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CLIMATE RECONSTRUCTION FROM SUBSURFACE TEMPERATURES

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■ **Abstract** Temperature changes at the Earth's surface propagate downward into the subsurface and impart a thermal signature to the rocks. This signature can be measured in boreholes and then analyzed to reconstruct the surface temperature history over the past several centuries. The ability to resolve surface temperature history from subsurface temperatures diminishes with time. Microclimatic effects associated with the topography and vegetation patterns at the site of a borehole, along with local anthropogenic perturbations associated with land use change, can obscure the regional climate change signal. Regional and global ensembles of boreholes reveal the broader patterns of temperature changes at the Earth's surface. The average surface temperature of the continents has increased by about 1.0 K over the past 5 centuries; half of this increase has occurred in the twentieth century alone.

INTRODUCTION

The ongoing debate about how humans affect Earth's climate has brought a new focus and urgency to understanding climate variability prior to the rapid growth of the human population and prior to the large-scale use of fossil fuels in the industrial economy. In this review, we describe the role that temperatures beneath the Earth's surface play in the reconstruction of Earth's climate over the past thousand years, and in some cases even earlier.

The past millennium is an important time interval to examine because it includes many significant changes. In the year 1000 AD, Earth's population was no more than 5% of the current population, and per capita energy consumption was a trivial fraction of modern usage. Moreover, the limited energy consumption at that time mainly involved the use of renewable resources such as falling water and wood. Significant consumption of fossil fuels began in the latter half of the eighteenth century, with the use of coal during the then-young Industrial Revolution. The discovery of hydrocarbons in the nineteenth century and their dramatic growth as fuels in the twentieth century came at the same time that the population was increasing by more than an order of magnitude. Thus, comparative

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climatology investigations that can assess and place in context the human perturbation of Earth's climate must focus on the industrial era, comprising approximately the past two centuries, and the preindustrial era, comprising the several centuries preceding that.

From approximately 1860, meteorological stations have provided an instrumental record of temperature, precipitation, and other significant climatologic indicators from the continents and some oceanic islands. There are, of course, important meteorologic observations over longer time periods in a few selected areas, but it was not until the latter decades of the nineteenth century that geographic coverage was widespread in both the northern and southern hemispheres. Land-based observations have been complemented by sea surface temperatures compiled from the navigational and engineering logs of ships at sea, and for the past two decades by satellite observations of mean tropospheric temperatures. For the time period prior to the development of an instrumental record, however, climate reconstruction must be based on indirect evidence derived from climate proxies. As the word proxy implies, indirect observations must serve as substitutes in some way for the lack of a global instrumental record before the mid–nineteenth century.

Traditional proxies that have been successfully employed include historical records of agricultural production; the composition, thickness, and structure of tree rings; isotopic chemistry of annual growth increments in corals; sequences of lacustrine varves; pollen composition and distribution; loess properties and isotopic variations in ice cores; and the abundance of various cosmogenic isotopes (a proxy for solar variability). Joining these proxies in comparatively recent times are temperatures in the rocks beneath the Earth's surface, as measured in boreholes. In a sense, this subsurface temperature distribution is not strictly a proxy because the observations are direct measurements of temperature with a thermometer. However, the subsurface temperature distribution is not a direct representation of the surface temperature history, but rather a consequence of it, and therefore the subsurface observations can also be considered a climate proxy.

The fundamental concept behind subsurface temperatures as a climate proxy can be succinctly stated: If Earth's atmosphere experiences a warming or cooling, the soil and rock in contact with the atmosphere will feel this change. Such temperature changes at the Earth's solid surface then propagate into the subsurface by heat conduction through the soil and rock. The process is analogous to the warming of a cold ceramic cup after hot tea is poured into it. The interior surface of the cup experiences an increase in temperature, which then propagates through the wall of the cup and can be sensed a short time later on the exterior surface. Similarly, variations of temperature at the Earth's surface associated with climate change can be thought of as a time-varying boundary condition on the upper boundary of the solid Earth. But whereas heat conducts through a cup in just minutes, temperature fluctuations at the Earth's surface take several hundred years to penetrate the upper few hundred meters of the subsurface. Several nontechnical overviews are available as general introductions to the geothermal approach to climate reconstruction (Pollack 1993, Pollack & Chapman 1993, Cermak et al 1993, Vasseur & Mareschal 1993, Beltrami & Chapman 1994).

HISTORICAL PERSPECTIVES

Perhaps the earliest recognition that climate change imposed a signature on subsurface temperatures was by Lane (1923), in the context of estimating the effect Pleistocene glaciations and the Holocene deglaciation had on temperature measurements in mines near the southern margin of Lake Superior. Later, Hotchkiss & Ingersoll (1934) analyzed these mine temperatures in an attempt to date the termination of the last glaciation.

As measurement of the terrestrial heat flux became a major endeavor in geophysics in the latter half of the twentieth century (Pollack 1982), interest in climate change centered on how it might affect the estimate of the geothermal gradient and thus the determination of heat flow from Earth's interior. Accordingly, various climate change scenarios, such as the generally increasing temperature as Earth emerged from the last glacial maximum about 20,000 years ago, were constructed from other geological evidence and climate proxies. The temperature history at the surface reconstructed from such sources was then used as a time-varying boundary condition for a forward model of the perturbed subsurface temperatures and temperature gradients, which in turn could be used to make a ''climatic correction'' to the observed heat flow (Birch 1948). These calculations revealed that climatic events occurring in the Late Pleistocene and Holocene perturbed temperatures to depths of a few kilometers and could have a modest effect on the estimate of the terrestrial heat flow (Beck 1977, Cull 1979, Clauser 1984, Kukkonen 1987, Pimenov et al 1996, Mareschal et al 1999) in the depth range of most continental heat flow determinations.

In contrast to assuming a climate history, Beck & Judge (1969) analyzed the variation of heat flow with depth in a borehole and obtained an estimate of the amplitude of temperature change and the timing of onset and termination of the last glaciation. Cermak (1971) provided the first detailed climate reconstruction on several timescales. The analysis of geothermal data from the north slope of Alaska by Lachenbruch & Marshall (1986) placed borehole temperature investigations into the context of the global warming debate and provided an impetus for much subsequent climate-related research.

GROUND SURFACE TEMPERATURE

The spatial variation of temperature over the planetary surface is set principally by the balance of incoming radiation (mainly solar) and outgoing terrestrial radiation, establishing a fundamental latitudinal variation. That simple distribution is modified by albedo variations between the land, sea, and ice, and by atmospheric and oceanic circulation that redistributes heat over the planetary surface. Because the energy flux reaching Earth from the Sun is some 4000 times greater than the energy flux from the Earth's interior, the surface temperature of the planet is dominated by external rather than internal forcings.

The local temperature of the ground surface itself is the outcome of coupled physical and biological processes in both the atmosphere and the ground (Geiger 1965, Van Wijk 1963, Sellers 1992, Sellers et al 1997, Putnam & Chapman 1996) that affect the radiation balance. These processes are quite complex in detail and involve factors such as latent and sensible heat fluxes; precipitation; ground or vegetative surface roughness; the chemistry, hydraulic conductivity, thermal diffusivity, and moisture content of the soil or rock; chemical fluxes to and from the atmosphere; wind; and many others. Moreover, the relative significance of these factors varies with time through the diurnal and seasonal oscillations, as well as in longer-term changes associated with changing land use, vegetation, and climate.

SUBSURFACE TEMPERATURES

Observations

Temperatures beneath the Earth's surface are most commonly obtained by lowering a thermometer to a given depth in a borehole and observing the temperature at that point. The process is repeated at successively greater depths until a profile of temperature versus depth is obtained (Figure 1). Another measurement scheme uses several temperature sensors fixed at various positions along a cable, which is then introduced into a borehole quasi-permanently for long-term monitoring of

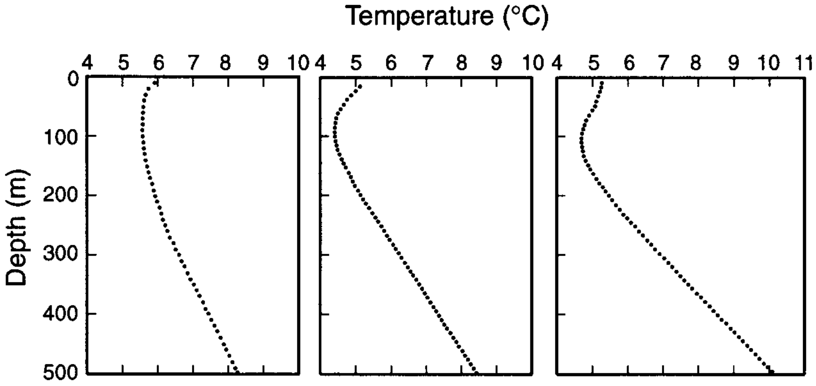

Figure 1 Temperature measurements (*dots*) at various depths in three boreholes in eastern Canada. The curvature in the *upper parts of the profiles* is a response, at least in part, to temperature changes at the surface. The linear increase of temperature with depth in the deeper sections of the holes is the undisturbed geothermal gradient.

temperatures at the selected depths. For measurements at or very near the surface, thermometers can be buried directly in the soil. Temperatures have also been obtained at various working levels of underground mines, where thermometers are inserted into horizontal borings in the walls of the shafts to reach virgin rock temperatures undisturbed by the opening of the mine shafts and tunnels. Liquid-in-glass thermometers with a precision of about 0.1 K were commonly used in some earlier surveys, but for the past several decades electrical resistance thermometers with a precision of better than 0.01 K have been the instrument of choice.

Many thousands of boreholes around the world have been subjected to temperature logging in the course of determining the terrestrial heat flux (Pollack et al 1993). Thus, an abundance of observations exists, but because of the many investigators and different measurement practices and techniques, the data are heterogeneous. The heterogeneity arises from different borehole depths, different logging depth intervals, and variable information about thermophysical properties, subsurface geological structure, and surface site characteristics. Even with such heterogeneity, however, quality data are sufficiently abundant and the analysis tools sufficiently flexible to allow credible climate reconstructions from these data at many sites around the world.

Another body of shallow subsurface temperature data comes from measurements of soil temperature at meteorological and agricultural research and experimental stations, and in boreholes drilled into permanently frozen ground (see, for example, Baker & Ruschy 1993, Osterkamp & Romanovsky 1994, Zhang et al 2000). These measurements typically are made at depths of a few centimeters to a few tens of meters, with permanent installations of the thermometers to enable monitoring of temporal changes. They frequently are accompanied by other instruments that determine air temperature and other meteorological variables at or near the surface, and soil moisture and various chemical parameters in the near subsurface. Diurnal temperature changes are observed in the upper 2 m of the soil, and annual (seasonal) changes in the upper 20 m. Annual time series for soil temperatures are rarely a century long, and usually much shorter.

An example of a shallow temperature time series is displayed in Figure 2. At the 12.8-m depth of observation at this site, inter-annual variations are still apparent, as is an upward trend of temperature of 0.04 K per year over the 28-year time interval of the measurements. Although these shallow measurements can provide information about the surface temperature history only for the time interval represented by the time series, they are useful complements to the longer but less well resolved histories determined from the deeper borehole temperature profiles.

Factors Affecting Subsurface Temperatures

The temperatures in the Earth's near subsurface are governed principally by two processes: (*a*) the spatial and temporal variations of temperature at the ground surface, which arise from topography, vegetation patterns, and hydrological and

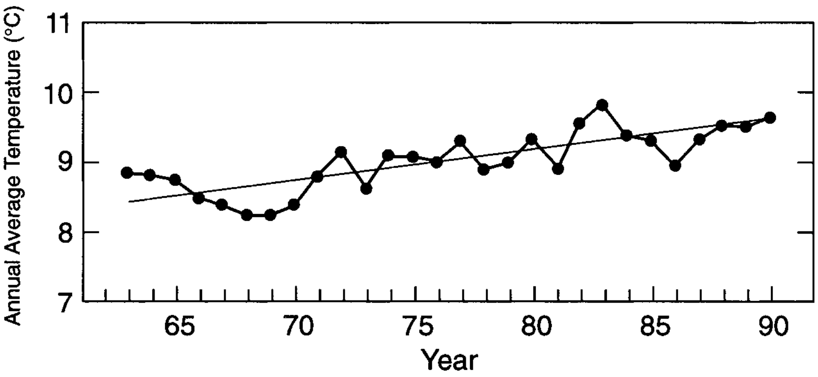

Figure 2 Annual mean subsurface temperature (12.8 m below surface) at a site in north-central United States in the interval 1963–1990. The *line* is the temperature trend over the 28-year time interval. (Modified from Baker & Ruschy 1993.)

climatological processes that have diurnal, seasonal, decadal, and millennial characteristic timescales; and (*b*) the outward flow of heat from the deeper interior. The determination of the deeper heat flux from subsurface temperatures is also influenced by three-dimensional subsurface structure and ground water movement. The deeper heat flux reflects long-term deep-seated geological processes, and has a characteristic timescale of change on the order of millions of years. The surface temperature variability occurs on much shorter timescales than do the geological processes that determine the deeper heat flow. Therefore, the climatological perturbations can be thought of as transient effects superimposed on the quasi steady state temperature regime of the deeper heat flow.

In the absence of any climatic or other surficial perturbations, the subsurface temperature distribution reflects only the deep heat flow, and in a homogeneous medium is characterized by a uniform increase of temperature with depth. The rate of increase, known as the geothermal gradient, is directly proportional to the amount of the heat flow from below (which varies regionally) and inversely proportional to the thermal conductivity of the rock through which it is being transported. The geothermal gradient falls in the range of 10–50 K km^{-1} in most geological settings on the continents. The steady state geothermal gradient is apparent in the deeper parts of the borehole temperature profiles shown in Figure 1.

Temporal variations of temperature at the Earth's surface can be spectrally decomposed into thermal disturbances of different periods, with variable amplitudes and phase relations. The theory of heat conduction (Carslaw & Jaeger 1959) shows that such surface disturbances propagate downward as thermal waves, and as they propagate their amplitudes diminish exponentially with depth beneath the surface. The attenuation during propagation is, however, frequency dependent. Longer period waves attenuate less with depth than do shorter period waves

(Figure 3). Thus the crustal rocks act as a low-pass frequency filter, allowing longer period waves to propagate to greater depths than shorter period waves before being attenuated below the level of detection. The diurnal and seasonal variations of surface temperature, although relatively large in amplitude compared with long-term climatological trends, cannot be detected at depths greater than a few meters and few tens of meters, respectively. Therefore, at increasing depths below the surface only progressively longer-term temperature trends are imprinted.

The pace at which the signal propagates is governed principally by the thermal diffusivity, a physical property that governs space-time relations in a conducting medium, and that is directly proportional to the thermal conductivity of the material. The characteristic values of these material properties in most crustal rocks are such that all temperature changes at the surface during the last millennium would be confined (at present levels of detection ability) to the upper 500 m of the Earth's crust. This slow diffusion places crustal rocks in the category of thermal insulators, as compared with metals which transport heat more easily.

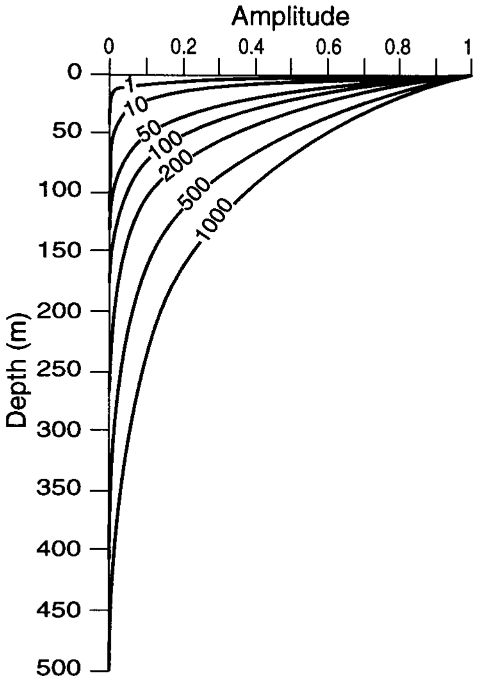

Figure 3 Attenuation with depth of a unit amplitude thermal wave propagating downward in a medium with thermal diffusivity of 10^{-6} m^2 s^{-1}. *Numbers on the curves* represent the period of the thermal wave in years.

INTERPRETATION OF SUBSURFACE TEMPERATURES

Virtually all of the common interpretive schemes that reconstruct ground surface temperature history from present-day subsurface temperature profiles are cast in terms of the one-dimensional theory of heat conduction. In such a representation, the link between a present-day temperature vs depth profile and the past surface temperature history that produced that profile is the thermal diffusivity of the medium.

All interpretive approaches must separate from the observed borehole temperature profile the steady state background temperatures associated with the deep heat flow. The temperature profile remaining after separation, sometimes referred to as a ‘‘residual’’ temperature profile (Chisholm & Chapman 1992), contains the components of the original observations that are deemed transient. It is this transient component that, when analyzed, yields a reconstruction of climate change at the surface. The separation sometimes is effected visually but can be incorporated directly within the interpretive algorithms (Shen & Beck 1991).

The approaches to reconstructing a ground surface temperature history generally fall into two broad categories: forward models and inverse models. In the forward model, a candidate climate history is assumed, its subsurface expression is calculated, and the differences between the model expression and the observed subsurface temperatures are quantified. Many models can be tested for their match to the data, and models with a minimum of mismatch are deemed acceptable results. Such a trial-and-error approach has been used, for example, in the analysis of the Greenland subsurface temperature profiles discussed below (Dahl-Jensen et al 1998).

Inverse models comprise an alternative interpretive methodology in which the observations play an active rather than passive role in the determination of a satisfactory model climate history. Inversion formulations generally allow more formal flexibility in addressing the parameterization of the reconstruction, the suppression of noise, the incorporation of prior information, and the assessment of uncertainty and resolution. Because the observations always contain noise of some magnitude, model accommodation of every detail of the observations, i.e. an absolute minimization of misfit between model and observations, amplifies noise as well as signal and leads to spurious interpretations (Shen et al 1995). It is therefore important to have available the tools offered by sophisticated inversion schemes that let the investigator exercise judgment about data quality, and that place constraints on the resulting reconstructions. Most of the reconstructions described later are the products of various inversion schemes; we review next some aspects of inversion relevant to the recovery of climate models from subsurface temperatures.

Inversion

The first formal inversion of temperature measurements in deep boreholes to reconstruct climate history was done by Cermak (1971). This work, cast as a linear inverse problem, set the stage for the application of several subsequent inversion schemes, both linear and nonlinear (Vasseur et al 1983, Shen & Beck 1991, MacAyeal et al 1991, Wang 1992, Mareschal & Beltrami 1992, Beltrami & Mareschal 1995, Bodri & Cermak 1995, Cooper & Jones 1998). Within each inversion scheme there are choices to be made with respect to model parameterization, stabilization factors, optimization norm, and use of a priori information. Adding to the complexity of application is the fact that such choices are probably data dependent, i.e. the optimum choices for one borehole temperature profile may not be the best for another. Not surprisingly, a number of studies have compared the results of different inversion schemes operating on common data sets (Shen et al 1992, Beck et al 1992, Shen et al 1996). Interpretation of apparent regional differences in climate history has been complicated somewhat by the problem of ‘‘comparing apples and oranges’’ in the context of the different inversion schemes used by different investigators.

Obscuring Factors

Although many borehole temperature logs exist, caution must be exercised in selecting data for analysis and in interpreting the climate reconstructions, because in addition to climatological perturbations of the subsurface temperature regime, there are many other nonclimatological perturbations to contend with. As noted previously, the theoretical framework of all climate reconstruction techniques is the one-dimensional theory of heat conduction in a laterally homogeneous medium (i.e. only vertical conductive heat transfer). Therefore, any subsurface temperature variations arising from conditions that depart from that theoretical model have the potential to be incorrectly interpreted as a climate change signature. Topography, vegetative patterns, and hydrological features at the surface, as well as lateral heterogeneity, phase changes, and advective (nonconductive) heat transfer by groundwater movement in the subsurface, can alter the subsurface temperature regime with perturbations of the same order of magnitude as a climate change signature. These factors have been investigated in some detail, and their effects can be quantitatively modeled if sufficient information about the setting of a borehole is available (Blackwell et al 1980; Bauer & Chapman 1986; Powell & Chapman 1990; Chisholm & Chapman 1992; Lewis & Wang 1992; Safanda 1994, 1998, 1999; Kukkonen et al 1993; Kukkonen & Clauser 1994; Shen et al 1995; Clauser et al 1997; Duchkov et al 1997; Kohl 1998, 1999; Guillou-Frottier et al 1998). Additionally, even if subsurface perturbations arise principally from surface temperature changes, several nonclimatological surficial processes such as deforestation, mining, wetland drainage, agricultural development, and urbanization can mimic natural climate change (Cermak et al 1992, Sebagenzi et al 1992, Whiteford 1993, Safanda 1994, Lewis 1998, Lewis & Wang 1998, Skinner & Majorowicz 1999).

Signal Enhancement and Noise Suppression

In many situations, however, the necessary detailed information for evaluating such nonclimatological disturbances is not available, and therefore the effects, if present, are manifest as noise in the inversion process. As a result, the tools available for noise suppression and signal enhancement in the various inversion methodologies take on special significance (Shen & Beck 1991, Shen et al 1995, Mareschal & Beltrami 1992, Beltrami & Mareschal 1995). Because the signal-to-noise ratio affects the ability to resolve past climate change (Clow 1992, Mareschal & Beltrami 1992, Beltrami & Mareschal 1995, Harris & Chapman 1998a), the various approaches to noise suppression have received considerable scrutiny.

Mareschal & Beltrami (1992) have experimented with various ways of designating singular value cutoffs in singular value decomposition algorithms. In Bayesian-type inversions (Shen & Beck 1991, Wang 1992) a probability distribution constraint can be placed on factors such as subsurface heterogeneity. Likewise, one can place smoothly varying constraints on the derived surface temperature history from prior knowledge of the general climate history of the region. Smooth and sparse temporal parameterization of the climate history (Huang et al 1996) also tends to suppress the effects of many types of noise.

Another approach to noise suppression has been the simultaneous inversion of observations from several boreholes (Pollack et al 1996, Beltrami et al 1997). Because it is unlikely that each borehole would have the same surficial topography and vegetative cover or the same subsurface geological structure and hydrologic regime as the other boreholes, a signal common to all the boreholes can more safely be attributed to regional climate change. Alternatively, one can average the individual inversion results from a number of boreholes spread across a region (Pollack et al 1996). This procedure is analogous to the stacking of seismograms in seismic data analysis, and can lead to the enhancement of a signal that may be present in the ensemble of the individual reconstructions (Huang et al 1996, Pollack et al 1998).

Meteorological Data as Constraints

The incorporation of the local meteorologic record of the surface air temperature (SAT), as determined from a nearby observatory or weather station, can be a useful test of how well ground temperatures represent a response to changes in the SAT. Chapman et al (1992) and Harris & Chapman (1997, 1998b) have used local and regional SATs to generate synthetic subsurface temperature profiles with which to compare the observed temperature-vs-depth profiles. Of course, the subsurface temperatures reflect surface conditions from times prior to the establishment of the local weather station, so the subsurface temperatures can also yield an estimate of the mean temperature of the surface before meteorologic observations began. This mean temperature has variously been termed a baseline (BT), preobservational mean (POM), or long-term mean (LTM) temperature.

CLIMATE RECONSTRUCTIONS

At the outset of a discussion of the many local, regional, and global reconstructions that have emerged from the analysis of subsurface temperatures, it is useful to list some of the characteristics of geothermal reconstructions in general.

Because of the progressive frequency filtering of the downward-propagating geothermal signal, annual and decadal information is quickly lost. Thus, geothermal reconstructions have low temporal resolution compared with the instrumental meteorologic record and compared with traditional proxies such as tree rings and sediment varves, which record annual variations. Compensating for the loss of temporal resolution, however, is a robust estimate of the integrated temperature change over the time interval studied. Additional compensation for the lesser temporal resolution comes from the widespread spatial distribution of the geothermal archive. Surface temperature fluctuations have been propagating into the Earth's crust everywhere on the continents, and borehole temperatures have been measured in thousands of locations, thus providing relatively good geographic sampling. Finally, geothermal reconstructions are not the outcomes of empirical correlations and calibrations but are based on actual temperature measurements underpinned by a well-developed physical model: the theory of heat conduction.

Since the single climate reconstruction of Cermak (1971) representing a small region in central Ontario, Canada, there have been many hundreds of analyses of borehole temperatures on six continents. The results of these efforts are rather heterogeneous, in that the individual investigators have used different data quality control criteria, different inversion schemes, different temporal parameterizations, different smoothing and stabilizing parameters, and different methods of spatial aggregation. But even in the face of this heterogeneity, in areas where there are many boreholes and an abundance of high-quality data, common features can be seen in the reconstructions of virtually all the investigators.

Greenland

An unusual trio of boreholes in ice, the GRIP and GISP2 boreholes in central Greenland and the Dye 3 hole in southern Greenland, have yielded high-precision temperature measurements to depths as great as 3 km. These records are particularly well suited for reconstructing surface temperature history because of the nearly featureless topography at the surface, the homogeneity of the medium the boreholes penetrate, and the absence of any subsurface hydrological perturbations. However, they have one important complication that holes in rock do not experience: The ice is moving, initially downward as annual layers of snow accumulate at the surface, and eventually laterally as the ice slowly creeps to the sea. Therefore, interpretation of the borehole temperature profiles must include the effects of the moving medium.

Because these boreholes are deep and in a very-low-noise environment, they enable surface temperature reconstructions back through much of the Holocene, and well into the late Pleistocene at the GRIP and GISP2 sites. These reconstructions (Dahl-Jensen et al 1998, Clow 1998, Clow & Waddington 1999) show that at the time of the last glacial maximum, ca 25 ka, the temperature in central Greenland was about 20–25 K colder than the present-day temperature there. From that temperature minimum, the temperature increased steadily to some 1.5–

2.5 K warmer than present in the time interval 8–4 ka, a period sometimes referred to as the climatic optimum. The last millennium began with temperatures about 1 K warmer than at present, but by the middle of the nineteenth century these had cooled to 0.5–1.0 K below the present temperature in the closing stages of the Little Ice Age. The area then warmed again in the first half of the twentieth century, but it has cooled somewhat in the decades that followed.

North America

Lachenbruch & Marshall (1986) analyzed data from more than 30 boreholes in the permafrost of the north slope of Alaska. They inferred a large twentieth century warming, some 2–4 K, a result consistent with greenhouse-forced climate models that predicted an amplification of climate change at high latitudes. This work almost single-handedly stimulated many geothermal investigators to search their data archives for borehole temperature logs suitable for reconstructing the ground surface temperature history.

Another particularly well-studied region is eastern Canada, where several different research groups have analyzed a large body of data made available by the Geological Survey of Canada, as well as other data representing individual field efforts. These studies (Beltrami & Mareschal 1991, 1992a; Beltrami et al 1992; Shen & Beck 1992; Wang et al 1992; Wang & Lewis 1992; Shen et al 1995) have all shown a warming of about 1–2 K during the past 150 years or so, most of which occurred in the twentieth century. Of the total warming, perhaps 0.5 K was a recovery from a previous, generally colder period of a few hundred years' duration.

Investigations in the mid-continent region of North America, comprising the Great Plains of the United States (Deming & Borel 1995, Gosnold et al 1997, Harris & Gosnold 1999) and the Prairie Provinces of Canada (Majorowicz 1996, Majorowicz & Skinner 1997a, Majorowicz & Safanda 1998, Majorowicz et al 1999, Guillou-Frottier et al 1998), have shown that the warming characteristic of eastern Canada extends west all the way to the front of the Cordillera. Somewhat greater change is exhibited in the prairies of Canada, ca 1.5–3 K in the nineteenth and twentieth century, compared with 1.2–1.5 K in the southern plains of the United States in roughly the same time interval.

Chisholm & Chapman (1992) and Harris & Chapman (1995) observed that the warming in and near the Great Basin in the western United States was only about half that experienced in central and eastern Canada. That contrast was also recognized by Wang et al (1994), who analyzed data from 85 boreholes in eastern and Cordilleran settings. These data showed that the Cordillera of western Canada warmed only about 0.8 K in the same interval that the area east of the Cordillera warmed by about 1.5 K. This contrast can easily be seen in the residual temperature patterns of the two regions (Figure 4). Using an even larger dataset comprising 243 boreholes, we have determined that the contrasting east-vs-west pattern holds for a broad region of North America (Figure 5).

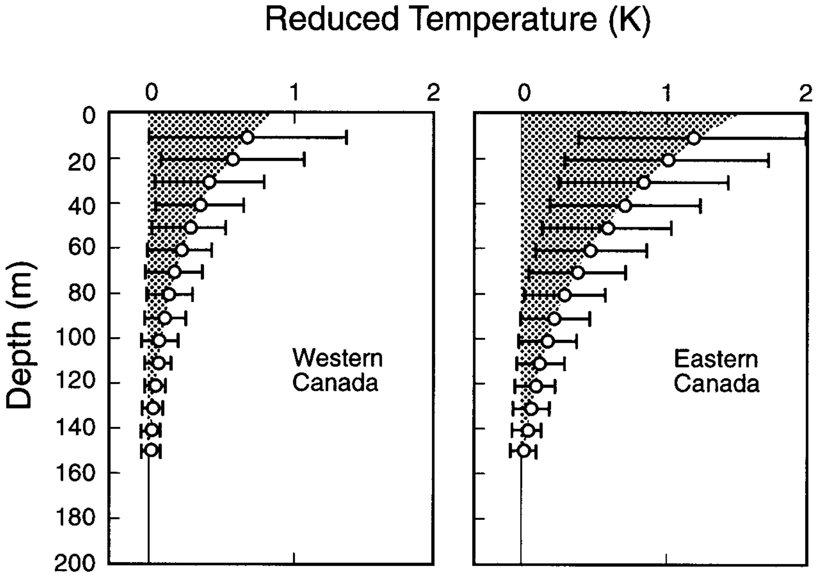

Figure 4 Composite reduced temperature profiles for ensembles of 34 and 51 boreholes in eastern and western Canada, respectively, illustrating the characteristic difference in ground warming in these two regions. *Circles* represent the mean value of the residuals at the indicated depths; uncertainty *bars* represent ±1 standard deviation from the mean. *Shaded area* represents the reduced temperature anomaly. (Modified from Wang et al 1994.)

Europe

Many boreholes in the Czech Republic have also been extensively studied (Bodri & Cermak 1995, 1997, 1998; Safanda et al 1997), and they reveal both spatial and temporal complexity. The Czech Republic, with the possible exception of its far western region, generally shows late nineteenth and twentieth century warming, but with a cool episode in the mid-twentieth century, and a warm interval of about four decades centered around 1800. The warming in the twentieth century has been particularly significant since about 1960, with a rate of 0.1–0.3 K per decade; the lower value characterizes the west of the country and the higher value the eastern region. Results from adjacent Germany (Clauser & Mareschal 1995) are only marginally similar to the picture developed for the western Czech Republic.

Boreholes in Finland have been carefully examined for structural, hydrological, and climatological signatures (Kukkonen & Safanda 1996, Kukkonen et al 1998), with the conclusion that a warming of more than 1 K occurred over the past 2 centuries, following a previous cooler period of lesser amplitude. Elsewhere in Europe, isolated results from relatively small numbers of boreholes have been reported (Correia 1999, Rajver et al 1998, Veliciu & Safanda 1998, Mareschal & Vasseur 1992), but as yet they do not allow regional generalization.

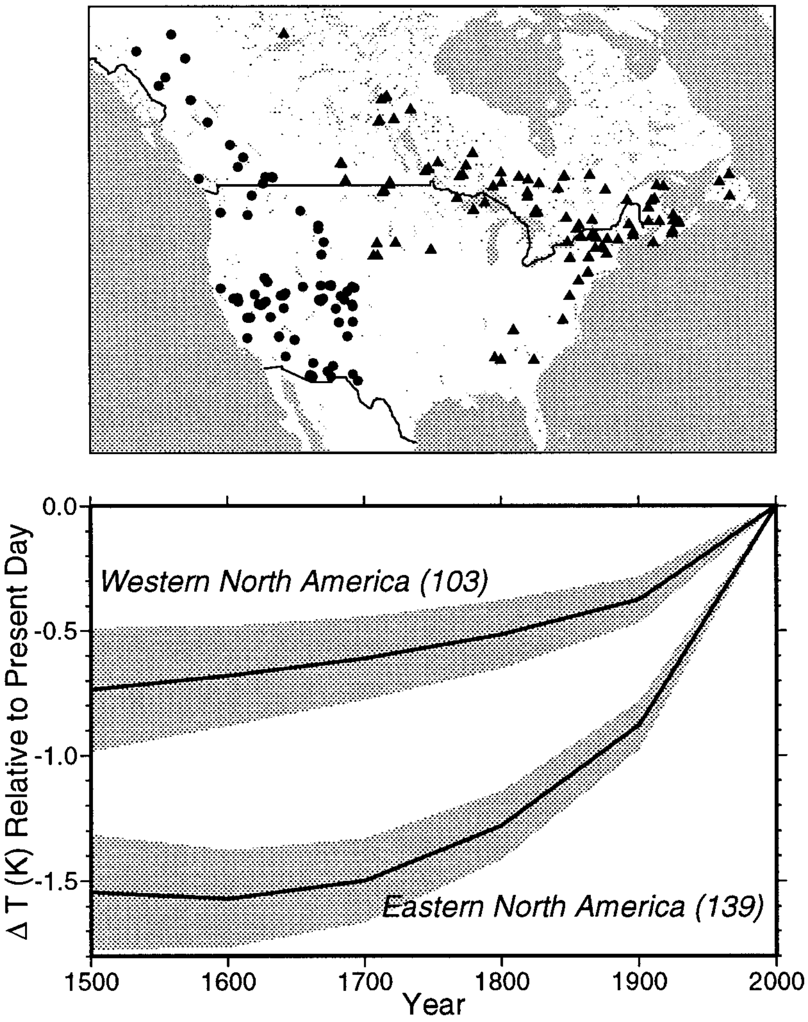

Figure 5 (*Top*) Map of borehole sites in North America; western sites shown by *dots*, eastern sites by *triangles*. (*Bottom*) Reconstruction of the surface temperature history over the past 5 centuries for western and eastern North America, as determined from borehole temperatures at sites shown at *top*. *Shaded areas* represent ±1 standard error about the mean histories.

Asia and the Southern Hemisphere

Another well-studied dataset is an array of boreholes from the western Ural region of Russia (Stulc et al 1997, 1998; Kukkonen et al 1997), where a warming in excess of 1 K occurred over the past 2 centuries, following a previous cool interval—a result very similar to that observed in Finland. Much of the rest of Asia remains unstudied from the perspective of borehole analyses, although datasets are being assembled in Russia, India, and China (Huang et al 1995; A Duchkov, R Dorofeeva, R Rao, J Wang, S Hu, unpublished data).

In the southern hemisphere, two important datasets have been assembled and analyzed. In Australia, preliminary results (Pollack & Huang 1994) from 57 boreholes indicate that the continent has warmed by only about 0.5 K over 5 centuries, with virtually all of the warming coming in the nineteenth and twentieth centuries. In southern and eastern Africa, 85 borehole profiles yield a composite 5-century history of warming just slightly less than 1 K, about three quarters of which occurred in the nineteenth and twentieth centuries. In South Africa alone, the warming in the past 2 centuries has been in excess of 1 K (Tyson et al 1998, Jones et al 1999a), a small part of which was a recovery from a preceding cooler interval. In South America, data from only a few boreholes have been analyzed, with insufficient distribution to permit even preliminary conclusions.

The Antarctic continent is virtually unsampled in the traditional sense of offering an array of exploration boreholes in which temperatures have been measured. However, one deep borehole in ice, in the Taylor Dome of East Antarctica, has been logged and analyzed (Clow & Waddington 1999). While showing, as in Greenland, a warming since the last glacial maximum that culminated in a mid-Holocene climatic optimum, the history of the last millennium appears to be anticorrelated with the medieval warm period and Little Ice Age seen in the Greenland ice.

Global Analysis

As discussed previously, many analyses of individual boreholes or small regional ensembles have revealed significant temporal patterns of surface temperature change over various time intervals. However, it is difficult to perceive from these individual analyses what larger spatial scale patterns, if any, exist. This difficulty stems in part from the heterogeneity both in analytical techniques and in the data used by the several investigators.

In 1991, the International Heat Flow Commission of IASPEI established a working group chaired by one of us (HNP), with the primary task of acquiring borehole temperature profiles from around the world for analysis in terms of paleoclimate. We now have an operational database (Huang & Pollack 1998), which comprises borehole temperatures and ancillary information from more than 600 sites on six continents. In the data selection we have applied certain quality control criteria, principally relating to the depth range of the temperature measurements and the level of noise present. Data included were obtained from boreholes at least 200 m in depth, with a depth interval between measurements of 20 m or less and a smooth variation of temperature with depth, free of evidence of advective perturbations or permafrost zones.

To address the heterogeneity in analytical technique, we have processed all the data in a uniform way, so that issues of ‘‘comparing apples to oranges’’ can be minimized. The basic inversion algorithm is a Bayesian scheme formulated as a variant of that described by Shen & Beck (1991). The parameterization we have selected for the surface temperature history is very simple: It comprises only century-long linear trends of temperature, one for each of the past 5 centuries (Huang et al 1996). The apparent steady state parameters, i.e. the surface temperature prior to the year 1500 AD and the subsurface temperature gradient, are also determined. Thermophysical properties of the materials penetrated by the borehole, when known, are incorporated into the inversion. The a priori estimate of the surface temperature history is a null hypothesis, a very conservative estimate that asserts there has been no surface temperature variation over the 5-century interval. Such an a priori hypothesis also has the virtue of being free of bias toward any extant hypotheses about the climate history. Together, the simple smooth parameterization of the surface temperature history, the a priori null hypothesis, and a middle of the road set of smoothing and stabilizing parameters yield reconstructions that achieve a good balance between century-scale resolution and stability for a wide variety of input data.

This standardized uniform treatment of more than 600 temperature profiles from boreholes on six continents has enabled regional, hemispheric, and global aggregations of reconstructions, as well as the determination of mean histories for the various ensembles (Pollack et al 1998, Pollack & Huang 1998, Huang et al 2000). Individually, and not surprisingly, the boreholes show a fair amount of variability, with some recording cooling and others indicating warming. However, more than 75% of the borehole sites show a warming of some magnitude over the past 5 centuries (Figure 6), clearly indicating a general warming of the ground surface in that time interval.

Taken as a global ensemble, the borehole data indicate a temperature increase over the past 5 centuries of about 1 K, half of which has occurred in the twentieth century alone (Figure 7). This estimate of twentieth century warming is similar in trend to the instrumental record of surface warming determined from meteorological stations (Jones et al 1999b). When this trend is added to the more gradual warming in the previous centuries, the twentieth century stands out as the warmest century of the past five, a result similar to many recent multi-proxy reconstructions (Overpeck et al 1997; Jones et al 1998; Mann et al 1998, 1999) that did not include any geothermal component.

On a longer timescale embracing all of the Holocene, Huang et al (1997) used the global heat flow database (Pollack et al 1993) to establish a composite profile of heat flow versus depth to 2 km beneath the surface. The inversion of this profile revealed a long mid-Holocene warm interval some 0.2–0.6 K above present day temperatures, and another similar but shorter warm interval 500–1,000 years ago. Temperatures then cooled to a minimum of approximately 0.5 K below present, about 200 years ago. This six-continent reconstruction shows essentially the same climate history, albeit more subdued in amplitude, as that revealed in the GRIP

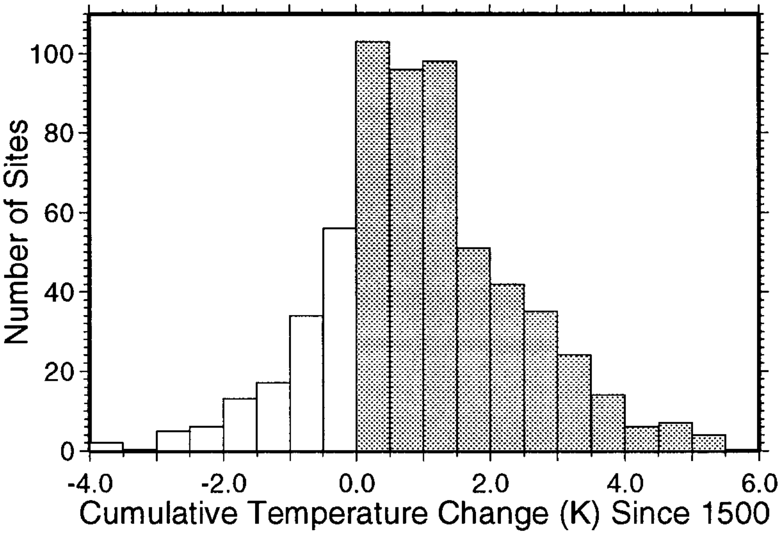

Figure 6 Distribution of temperature change since 1500 at the borehole sites in the global database of borehole temperatures (Huang & Pollack 1998). *Columns with shading* indicate a net warming over the past 5 centuries, and *columns without shading* indicate a net cooling. More than 75% of the sites have experienced warming in this time interval.

and GISP2 boreholes in Greenland (Dahl-Jensen et al 1998, Clow 1998, Clow & Waddington 1999).

GROUND TEMPERATURE TREND COMPARISONS

A principal goal of reconstructing past surface temperature changes is to extend the record of change farther back in time, well beyond the instrumental surface air temperature records obtained from the global network of meteorologic stations. Thus, it is important to understand the relationship between air temperatures, ground temperatures, and the various proxies.

Air and Ground Temperatures

Surface observations of both the air and ground temperatures at many sites indicate that the two are rarely the same. Differences of several degrees are not uncommon, with the annual mean ground temperature usually warmer than the annual mean air temperature. These differences sometimes arise from simple and obvious causes, such as the effect of snow cover on the ground during winter months, which insulates the ground from the much colder diurnal and seasonal air temperature variations (Goodrich 1982, Lewis & Wang 1992, Beltrami &

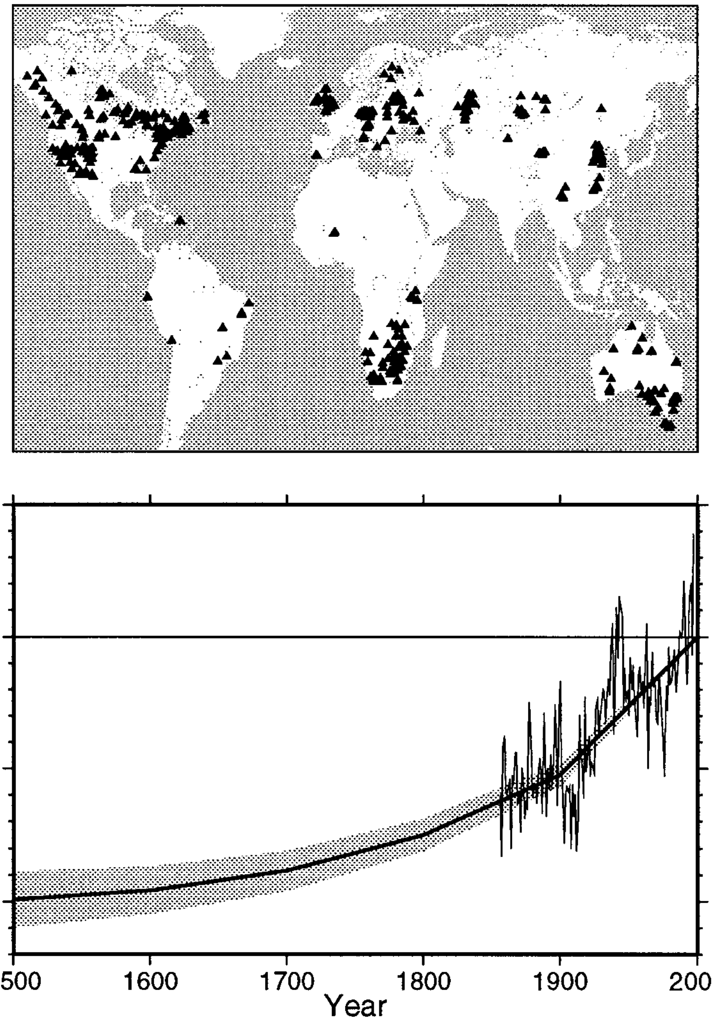

Figure 7 (*Top*) Map of borehole sites in the global database of borehole temperatures (Huang & Pollack 1998) used in reconstructing a global mean ground surface temperature history. (*Bottom*) Reconstruction of the surface temperature history inferred from borehole temperatures at sites shown above (Pollack & Huang 1998, Huang et al 2000). *Shaded area* represents ±1 standard error about the mean history. Also shown for comparison is a 5-year running mean of the globally averaged instrumental record of surface air temperature since 1860 (Jones et al 1999a).

Taylor 1995, Gosnold et al 1997). Latent heat effects during the freezing and thawing of soil moisture also hold the soil temperature near 0°C, independent of what the air temperature may be (Beltrami 1996, Gosnold et al 1997, Zhang et al 2000). In areas free of snow cover and freezing temperatures, the temperature difference between ground and air still exists as a result of the complicated heat and mass transfer at the interface, comprising both physical and biological components (Geiger 1965, Van Wijk 1963, Putnam & Chapman 1996). The representation and parameterization of this complex interface in climate models remains a challenge to global climate modelers (Sellers 1992, Sellers et al 1997).

For the purpose of reconstructing climate change, however, it is not the absolute temperature that is of greatest importance, but rather that both the air and ground temperatures exhibit the same trends over long time intervals, i.e. that they track each other. For ground temperatures only a few meters beneath the surface, many observations show that mean annual air and ground temperatures exhibit generally similar trends (Baker & Ruschy 1993). But if long-term changes in soil moisture accompany long-term changes in ground surface temperature—such as soil dessication associated with long-term warming—then the trends of air and ground temperature may slowly diverge, because the latent heat effects in the soil play a diminished role over time (Majorowicz & Skinner 1997b).

A useful test of how well subsurface temperatures track air temperatures is the direct comparison of the meteorologic record with the borehole reconstructions over the time interval represented by the instrumental record. This can be a passive side-by-side visual comparison of long-term trends, as in Figure 7, or a quantitative comparison of the entire borehole temperature profile with a synthetic subsurface temperature profile generated by subjecting the surface of the Earth to the temperature variations present in the instrumental meteorological record. This latter approach, which subjects the meteorological record to the same filter that ground temperatures have experienced, has been carefully developed by Chapman and colleagues (Chapman et al 1992; Harris & Chapman 1997, 1998b). Their results clearly indicate that a high percentage of temperature information in the subsurface is directly related to the SAT history.

We have also incorporated this concept on a global basis, by comparing synthetic subsurface temperatures from both the global SAT record (Jones et al 1999a) and our six-continent century-long trend representation for the time interval of the SAT record. The comparison, displayed in Figure 8, shows that the composite geothermal reconstruction represents most of the information contained in the global SAT record. Deviations between the two representations above about 100 m arise from the decadal-scale information in the SAT that is not present in the century-long trend estimate.

Proxies and Ground Temperatures

As noted in the introduction, estimates of climate variability prior to the existence of an instrumental record of surface temperature are derived principally from climate proxies, each representing some aspect of climate. The characteristics range from summer growing season temperatures on continents to low-latitude seasonal fluctuations of sea surface temperatures; from hydrological and sediment

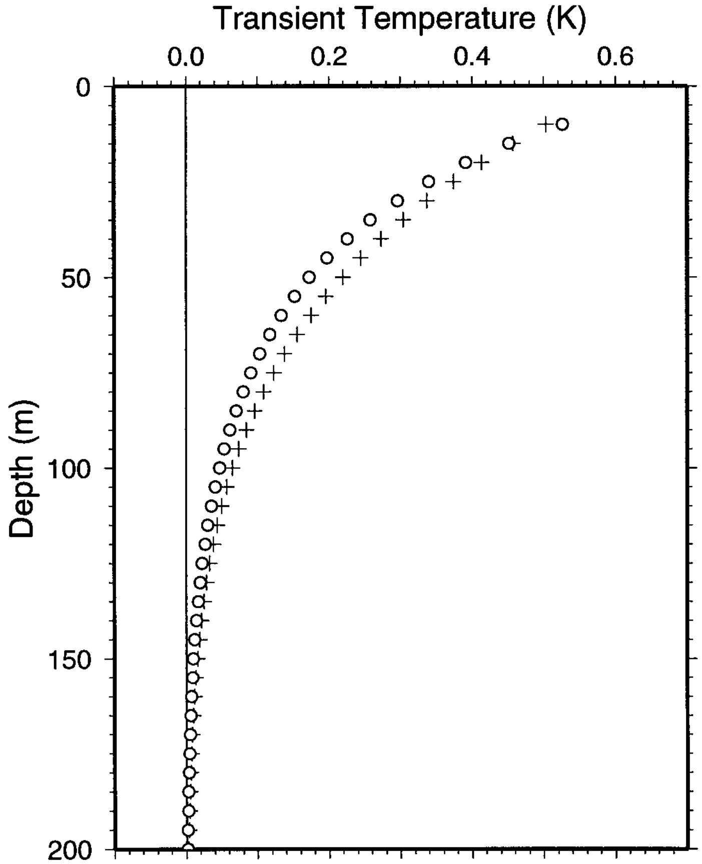

Figure 8 Synthetic subsurface transient temperatures calculated from the global SAT (*circles*) compared with those calculated from geothermal century-long trend representation (+). Both show the significant warming over the time interval of the SAT that is apparent in Figure 7.

inflows to freshwater lakes to snow accumulation rates in high-latitude ice fields; and from annual resolution of tree rings to century-long geothermal trends. No single proxy carries the full geographic or temporal representation of climate variability, so multi-proxy integration is an attractive target. Multi-proxy, multi-century reconstructions for large regions formulated independently of geothermal data include those of Overpeck et al (1997), Jones et al (1998), and Mann et al (1998, 1999), all of which reconstruct the twentieth century as the warmest century in the time interval examined. But differences can be seen in the longer-term, pre–twentieth century trends that are not yet understood. The resolution of the differences may lie with one aspect of tree ring data analysis. Tree ring widths, for example, must be prefiltered (“standardized”) to mute long-term growth trends related to age. However, long-term climatic trends, if present, are vulnerable to removal by the same filter. The incorporation of geothermal data into a multi-proxy reconstruction therefore offers an independent estimate of long-term temperature trends that can be integrated with estimates of annual variability deduced from tree ring widths. Various efforts to effect that marriage (Beltrami & Mareschal 1992b, Beltrami et al 1995, Putnam et al 1997, Huang & Pollack 1999) have yet to find uniform acceptance.

CAUSES OF CLIMATE CHANGE

The ultimate utility of climate reconstructions will be their contribution to identifying the causes of climate change. The warming of the Earth over the past 2 centuries is now well established by the instrumental record and various proxies, including subsurface temperatures. But the proportions of the warming that may be due to variable solar radiation, or to changing concentrations of greenhouse gases in the atmosphere, or to other factors, and how those proportions may be changing with time, are questions yet unresolved (Briffa et al 1998, Crowley & Kim 1999). Greater uncertainty exists in the estimates of temperature change in prior centuries; this uncertainty needs to be resolved to enable progress in the determination of the sensitivity of climate change to various forcing factors. What subsurface temperatures and other proxies may contribute in the future is the delineation of patterns of regional climatic variation that can be associated with one or another forcing mechanism. Subsurface temperatures have the potential to provide significant information because of the wide geographic availability of the geothermal archive. It exists, in principle, everywhere beneath the surface of the continents—and large areas, particularly in Asia and the southern hemisphere, still remain to be sampled.

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