of heat conduction and with reasonable constraints on the possible amplitudes of climatic fluctuations.

The surface temperature histories shown in Figure 2 extend back only 20,000 years, but the inversions also provide an estimate (shown by the arrows in Figure 2) of the prior steady-state, i.e. the long term mean surface temperature for earlier times, beyond the ability of the present-day subsurface thermal data to resolve a transient. These estimates are below the present-day surface temperature, a not-unexpected result considering that the present-day is near the warm peak of an interglacial interval, whereas the apparent steady-state would be an average of both glacial and interglacial intervals in the Quaternary. For the same reason the apparent steady-state temperature is warmer than estimated temperatures during a glacial maximum

The geothermal record of climate change loses resolution with depth and thus with time, and is noisy because of regional variation. Nevertheless, we have shown that with the statistical bolstering of thousands of observations, the geothermal archive yields an independent reconstruction of the broad outline of the late Quaternary temperature history, complementary to and not inconsistent with other perspectives of Holocene climate derived from a variety of proxies. Preliminary data processing experiments with the heat flow data set also suggest that the information content of the data set may be adequate to permit inter-regional comparisons, and thus enable questions of latitudinal modulation and hemispherical differences in Holocene climate to be addressed.

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