

Global Database of Borehole Temperatures and Climate Reconstructions

The thermal regime of the Earth's outer continental crust comprises the superposition of two conductive processes: the steady state outward flow of heat from the deeper interior, and transient perturbations to the deep regime by changes of temperature at the surface. The latter effects are commonly climatological in origin. The identification of the transient component of the subsurface thermal regime is central to the geothermal approach to climate reconstruction, and has drawn increasing attention over the past decade. With support from the international heat flow community and under the sponsorships of the US National Science Foundation (NSF) and National Oceanic and Atmospheric Administration (NOAA), a database of borehole temperatures has been assembled and analyzed for the special purpose of climate reconstruction (Huang & Pollack, 1998). This database currently contains 616 borehole temperature profiles from North America, Europe, Asia, Africa, Australia, and South America (Figure 1).

Climate reconstruction from geothermal data has its foundations in the theory of thermal diffusion. In homogeneous rock, if the surface temperature is steady, the subsurface temperature (T) is a linear function of depth (z), i.e., $T = T_0 + Gz$, where T_0 is the steady state temperature at the surface, G is the temperature gradient which is related to the thermal conductivity of the rock (k) and the deep heat flow (q) by the ratio q/k . However, if the surface temperature is not steady but changes with time, the subsurface temperature will depart from the linear distribution. A progressive cooling at the surface will increase the temperature gradient at shallow depth, while a progressive warming will result in a lesser gradient or even a negative gradient at shallow depths. If the surface temperature oscillates with time, oscillations in the subsurface temperature profile will follow. The magnitude of the departure of the subsurface temperature from its undisturbed steady state is related to the amplitude of the surface temperature variation. The depth to which disturbances to the steady state temperatures can be observed is determined by the duration and spectral composition of the temperature change at the surface. The ground surface temperature (GST) history is therefore recorded in the subsurface,

and by careful analysis of the variation of temperature with depth, one can reconstruct the past fluctuations of temperature at the ground surface.

The pace of climatic signal propagation in the subsurface is related principally to the thermal diffusivity of rocks. Following a change in temperature at the surface, it takes about 100 years for the perturbation to reach a depth of 150 m and 1000 years to reach 500 m depth. Moreover, the amplitude of a surface perturbation diminishes exponentially with depth as it propagates downward. Surface temperature variations of shorter period diminish in amplitude more quickly than do longer period disturbances. Because of period-dependent amplitude reduction, the effects of short period surface temperature changes are restricted to shallower depths than are the disturbances from longer period changes in surface temperature. The daily surface temperature oscillation penetrates only about 1 m and the seasonal oscillation about 15 m. Only longer term surface temperature changes are recorded at greater depths. Therefore, a geothermal climate reconstruction is characterized by a progressive inability to resolve the details of climatic excursions in the more remote past (Clow, 1992; Beltrami & Mareschal, 1995). But the compensation for the loss of resolution are increasingly robust determinations of the mean surface temperature prior to the interval of time for which some detail can be resolved, and the total temperature change from that prior mean.

Most of the boreholes that we selected for analysis penetrated to depths of 200 to 600 m, and have temperature measurements at 10 m intervals. Complications in climate reconstruction, however, stem from the fact that subsurface temperatures are also sensitive to various non-climatic disturbances (Shen et al., 1995). Attention must be given to other disturbances such as topography and vegetation patterns at the surface, and groundwater movement and lateral variation in thermophysical properties in the subsurface.

The combination of the predominant depth range of observations and the characteristic magnitude of noise has led us to choose five centuries as the standard interval over which to develop climate reconstructions (Huang et al., 1996). In the parameterization of the surface temperature history, we seek only century-long trends of temperature change. By estimating century-long parameters, we explicitly designate an adequate averaging interval rather than implicitly incorporate the variable averaging that characterizes the resolution of point estimates. This simple parameterization also enables one to easily estimate the total temperature change over the five-century time interval.

Shown in Figure 2 is a global perspective of the century-long trend of ground surface temperature change over the last 500 years based on analysis of the ensemble of borehole temperatures in this database. Superimposed for comparison is a global surface air temperature instru-

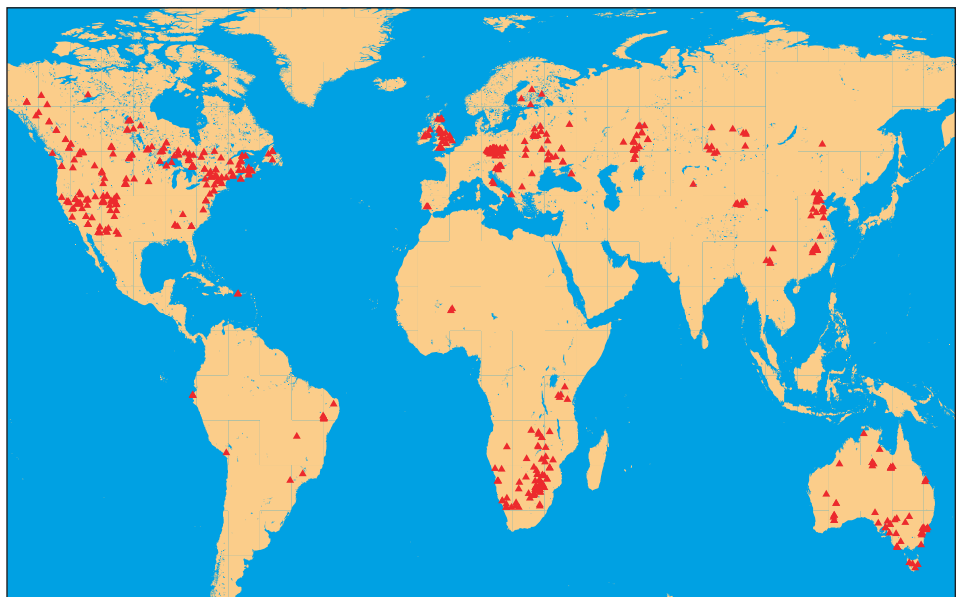


Figure 1: Location of the borehole sites.

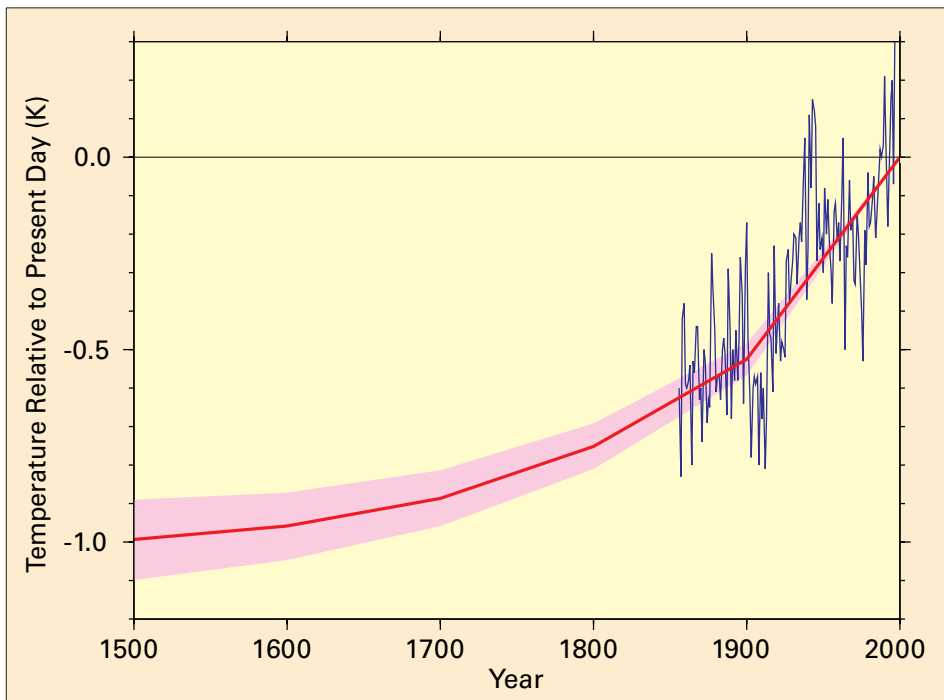


Figure 2: A global perspective of ground surface temperature change over the last five centuries. Shaded areas represent ± 1 standard error from the mean. Shown in red for comparison is the meteorological time series by Jones *et al.* (1997).

mental record, which was shifted to enable a visual comparison of the trends by a direct overlay. In the 20th century the average surface temperature of the Earth has increased by about 0.5°K, and the 20th century has been the warmest century of the past five. Almost 80% of the sites experienced a net warming over the past five centuries. The mean of the cumulative temperature change over the five century frame is a warming of about 1.0°K. The results derived from 616 borehole temperature profiles is consistent with an earlier result derived from a smaller data set from 356 boreholes (Pollack *et al.*, 1998). This geothermal analysis provides independent confirmation of the unusual character of 20th century climate.

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INSIDE PAGES

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