Hochschule–Zürich according to procedures in S. D'Hondt and M. Lindinger, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **112**, 363 (1994). Magnetostratigraphy is from A. D. Chave [*Init. Rep. Deep Sea Drill. Proj.* **74**, 525 (1984)]. Age estimates were based on the magnetic polarity time scale of S. C. Cande and D. V. Kent [*J. Geophys. Res.* **100**, 6093 (1995)].

24. Isotopic data for most planktic foraminiferal samples and several benthic samples were generated at the University of California, Santa Cruz, stable isotope laboratory. For planktic samples, we relied on narrowly constrained (one-quarter phi) size fractions of individual species (*Praemurica taurica* and *R. rotundata* were 212 to 250 μm in mean diameter, *P. ultimatumida* was 250 to 300 μm in mean diameter, and all other planktic taxa were 150 to 180 μm in diameter). In preparation for analysis, samples were roasted at 380°C under vacuum for 1 hour. Isotopic analyses were performed with an Autocarb Preparation Device coupled to a Fisons Prism Mass Spectrometer. In this system, each sample is reacted with H_3PO_4 (8 ml) in a common acid bath at 90°C. External analytical precision, based on replicate analyses of two standards, NBS-19 and Carrera Marble, was better than 0.08 and 0.05‰ for O and C isotopes, respectively. Corrections to measured isotope values were made according to H. Craig, *Geochim. Cosmochim. Acta* **12**, 133 (1957). These isotopic data were combined with data from (*23*).

25. *Morozovella* data are from N. J. Shackleton, R. M. Corfield, and M. A. Hall [*J. Foram. Res.* **15**, 321 (1985)] and R .M. Corfield and J. E. Cartlidge [*Terra Nova* **4**, 443 (1992)]. *Nuttalides* data are from (*3*) and K. G. Miller, T. R. Janecek, M. E. Katz, and D. J. Keil [*Paleoceanography* **2**, 741 (1987)]. Several bulk carbonate data are from N. J. Shackleton, M. A. Hall, and U. Bleil [*Init. Rep. Deep Sea Drill. Proj.* **86**, 503 (1985)]. The remaining isotopic data are from (*3*). Because planktic and benthic samples were not consistently paired, many benthic $\delta^{13}C$ estimates were derived by linear interpolation of measured data. The magnetostratigraphy is from U. Bleil, [*Init. Rep. Deep Sea Drill. Proj.* **86**, 441 (1985)]. Age estimates are as in (*23*).

26. This research was supported in part by NSF (Division of Earth Sciences). Samples were provided by the Ocean Drilling Program. The manuscript was improved by the thoughtful comments of two anonymous reviewers.

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Climate Change Record in Subsurface Temperatures: A Global Perspective

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Analyses of underground temperature measurements from 358 boreholes in eastern North America, central Europe, southern Africa, and Australia indicate that, in the 20th century, the average surface temperature of Earth has increased by about 0.5°C and that the 20th century has been the warmest of the past five centuries. The subsurface temperatures also indicate that Earth's mean surface temperature has increased by about 1.0°C over the past five centuries. The geothermal data offer an independent confirmation of the unusual character of 20th-century climate that has emerged from recent multiproxy studies.

Temperature changes at Earth's surface propagate slowly downward into the rocks beneath the surface and modify the ambient thermal regime. Thus, present-day subsurface temperatures provide evidence of temperature changes that have occurred at the surface in the past. The information contained in this geothermal archive is a valuable complement to instrumentally acquired temperature data and to various types of temperature proxies for understanding Earth's recent surface temperature history (particularly, for the surface temperature history during the several centuries before the acquisition of an instrumental record). Here we report a five-century surface temperature history that was derived from subsurface temperature observations in 358 boreholes (*1*) in eastern North America, central Europe, southern Africa, and Australia (Fig. 1).

As temperature fluctuations at Earth's surface diffuse downward, their amplitudes diminish exponentially with depth. Shorter period oscillations, such as diurnal and seasonal changes, attenuate more rapidly with depth than do longer period oscillations. Because of this selective filtering, Earth records progressively longer term trends at increasing depths. Thus, the geothermal archive is a natural complement to climate proxies (such as tree rings) that display excellent annual resolution but are more difficult to use in resolving long-term trends.

Typically, borehole temperature measurements are made at 10-m depth intervals with an electrical resistance thermometer that can resolve temperature changes of 0.01°C. Most of the boreholes that we selected for analysis penetrated to depths of 200 to 600 m. In general, all subsurface perturbations arising from surface temperature changes that occurred in the past five centuries are confined to the upper 500 m of Earth's crust.

The reconstruction of surface temperature history from borehole temperatures has drawn increasing attention (*2*) over the past two decades. Most reconstruction techniques involve the process of inversion and therefore must contend with incomplete (finite) and noisy data that make it increasingly difficult to resolve climatic excursions in the more remote past (*3*). Noise in the system is principally of two types: (i) errors in the measurement of temperatures, depths, and thermophysical properties and (ii) errors that arise from departures of the mathematical representation of the system from conditions existing in the real world. Most analyses of borehole climatic perturbations assume that heat is transferred solely through one-dimensional heat conduction. Deviations from this idealization (for example, moving fluids with an associated advective component of heat transfer, lateral heterogeneity in thermal conductivity, and topography and nonuniform vegetation along the surface) are manifest as noise in the analysis (*4*).

In attempting to extract a signal in the presence of noise, one has a number of tools with which to work. Within the process of inversion, there exist various smoothing constraints that can be used to suppress the amplification of noise, but they also mute the signal that is recovered. Smoothing can also be accomplished by the nature of the parameterization of the signal and, in a Bayesian inversion, by the nature of the a priori model. Because individual reconstructions exhibit site-to-site variability (arising from local vegetation, subsurface heterogeneity, and topographic and hydrologic effects) that may mask the regional climatic signal, signal enhancement can also be achieved after inversion by stacking (averaging) a large number of individual results (*5*).

The combination of the predominant depth range of observations and the characteristic magnitude of noise has led us to choose five centuries as the practical interval over which to develop climate reconstructions (*6*). In the parameterization of the surface temperature history, we examine only century-long trends of temperature change. By seeking rates of change, one circumvents the problem of comparing the actual air and ground temperatures. Although the air and ground temperatures are usually not the same, they generally have similar trends (*7*). This sparse parameterization yields estimates of only a few smooth quantities that represent relatively long intervals of time. 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 (*3*). This simple parameterization also enables one to estimate the total temperature change over the five-century time interval.

In the inversion of individual borehole

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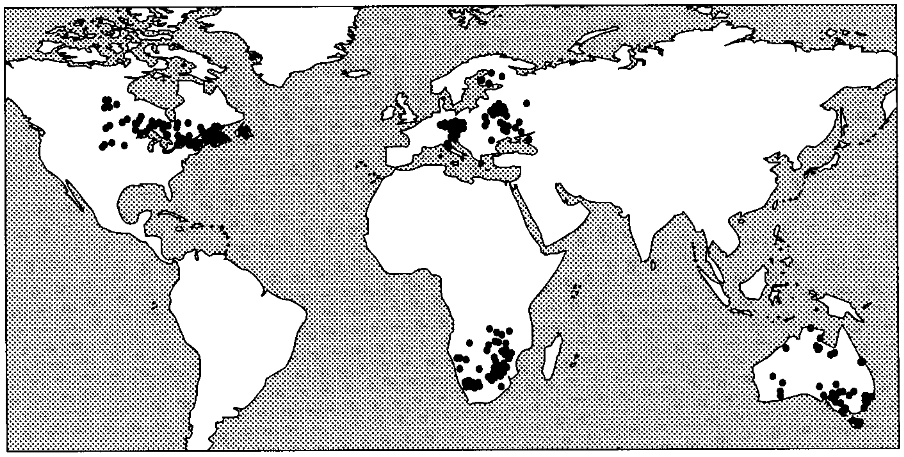

Fig. 1. Locations of 358 boreholes, whose subsurface temperature measurements were analyzed to reconstruct a surface temperature history. There are 116 sites in eastern North America, 98 in central Europe, 86 in southern Africa, and 58 in Australia.

data, we use a Bayesian formulation (*8*), which embodies an a priori estimate of the parameters to be resolved. Our a priori estimate of each century-long trend is identically zero (a de facto null hypothesis), which places the burden of proof on the data to demonstrate that there have been changes in the surface temperature. Such a null hypothesis is conservative and fully independent of any preconceptions about past climate change.

Of the 358 individual reconstructions, almost 80% of the sites experienced a net warming over the past five centuries (Fig. 2). The mean of the cumulative temperature change over the past five centuries is a warming of ~1.0°C. The range of the distribution reflects both regional differences and the myriad details of local site-specific effects. The fact that there are some sites that display a net cooling over five centuries suggests a measure of regional variability that is similar to that commonly found in meteorological records.

A composite temperature history (*9*) for the 358 sites (Fig. 3), which was obtained by stacking the individual site reconstructions, indicates that the present-day mean temperature of these sites is ~1.0° ± 0.2°C warmer, on average, than five centuries ago. The change of temperature in the 20th century alone has been 0.5° ± 0.1°C and equals the cumulative change that is inferred for the previous four centuries. The temperature of the 20th century appears to be warmer than the mean temperature of any of the previous four centuries. The composite meteorological record for the sites (*10*), also shown in Fig. 3, displays similar trends in the time interval of overlap.

The composite 20th-century trend that was inferred from the geothermal data is also consistent with the global estimate by the 1995 Intergovernmental Panel on Climate Change (*11*), which shows an increase of ~0.3° to 0.6°C since the late 19th century. The 358 sites in the geothermal composite are well distributed longitudinally and represent two continents in both the Northern and Southern Hemispheres. Although the global meteorological record incorporates sea-surface temperatures as well as continental temperatures, the similarity between the four-continent and global histories since the mid-19th century suggests that the temperature history of the continents may be a representative subset of the temperature history of Earth as a whole. This suggestion is supported by the close correspondence of surface air temperatures (SATs) of both sea and land in the 20th century (*11*) and by a satellite radiometric analysis (*12*), which showed nearly identical temperature trends over continental and oceanic regions (albeit over a much shorter time interval).

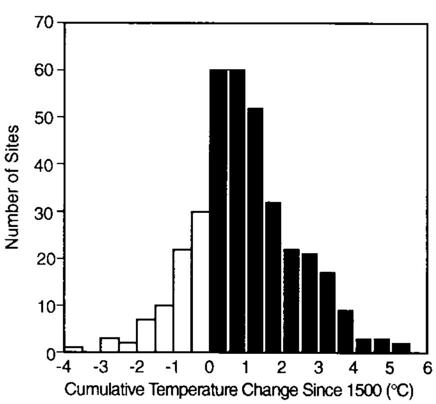

Fig. 2. Histogram of cumulative five-century temperature changes at sites shown in Fig. 1. Black columns indicate net warming and white columns indicate net cooling.

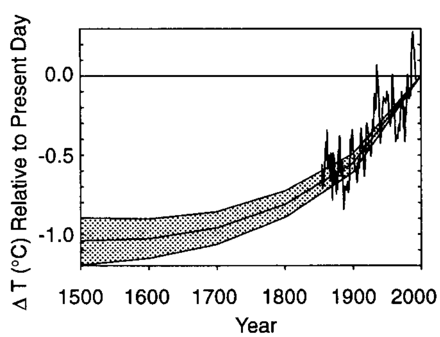

Fig. 3. Composite four-region surface temperature change over the past five centuries, relative to the present, as determined from geothermal data. Shaded areas represent ±1 standard error about the mean history. Superimposed is a smoothed (5-year running average) SAT instrumental record (*10*) representing a composite of the same regions as the geothermal data. Because the SAT series is referenced to the mean anomaly over the interval from 1961 to 1990 and because the geothermal result is referenced to the present, we have shifted the SAT series downward by 0.2°C to enable a visual comparison of the trends by a direct overlay.

The temperature history that we reconstruct from geothermal data can also be compared to three recent multiproxy reconstructions: (i) a four-century time series that was assembled from proxies occurring principally in the latitude range of 60° to 80°N (*13*), (ii) a six-century time series that was assembled from globally distributed continental and marine proxies (*14*), and (iii) a millennial summer temperature history that was assembled from global data (*15*). The geothermal reconstruction and all multiproxy reconstructions show that the 20th century is the warmest recent century and that the mean rate of temperature increase in the 20th century is well in excess of temperature trends of earlier centuries. Thus, the geothermal analysis, which is based on direct temperature data and a methodology that is totally different from the multiproxy investigations, provides an independent confirmation of the unusual character of 20th-century climate. The various estimates of net temperature change over the past four centuries show more apparent variability, ranging from ~0.4° to 1.0°C, but these apparent differences may arise from different regional and seasonal sampling in the several data sets (*16*).

References and Notes

1. The data that we analyzed were extracted from published materials or from a database of borehole temperatures that is being compiled by a working group of the International Heat Flow Commission of the International Association of Seismology and Physics of the Earth's Interior. We have, however, made a uniform quality-control assessment of all the data analyzed.
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9. A mean temperature history that was determined by averaging the individual borehole site results for each of the four continental ensembles and then forming an equally weighted average of the four continental reconstructions yields a reconstruction that is very similar to that shown in Fig. 3, indicating that the mean temperature history is insensitive to the details of aggregation.
10. The meteorological time series is derived from the land-only gridded SAT anomalies assembled by P. D. Jones, T. J. Osborn, and K. R. Briffa [*J. Clim.* **10**, 2548 (1997)] (also available from the Climatic Research Unit at the University of East Anglia, Norwich, UK, as a data set at www.cru.uea.ac.uk/cru/data/temperat.htm).
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Isolation of Acidophilic Methane-Oxidizing Bacteria from Northern Peat Wetlands

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Acidic northern wetlands are an important source of methane, one of the gases that contributes to global warming. Methane oxidation in the surface of these acidic wetlands can reduce the methane flux to the atmosphere up to 90 percent. Here the isolation of three methanotrophic microorganisms from three boreal forest sites is reported. They are moderately acidophilic organisms and have a soluble methane monooxygenase. In contrast to the known groups of methanotrophs, 16*S* ribosomal DNA sequence analysis shows that they are affiliated with the acidophilic heterotrophic bacterium *Beijerinckia indica* subsp. *indica*.

The methane (CH_4) concentration in the atmosphere has more than doubled over the last 300 years (*1*) and is currently increasing at an annual rate of 0.8 to 1.0% per year (*2*). About half of the total annual flux of CH_4 to the atmosphere is contributed by wetlands (*3*). The massive northern wetlands account for 50% of the global wetland area (*4*), and their most extensive type, found in northern Europe, West Siberia, the United States, and Canada, is the acidic *Sphagnum* peat bogs, which have pH values ranging from 3.5 to 5.

The primary barrier that limits the release of CH_4 from methanogenic peatlands is its in situ consumption by indigenous methane-oxidizing bacteria (MOB). MOB inhabit a spectrum of diverse environments and have the unique ability to use CH_4 as a sole carbon and energy source (*5*). The colonization of acidic bogs by MOB has been established by measurement of methanotrophic activity (*6*), MOB signatures in phospholipids (*7*), and DNA (*8*, *9*) extracted from peat. Nevertheless, virtually all MOB available in pure culture are neutrophiles, and there are no reports of methanotrophs that grow at pH values below 5.0 (*10*).

We recently reported on the enrichment of methanotrophic communities from acidic peat bogs of four boreal forest sites in West Siberia and European North Russia (*11*). The key to successful enrichment was the use of a medium of very low ionic strength and low pH (3 to 6), and incubation under CH_4-air mixture at moderate temperature (20°C). These communities were moderately acidophilic with growth and activity optima at pH 4.5 to 5.5. We have now isolated in pure culture MOB from three of these four enrichments (*12*). The colonies of MOB developed after 4 to 5 weeks of incubation. We selected three strains (strains K, M131, and S6), each representing one enriched community, and confirmed their purity (*13*). The cells of these three strains were Gram-negative, nonmotile, polymorphic, straight or curved rods with a diameter of 0.7 to 1.0 μm and length of 1.0 to 2.0 μm. They shared an identical morphotype, that is, a specific flattened shape with a concave center and round, bent ends (*14*) (Fig. 1). The same morphotype was observed as one of the dominant components of the primary communities (*11*).

Strains S6, K, and M131 grew on minimal mineral medium with the addition of a vitamin mixture and CH_4 as a sole source of carbon and energy (*15*). Growth did not occur in control experiments on the same mineral medium containing vitamins and no CH_4. The isolates were slow growing with a specific growth rate $\leq$ 0.8 to 1.0 day^{-1}, which is consistent with the in situ growth rate for MOB of 0.02 day^{-1} (*16*). The temperature range for growth of isolates was from 10° to 25°C with the optimum at ~20°C. The same optimum was found for CH_4 consumption by native peat samples (*17*). No growth of isolates occurred at 30°C. Clearly these bacteria are adapted to conditions of their natural habitat where the temperature never exceeds 25°C, even during summer.

Methane consumption peaked at pH 5.1 for all three strains (Fig. 2). The same pattern of pH dependence was also found for the original peat samples and the methanotrophic enrichments (*11*, *17–19*). The acidophilic nature of the isolated bacteria was confirmed by observing exponential growth without a lag phase and the highest specific growth rate at pH 4.8, whereas no growth was recorded in a medium at initial pH 7.4 (Fig. 2). Furthermore, growth of isolates was sustained in serial transfers in pH 5.0 to 5.5 medium.

Polymerase chain reaction (PCR) assays for the *mmoX* and *mmoY* genes, encoding the α and β subunits of the soluble methane monooxy-

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