9. Bai, T. & Pollard, D. D. Fracture spacing in layered rocks: a new explanation based on the stress transition. *J. Struct. Geol.* **22,** 43–57 (2000).
10. Bai, T. & Pollard, D. D. Spacing of fractures in a multilayer at fracture saturation. *Int. J. Fract.* (in the press).
11. Price, N. J. *Fault and Joint Development in Brittle and Semi-Brittle Rocks* 176 (Pergamon, Oxford, 1966).
12. Pollard, D. D. & Aydin, A. Progress in understanding jointing over the past century. *Geol. Soc. Am. Bull.* **100,** 1181–1204 (1988).
13. National Research Council *Rock Fractures and Fluid Flow: Contemporary Understanding and Applications* 551 (National Academy Press, Washington DC, 1996).
14. Whittaker, B. N., Gaskell, P. & Reddish, D. J. Subsurface ground strain and fracture development associated with longwall mining. *Mining Sci. Technol.* **10,** 71–80 (1990).
15. Thouless, M. D., Olsson, E. & Gupta, A. Cracking of brittle films on elastic substrates. *Acta Metall. Mater.* **40,** 1287–1292 (1992).
16. Hong, A. P., Li, Y. N. & Bazant, P. Theory of crack spacing in concrete pavements. *J. Eng. Mech.* **123,** 267–275 (1997).
17. Lachenbruch, A. H. Depth and spacing of tension cracks. *J. Geophys. Res.* **66,** 4273–4292 (1961).
18. Hu, M. S. & Evans, A. G. The cracking and decohesion of thin films on ductile substrates. *Acta Metall.* **37,** 917–925 (1989).
19. Thouless, M. D. Some mechanics for the adhesion of thin films. *Thin Solid Films* **181,** 397–406 (1989).
20. Thouless, M. D. Crack spacing in brittle films on elastic substrates. *J. Am. Ceram. Soc.* **73,** 2144–2146 (1990).
21. Timoshenko, S. P. & Goodier, J. N. *Theory of Elasticity* 3rd edn, 567 (McGraw-Hill, New York, 1970).
22. Wawrzynek, P. A. & Ingraffea, A. R. Interactive finite element analysis of fracture processes: An integrated approach. *Theor. Appl. Fract. Mech.* **8,** 137–150 (1987).

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Temperature trends over the past five centuries reconstructed from borehole temperatures

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For an accurate assessment of the relative roles of natural variability and anthropogenic influence in the Earth's climate, reconstructions of past temperatures from the pre-industrial as well as the industrial period are essential. But instrumental records are typically available for no more than the past 150 years. Therefore reconstructions of pre-industrial climate rely principally on traditional climate proxy records[1–5], each with particular strengths and limitations in representing climatic variability. Subsurface temperatures comprise an independent archive of past surface temperature changes that is complementary to both the instrumental record and the climate proxies. Here we use present-day temperatures in 616 boreholes from all continents except Antarctica to reconstruct century-long trends in temperatures over the past 500 years at global, hemispheric and continental scales. The results confirm the unusual warming of the twentieth century revealed by the instrumental record[6], but suggest that the cumulative change over the past five centuries amounts to about 1 K, exceeding recent estimates from conventional climate proxies[2–5]. The strength of temperature reconstructions from boreholes lies in the detection of long-term trends, complementary to conventional climate proxies, but to obtain a complete picture of past warming, the differences between the approaches need to be investigated in detail.

The thermal regime of the uppermost continental crust is determined in part by the outward flow of heat from the deep interior of the Earth and in part by fluctuations of temperature at the surface. In homogeneous rock and in the absence of changes at the surface, the temperature in the subsurface increases linearly with depth, at a rate which is governed by the magnitude of the terrestrial heat flow and the thermal conductivity of the rock. Fluctuations of surface temperature propagate downward into the rock as attenuating thermal waves superimposed on the temperature profile associated with the deeper heat flow. The depth to which disturbances can be observed is determined by the amplitude, duration and spectral composition of the temperature change at the surface. Owing to the generally low thermal diffusivity of rock, propagation of climate signals in the subsurface is slow. Following a change in temperature at the surface, it takes about 100 years for the perturbation to reach a depth of 150 m, and 1,000 years to reach 500 m depth. Complications in reconstructing a ground surface temperature (GST) history from subsurface temperature data can, however, arise from various non-climatic disturbances[7] that perturb subsurface temperatures.

We have assembled a database of borehole temperatures for climate reconstruction[8]. The database currently contains 616 borehole temperature profiles that meet certain quality-control criteria; 453 are in the Northern Hemisphere and 163 in the Southern Hemisphere. These borehole sites (Fig. 1) sample all continents except Antarctica, although the geographical distribution of the sites is uneven. The borehole temperatures in this global database were typically measured at 10-m depth intervals to depths as great as 600 m.

The reconstruction of a GST history by inversion of subsurface temperatures has its foundation in the theory of heat conduction[9–11]. Because of the diffusion of the climate signal through the rocks, a geothermal climate reconstruction is characterized by a progressive inability to resolve the details of climate excursions in the more remote past[12–14]. For inverting subsurface temperatures to yield a GST history, we use a bayesian estimation technique[15] that is a simplification and extension of the functional space inversion formulation of Shen and Beck[16]. Rather than treating the GST history as an arbitrary function of time, we have chosen to parametrize the reconstruction simply, in terms of century-long rates of change over the past five centuries. This simple parametrization leads to a very smooth GST reconstruction. The absence of shorter-period representation in the reconstruction, however, is offset by a reduction of variance in the estimated century-long rates, and by the ease with which these rates may be compared to corresponding quantities that emerge from analyses of the instrumental record. If

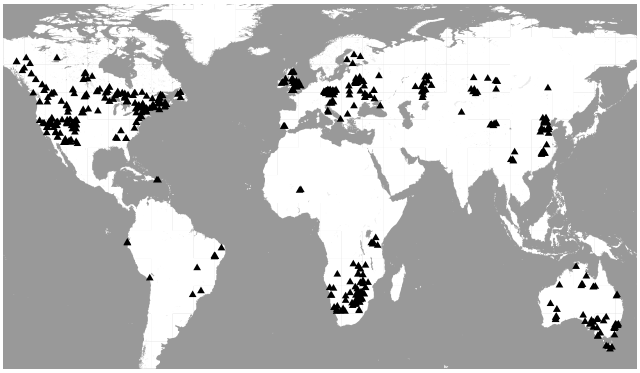

Figure 1 Location map of the boreholes where subsurface temperature measurements have been analysed to reconstruct a ground surface temperature (GST) history. The numbers of boreholes on each continent are respectively 245 (North America), 16 (South America), 146 (Europe), 92 (Africa), 60 (Asia), and 57 (Australia).

climate-change trends do not coincide closely with the calendar centuries, such as when a natural century-long trend straddles two calendar centuries, the inversion will attribute part to one century and part to the other, thus creating a temporal smearing of the temperature trend. In the inversion we employ an *a priori* null hypothesis for the GST history; that is, an initial estimate that there has been no climate change. This is a conservative hypothesis that is also fully independent of any extant models of climate change. As resolution diminishes further back in time, the null hypothesis becomes more difficult to reject.

Of the 616 borehole temperature profiles we analysed, 479 show a net warming over the past five centuries. The average of the cumulative temperature change over the five-century interval is a warming of about 1.0 K (Fig. 2). In the twentieth century alone, the average surface temperature of the continents has increased by about 0.5 K, and the twentieth century has been the warmest century of the past five**.** This ensemble average is consistent with that derived earlier from a smaller and geographically more restricted data set of 358 boreholes from eastern North America, central Europe, southern Africa, and Australia[17]. Although the mechanism of the coupling between the air temperature at the surface and the GST is not simple, and varies from one geographical setting to another[18–20], at a large spatial scale the trends of the surface air temperature anomaly and the GST anomaly match well (Fig. 2). Both the global mean surface air temperature (SAT) anomaly series[6] and the GST continental reconstruction show substantial warming in the twentieth century. The geothermal reconstruction is in generally good agreement with the trend of the global SAT record in both the late nineteenth and twentieth centuries, and extends the climate history back several hundred years before the instrumental record. Almost 80% of the net temperature increase observed has occurred in the nineteenth and twentieth centuries.

The magnitude of ground surface warming over the past five centuries is greater in the Northern Hemisphere than in the Southern Hemisphere: the five-century cumulative change is 1.1 K in the former, and 0.8 K in the latter. The twentieth-century temperature change is 0.6 K in the Northern Hemisphere compared with 0.4 K in the Southern Hemisphere. These values compare, respectively, with 0.60 and 0.65 K per century for hemispheric trends in the combined land and sea surface air temperature[6]. The geothermal hemispheric estimates for the twentieth century show even greater consistency with the land-only hemispheric trends of 0.56 and 0.47 K per century reported by Jones[21]. We note that the relatively small number of geothermal observations—and the limited geographical regions represented by them, particularly in the Southern Hemisphere—make tentative any comparisons with hemispheric SAT trends.

Additional regional and temporal variability can be seen in the individual continental GST histories (Fig. 3), although the absence of data in large parts of several continents precludes a detailed interpretation. The five-century cumulative temperature changes are respectively 1.2 K for North America, 1.4 K for South America, 0.8 K for Europe, 0.8 K for Africa, 1.2 K for Asia and 0.5 K for Australia. The GST reconstructions for all six continents exhibit a common characteristic: the temperature change in the twentieth century is the largest of the past five centuries. Intercontinental comparisons for the earlier centuries must be assessed with caution, particularly because of the sparseness of observations in South America and Asia.

Considerable effort has been given recently to combining several proxies in order to produce global, hemispheric and regional-scale climate reconstructions[1–5,21–23]. Figure 4 shows the comparison of our Northern Hemisphere geothermal reconstruction with three recent multi-proxy representations. All show significant increases of temperature in the twentieth century, but display differences in the previous four centuries. The differences between the various reconstructions may arise in part because of the different geographical distribution of the data used in the respective reconstructions, or perhaps because of differing weights given to individual proxy data sets in the multi-proxy reconstructions[22]. Of the full hemispheric reconstructions, the geothermal estimate of the five-century temperature change is the largest.

The differences in the pre-instrumental centuries between the geothermal reconstruction and the multi-proxy reconstructions

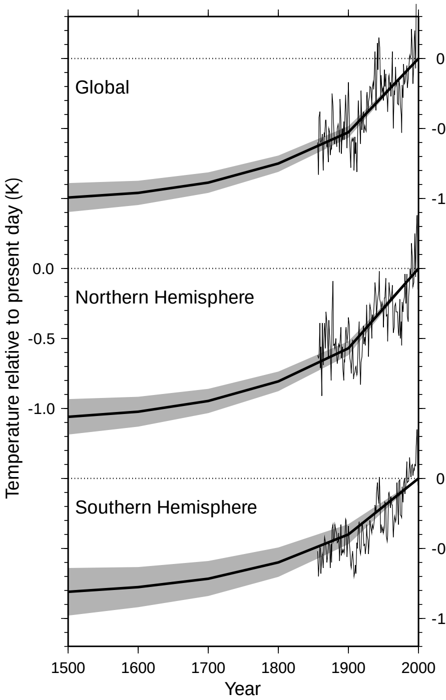

Figure 2 Global and hemispheric averages of GST history over the past five centuries. Shaded areas represent ±1 standard error about the mean. Superimposed are the corresponding series of instrumental surface air temperatures (SAT)[6]. Because the geothermal reconstruction is the concatenation of century-long trends, and the SAT anomaly series are referenced to the mean over the period 1961–90, we have shifted the SAT series along the temperature axis to enable an easy comparison of their respective trends. The SAT records have been shifted –0.20 K for the global series, –0.28 K for the Northern Hemisphere and –0.13 K for the Southern Hemisphere.

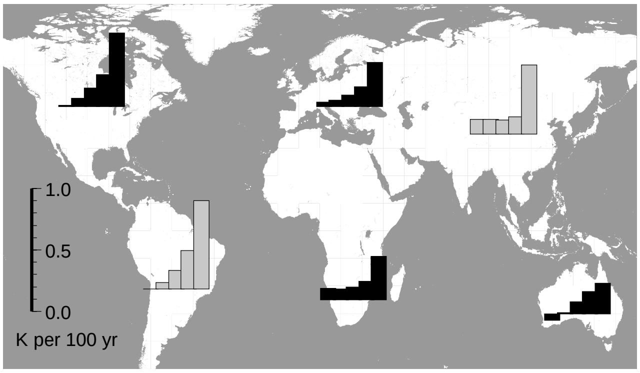

Figure 3 Continental century-long GST changes. In each histogram, the five columns from left to right represent respectively the sixteenth, seventeenth, eighteenth, nineteenth and twentieth centuries. The magnitude of the temperature change is shown as the height of the column. The continental reconstructions for South America and Asia are lightly shaded to indicate the larger uncertainties in these two continents because of the low spatial density of observations.

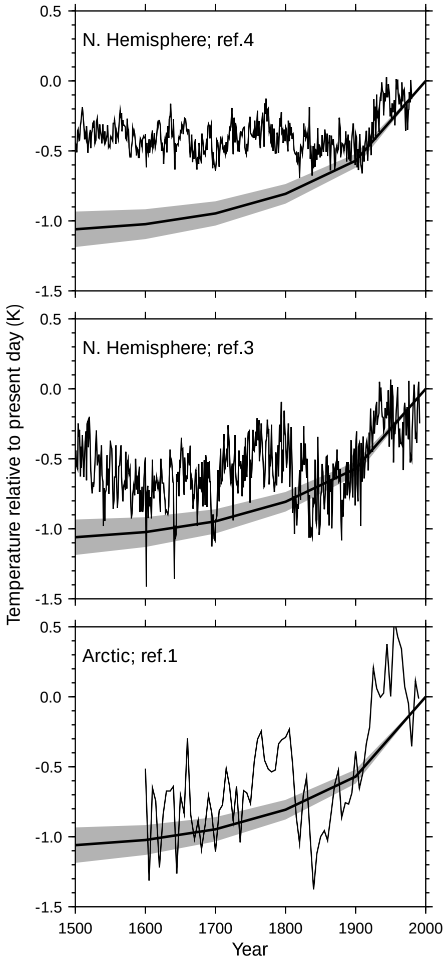

Figure 4 Comparison of five-century Northern Hemisphere geothermal reconstructions with three multi-proxy reconstructions (refs 4, 3 and 1). The Mann *et al.*[4] and Jones *et al.*[3] reconstructions have been shifted along the temperature axis –0.25 K and –0.20 K, respectively, to enable direct comparison of the trends. The Overpeck *et al.*[1] reconstruction has not been shifted.

may also arise in part from the role of tree-ring series in their reconstructions[22]. Tree-ring data are an important resource in palaeoclimate reconstruction because of their annual resolution and relatively good spatial and temporal coverage. However, tree-ring analyses generally involve some temporal detrending[23], a process that is intended to mute long-term growth trends that may be present in the data. For this reason, the long-term trends derived from borehole temperatures may have a role as useful complements to the traditional proxy reconstructions. Whatever the underlying causes of the differences between the various reconstructions may be, however, the resolution of these differences, particularly in determining the total temperature change over the five-century interval, is important. This temperature change has the potential to be a useful empirical constraint on the climate-sensitivity factor of global climate models. M

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1. Overpeck, J. *et al.* Arctic environmental change of the last four centuries. *Science* **278,** 1251–1256 (1997).
2. Briffa, K. R., Jones, P. D., Schweingruber, F. H. & Osborn, T. J. Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years. *Nature* **393,** 450–455 (1998).
3. Jones, P.D., Briffa, K.R., Barnett, T.P. & Tett, S.F.B. High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with general circulation model control-run temperatures. *Holocene* **8,** 455–71 (1998).
4. Mann, M.E., Bradley, R.S. & Hughes, M.K. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392,** 779–787 (1998).
5. Mann, M.E., Bradley, R.S. & Hughes, M.K. Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophys. Res. Lett*. **26,** 759–762 (1999).
6. Jones, P.D., New, M., Parker, D.E., Martin, S. & Rigor, I.G. Surface air temperature and its changes over the past 150 years. *Rev. Geophys.* **37,** 173–199 (1999).
7. Shen, P.-Y., Pollack, H.N., Huang, S. & Wang, K. Effects of subsurface heterogeneity on the inference of climate change from borehole temperature data: model studies and field examples from Canada. *J. Geophys. Res.* **100,** 6383–6396 (1995).
8. Huang, S. & Pollack, H.N. *Global Borehole Temperature Database for Climate Reconstruction* (IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series No. 1998-044, NOAA/NGDC Paleoclimatology Program, Boulder, Colorado, 1998).
9. Birch, F. The effects of Pleistocene climatic variations upon geothermal gradients. *Am. J. Sci.* **246,** 729–760 (1948).
10. Cermak, V. Underground temperature and inferred climatic temperature of the past millennium. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **10,** 1–19 (1971).
11. Lachenbruch, A.H. & Marshall, B.V. Changing climate: geothermal evidence from permafrost in the Alaskan Arctic. *Science* **234,** 689–696 (1986).
12. Clow, G.D. Temporal resolution of surface temperature histories inferred from borehole temperature data. *Palaeogeogr. Palaeoclimatol. Paleoecol.* **98,** 81–86 (1992).
13. Beltrami, H. & Mareschal, J.C. Resolution of ground temperature histories inverted from borehole temperature data. *Glob. Planet. Change* **11,** 57–70 (1995).
14. Harris, R.H. & Chapman, D.S. Climate change on the Colorado Plateau of eastern Utah inferred from borehole temperatures. *J. Geophys. Res.* **103,** 7363–6381 (1998).
15. Huang, S., Shen, P.-Y. & Pollack, H.N. Deriving century-long trends of surface temperature from borehole temperatures. *Geophys. Res. Lett.* **23,** 257–260 (1996).
16. Shen, P.-Y & Beck, A.E. Least squares inversion of borehole temperature measurements in functional space. *J. Geophys. Res.* **96,** 19965–19979 (1991).
17. Pollack, H.N., Huang, S. & Shen, P.-Y. Climate change record in subsurface temperatures: a global perspective. *Science* **282,** 279–281 (1998).
18. Chapman, D.S., Chisolm, T.J. & Harris, R.N. Combining borehole temperature and meteorological data to constrain past climate change. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **98,** 269–281 (1992).
19. Lewis, T.J. The effect of deforestation on ground surface temperatures. *Glob. Planet. Change* **18,** 1–13 (1998).
20. Majorowicz, J.A. & Skinner, W.R. Potential causes of differences between ground and surface air temperature warming across different ecozones in Alberta, Canada. *Glob. Planet. Change* **15,** 79–91 (1997).
21. Jones, P.D. Hemispheric surface air temperature variations: A reanalysis and an update to 1993. *J. Clim*. **7,** 1794–1802 (1994).
22. Jones, P.D. It was the best of times, it was the worst of times. *Science* **280,** 544–545 (1998).
23. Briffa, K. R. & Osborn, T. J. Seeing the wood from the trees. *Science* **284,** 926–927 (1999).

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Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico

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An increase in the flux of nitrogen from the Mississippi river during the latter half of the twentieth century has caused eutrophication and chronic seasonal hypoxia in the shallow waters of the Louisiana shelf in the northern Gulf of Mexico[1–5]. This has led to reductions in species diversity, mortality of benthic communities and stress in fishery resources[4]. There is evidence for a predominantly anthropogenic origin of the increased nitrogen flux[2,5–7], but the location of the most significant sources in the Mississippi basin responsible for the delivery of nitrogen to the Gulf of Mexico have not been clearly identified, because the parameters influencing nitrogen-loss rates in rivers are not well known. Here we present an analysis of data from 374 US monitor-