Climate change inferred from borehole temperatures

Henry N. Pollack

Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109, USA

(Received January 11, 1992, revised and accepted April 16, 1992)

ABSTRACT

Pollack, H.N., 1993 Climate change inferred from borehole temperatures Global Planet Change, 7 173-179

Temperature changes at the Earth's surface propagate downward into the subsurface and impart a thermal signature to the rocks that can be analyzed to yield a surface temperature history over the past few centuries. Thus subsurface temperatures have the potential to extend the 20th century meteorologic temperature record back well into the pre-industrial era and therefore to provide information relevant to an assessment of the role of greenhouse gases in atmospheric warming. Short period variations in surface temperature are attenuated at shallow depths, whereas longer period excursions propagate deeper. The ability to resolve details of the surface temperature history diminishes with time. Care must be taken to identify and evaluate local anthropogenic temperature perturbations such as urbanization, deforestation and wetland destruction and microclimatic effects associated with topography and vegetation patterns, in order to isolate true regional climate change. Investigations in North America indicate significant regional variability in the surface temperature history inferred from borehole profiles, similar to that observed in the meteorologic record of the 20th century.

Introduction

Rock temperatures at shallow depths within the Earth are an archive of temperature changes that have occurred at the surface of the Earth in the recent past. Thus subsurface temperatures comprise a valuable complement to surface meteorological data in understanding the Earth's surface temperature history, particularly for the 19th century and earlier, prior to the establishment of a worldwide network of meteorological stations. Meteorological station records, while individually showing considerable variability, have collectively shown that the mean temperature of the atmosphere at the Earth's surface has increased by about 0.6°C over the past century (Hansen and Lebedeff, 1987). This observed increase of mean atmospheric temperature (Fig. 1) is the foundation of the assertion that Earth is experiencing global warming.

Subsurface temperatures offer a widespread and continuous filtered record of surface temperature variations over the past few centuries. In the context of the current discussion over global warming and its likely causes, the time interval represented in the borehole record, comprising both the pre-industrial and industrial eras, is of particular significance and makes the subsurface observations relevant to an assessment of the role of atmospheric greenhouse gases in the warming of the 20th century.

Investigations of ice cores have shown that the concentrations of both CO₂ and CH₄ in the atmosphere were relatively unchanging until the middle of the 19th century, a time well correlated with the acceleration of the industrial revolution and the increasing combustion of fossil fuels. Then the CO₂ and CH₄ concentrations began an increase that continues to the present day (Fig. 1). Surprisingly, the history of CO₂ and CH₄
concentrations in the atmosphere (Neftel et al., 1985; Pearman et al., 1986) is longer than the meteorological record of surface temperatures, which on a global basis is only a century long. Thus no directly observed surface temperature record exists with which to compare the historical pattern of greenhouse gases concentrations deduced from the pre-industrial era to the present.

The Earth, however, has been maintaining a long archive of surface temperature history in its subsurface, where temperatures have been perturbed by changing conditions at the surface. This archive in principle exists everywhere on the continents (the deep ocean floor is shielded from surface temperature fluctuations) and can be accessed by drilling a borehole and lowering a thermometer to obtain a profile of temperature versus depth. In many boreholes, however, the linear increase of temperature with depth that characterizes the geothermal gradient is observed only in the deeper parts of the borehole, shallow temperatures show departures from linearity that indicate other influences on the near-surface heat transfer process, including such possibilities as ground-water movement, topography, vegetation patterns and a changing temperature at the surface.

**Surface and subsurface temperatures**

The most obvious temperature oscillations at the Earth's surface are the diurnal and seasonal changes, periodic disturbances with daily and annual periods, respectively. The theory of heat conduction shows that the surface oscillations diffuse downward as a thermal wave, the amplitude of which diminishes exponentially with depth (Fig. 2). Moreover, shorter period oscillations attenuate more rapidly with depth than do longer periods and the process effectively acts as a selective filter, allowing only longer term variations to penetrate to greater depths. The daily temperature oscillation penetrates only 1 m and the seasonal oscillation to about 15 m before the signal is lost. Longer-term oscillations penetrate more deeply, a century long cycle can be observed to 150 m depth and a millennial period to 500 m. Thus at increasing depths the Earth selectively records longer term trends and excludes short period excursions from the archive, an ideal property for a climate change recorder (Fig. 3).
The solid Earth is also a good recorder because of the slow pace at which thermal signals diffuse into the subsurface. In general all changes in surface temperature that have occurred in the last millennium are imprinted in the uppermost 500 m of the Earth's crust, a depth easily attainable by inexpensive drilling. The apparent velocity at which a thermal wave travels downward from the surface depends on the period of the oscillation, with the longer periods penetrating more slowly. For periods of interest, in the range of decades to millennia, the apparent velocity ranges over an order of magnitude from about 5 to 0.5 m per year. A century long oscillation begun in 1900 would just be reaching 150 m depth today; over the next century, no matter what might be happening at the surface, the temperature at 150 m depth would be showing a muted and filtered representation of the 20th century and earlier surface temperature history. Thus subsurface temperature fluctuations lag surface temperature variations in time.

What are the characteristics of a borehole temperature profile that allow the reconstruction of a surface temperature history? First, the borehole must display at some depth a uniform conductive heat flux from greater depths. Because the heat flux is the product of the geothermal gradient and the thermal conductivity of the rock, a determination of the thermal transport properties of the rock is also required. In a homogeneous material the condition of uniform heat flux is equivalent to a constant geothermal gradient, i.e. a linear increase of temperature with depth (Fig. 4). The upward extrapolation of this linear part of the temperature profile reconstructs temperatures that existed at shallower depths prior to the onset of a surface temperature excursion. The difference between the surface intercept of the extrapolated geothermal gradient and the present-day ground surface temperature indicates the present-day magnitude of the temperature excursion. A second characteristic is the depth at which the curved portion of the profile departs from the undisturbed geothermal gradient; this

---

**Fig 4** Schematic illustration of subsurface temperature perturbation due to either warming or cooling by an amount $\Delta T$ at the surface. The unperturbed linear increase of temperature with depth is the geothermal gradient.

---

**Fig 3** Observed surface air temperature history for northeastern USA since 1880, and calculated temperature histories at different depths. Calculations assume a uniform surface temperature prior to 1880. The details of the surface history are increasingly filtered out at depth. The increase in surface temperature over the 110-yr interval begins to appear at 150 m depth only around 1970.
depth is a function of the time of onset of the temperature excursion. Third, the variable curvature in the temperature profile in the perturbed zone above the undisturbed geothermal gradient provides detail about the changes in the surface temperature through time which have led to the present-day value. Both forward and inverse modelling techniques have been developed to analyze temperature profiles (Birch, 1948; Beck and Judge, 1969; Cermak, 1971; Beck, 1982; Shen and Beck, 1983, 1991; Vasseur et al., 1983; Lachenbruch and Marshall, 1986; Mareschal and Beltrami, 1992; Wang, 1992). The inversions generally show that the resolved surface temperature at a time in the past is roughly the average temperature experienced in a time window of duration similar to the interval of time that has elapsed between the earlier time and the present day (Fig. 5). Thus the resolved temperature at the surface ten years ago would be roughly the mean temperature the surface experienced between five and fifteen years ago. Further back in time, e.g. 200 years ago, the resolved temperature at the surface would be the average temperature experienced between 100 and 300 years ago. Clearly the ability to resolve details of the surface temperature history diminishes with time.

**Problems**

In practice, the extraction of local histories from subsurface temperatures is strewn with pitfalls, because there are many processes and situations that lead to borehole temperature profiles similar to those expected from a variation of surface temperature over time. Several fall into the category of anthropogenic microclimatic change and include the effects of deforestation and agricultural expansion each of which leads to a warming of the Earth's surface by direct exposure to solar radiation. Wetland destruction eliminates the cooling effect of evaporation and is followed by a surface warming. Urbanization also leads to a warming through increased absorption of solar radiation by roads and structures and the interior heating of buildings. The onset of each of the environmental modifications is closely associated with increased human activity and therefore has a time scale not unlike that associated with anthropogenic modifications of the atmosphere through increased production of CO₂ and CH₄.

Aspects of the local topography, hydrology and vegetative patterns can also lead to thermal perturbations in the subsurface that can be mistaken for regional climate change. Topographic relief is typically accompanied by an increase of the geothermal gradient beneath valleys and a decrease beneath hills; both effects diminish with depth below the irregular surface, but in the shallow subsurface produce temperature distortions that mimic a changing surface temperature. Some lakes do not completely freeze through their depth even though seasonal temperatures fall well below freezing over adjacent land. Such “warm bottom” lakes distort the subsurface temperatures nearby and could lead to a misinterpretation in terms of a changing climate. Ground water movements and non-uniform rock properties can also affect subsurface temperatures and leave a signature that in some circumstances looks remarkably like a response to surface temperature change. Fortunately, most of these geologic thermal disturbances can be quantitatively modeled and their magnitudes estimated. Another approach with certain advantages focuses on regional ensembles of borehole logs, to see if bore-
holes spread across hundreds of kilometers of continental terrain have common perturbations in their temperature profiles. As it is highly unlikely that all of the boreholes would have identical topography, vegetation, geological structure, or hydrologic settings and disturbances, a common temperature perturbation can more safely be ascribed to climate change.

**Preliminary results**

Already several geothermal data sets from North America have been analyzed for evidence of surface temperature changes. Investigations in the Alaskan arctic (Lachenbruch et al., 1982; Lachenbruch and Marshall, 1986) have provided evidence of significant warming in the northern high latitudes. Temperature profiles from a number of wells spread across 500 km of northern Alaska have anomalous curvature in the upper 100–150 m of the wells (Fig. 6). The curvature is consistent with a warming at the top of the permafrost of some 2–4°C, the duration of the warming event varies for different sites, but at nearly all sites it has a 20th century onset. The magnitude of the surface warming inferred from the Alaskan boreholes is substantially greater than global average warming of the 20th century, but is consistent with the few polar meteorologic records.

An equally clear but lower amplitude warming is documented in temperature profiles from boreholes in eastern and central Canada. Independent studies (Cermak, 1971, Sass et al., 1971; Nielsen and Beck, 1988; Beltrami and Mareschal, 1991, Mareschal and Beltrami, 1991; Wang, 1992) show warming of 1–2°C in the last 100–200 years. The 20th century warming appears to be in part a recovery from an earlier one or two-century cooling trend that bottomed out in the 1800’s. The sites are spread across Ontario and Quebec and, as is the case in the Alaskan arctic, the warming is variable between sites in both magnitude and timing and occasionally absent.

Anomalous curvature is also found in temperature profiles from boreholes in the North American Great Plains (Gosnold and Bauer, 1990), from which a temperature increase of about 2°C in North Dakota and Wyoming has been inferred. Data from southern South Dakota and Nebraska, on the other hand, indicate little change over the past 100 years. And in the desert of western Utah, borehole temperature profiles suggest only a small amount of warming in this century, averaging 0.3°C at six sites and local cooling at one site (Chisholm and Chapman, 1992).

These preliminary results indicate that the broad outlines of the regional and temporal variation of the Earth’s surface temperature over the past few centuries is recoverable from the subsur-
face thermal record. What is the potential for these studies to be extended to other areas, to provide the geographic coverage necessary to delineate global trends over the past few centuries? As noted earlier, the subsurface temperature archive is confined to the continents where the Earth's solid surface is exposed to the atmosphere. Geophysicists have for three decades been systematically taking the Earth's temperature at many continental locations as part of an effort to map the heat loss from the Earth's interior (Pollack et al., 1990). Thus a considerable body of subsurface temperature observations already exists, some of which have sufficient depth extent, resolution and ancillary information available to enable the reconstruction of the surface temperature history. At the 1991 meeting of the International Heat Flow Commission, a group comprising geothermal researchers organized under the auspices of the International Association of Seismology and Physics of the Earth's Interior, a new working group was established to collect these existing data and develop a unified data base of subsurface temperatures and other relevant information to serve as the observational foundation for a worldwide analysis of historical temperature trends.

The Earth, while richly and widely endowed with subsurface temperature information, will not yield a global history easily. One important reason is that a global history must be developed as a weighted integration of many local histories. As the meteorological records have shown, there is significant regional variability in the 20th century history of atmospheric temperatures; some areas show warming that exceeds the global average, some show warming that falls short of the global mean and some even show cooling. The significant point is that no single area yields a signal that represents the global average; a global history comprises a wide range of local histories and is derived from them.

Reconstructing the recent history of the Earth's climate, however, will ultimately require more than just a knowledge of the surface temperature history, because climate is the complex composite of temperature, precipitation, wind, cloud cover and other factors. Information about these several factors can be gleaned from many sources, including tree rings, coral growth patterns, ice cores, lake and ocean sediments and historical commercial and agricultural records. Studies in all these areas are revealing that changes in the Earth's climate take place on many different time scales and with considerable regional variability. The integration of these diverse regional observations has the promise of yielding a coherent global picture.

Acknowledgments

This paper is an adaptation of an article submitted to Scientific American (Pollack and Chapman, 1993) The preparation of both papers has been supported in part by the US National Science Foundation, Grants EAR-9104292 and ATM-9121450.

References

Beck, A. E., 1982 Precision logging of temperature gradients and the extraction of past climate. Tectonophysics, 83 1–11
CLIMATE CHANGE INFERRED FROM BOREHOLE TEMPERATURES

Mareschal, J C and Beltrami, H, 1992 Evidence for recent warming from perturbed geothermal gradients examples from eastern Canada Clim Dyn., 6 135–143
Neftel, A, Moor, E, Oeschger, H and Stauffer, B, 1985 Evidence from polar ice cores for the increase in atmospheric CO₂ in the past two centuries, Nature, 315 45–47
Nielsen, S B and Beck, A, 1988 Heat flow density values and paleoclimate determined from stochastic inversion of four temperature–depth profiles from the Superior province of the Canadian shield Tectonophysics, 164 345–359

Note added in proof
A special issue of this journal (vol 6, issue 2–4, December 1992, edited by T Lewis) contains 18 research papers addressing aspects of climate change inferred from underground temperatures

Pearman, G I, and Fraser, P J, 1988 Sources of increased methane Nature, 332 489–490
Pearman, G I, Etheridge, D., de Silva, F and Fraser, P J, 1986 Evidence of changing concentrations of atmospheric CO₂, N₂O and CH₄ from air bubbles in Antarctic ice Nature, 320 248–250
Pollack, H N and Chapman, D S, 1993 Earth’s changing climate a history read from subsurface temperatures Sci. Am., 286, in press
Shen, P Y and Beck, A E, 1983 Determination of surface temperature history from borehole temperature gradients J Geophys Res., 88 7485–7493
Wang, K, 1992 Estimation of ground surface temperatures from borehole temperature data J Geophys Res., 97 2095–2106