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Climate Change: Past, Present, and Future

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Questions about global warming concern climate scientists and the general public alike. Specifically, what are the reliable surface temperature reconstructions over the past few centuries? And what are the best predictions of global temperature change the Earth might expect for the next century?

Recent publications [*National Research Council* (*NRC*), 2006; *Intergovernmental Panel on Climate Change* (*IPCC*), 2007] permit these questions to be answered in a single informative illustration by assembling temperature reconstructions of the past thousand years with predictions for the next century. The result, shown in Figure 1, illustrates present and future warming in the context of natural variations in the past [see also *Oldfield and Alverson*, 2003]. To quote a Chinese proverb, "A picture's meaning can express ten thousand words." Because it succinctly captures past inferences and future projections of climate, the illustration should be of interest to scientists, educators, policy makers, and the public.

Surface Temperatures in the Past

Surface temperatures for Earth are most reliably known for the period 1850 to present, the time interval for which there is reasonable global coverage of meteorological stations measuring temperature in a systematic manner [*Hansen et al.,* 2001; *Smith and Reynolds,* 2005; *Brohan et al.,* 2006].

The instrumental record part of Figure 1 represents global annual temperature anomalies for 1850–2008 [*Brohan et al*., 2006]. Temperature during this time has increased by about 0.8°C, with much of the warming occurring since 1975. Annual records for individual stations and for groups of stations exhibit both large (~1°C) interannual variability and decadal or longer periods of both warming and cooling.

Because temperature reconstructions are generally made in terms of a temperature change, also referred to as a temperature anomaly, the zero point on the scale is arbitrary. The reference level in Figure 1 is defined as the 10-year average of temperatures for the years 1995–2004, centered on 1 January 2000. It is a convenient reference for changes in past centuries and for viewing temperature change in this century.

Temperatures prior to the instrumental record are derived from various proxy estimates such as tree rings, corals, and sediments; from observations and inferences of glacier length changes; and from subsurface temperatures measured at regular intervals within boreholes. The curves in Figure 1 are taken from *NRC* [2006] and represent different estimates of temperature for the Northern Hemisphere. Weighted to midlatitudes, they are also smoothed versions of actual temperature changes with the degree of smoothing unique to the particular reconstruction method [*NRC*, 2006, and references therein]. Differences between the various curves represent different spatial sampling, latitudinal emphasis, seasonality, and methodologies. This collection of curves suggests that the Northern Hemisphere was relatively warm around 1000 C.E. (but not as warm as current temperature), that the period 1500–1850 was relatively cool, and that there has been considerable warming since 1900 [*NRC,* 2006].

Borehole Temperatures Confirm Long-Term Climate Change

Subsurface temperatures measured in boreholes register not only the steady state heat flowing out from the interior of the Earth but also transient departures attributable to past surface temperature changes [e.g., *Lachenbruch and Marshall,* 1986; *Harris and Chapman,* 2001]—in essence, the heat of the Earth's atmosphere diffuses into the Earth's crust such that progressively deeper regions hold signatures for the temperatures of progressively older times. Through the

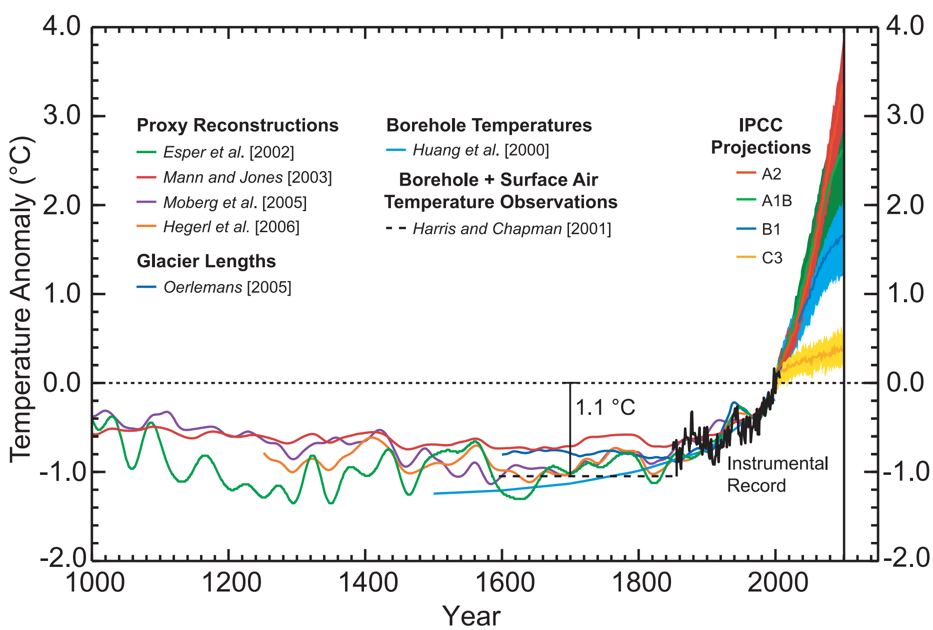

Fig. 1. Views of temperature change in the next century are informed by temperature changes in the past. For illustrative and educational purposes, three sets of surface temperatures have been assembled: 1000-year reconstructions of past temperature change based on proxies (tree rings, corals, etc.), glacier lengths, and borehole temperatures; the instrumental record; and Intergovernmental Panel on Climate Change (IPCC) projections for temperature change from 2000 to 2100. Figure modified from National Research Council *[2006] and* IPCC *[2007].*

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process of thermal diffusion, short-term fluctuations in surface temperatures are filtered out, leaving behind decade- to century-long trends and averages. These data provide an independent estimate of surface temperature change but, unlike proxy measurements, are a direct measure of past temperatures.

An archive of borehole temperature profiles at 862 sites suitable for studying climate change exists at the University of Michigan [*Huang et al.,* 2000] (see http://www.geo.lsa.umich.edu/climate/ for data and a map of borehole site locations). Boreholes at all sites in the archive extend to at least a 200-meter depth (Figure 2). Fewer than 10% extend more than 600 meters into the subsurface; these sites are primarily in northeastern Canada, central Eurasia, and South Africa. The depth distribution of boreholes is important because the depth of borehole temperature anomalies is related to the timing of past surface temperature changes (Figure 2).

The collection of borehole temperature profiles exhibits many characteristics of the meteorological record of climate change: hemisphere-scale variation, regional variation, local effects, and noise. Collectively, borehole temperatures show clear evidence of significant twentieth-century warming and a potential for quantitatively constraining longer-term climate changes of the past few centuries, a time prior to the instrumental record when temperature reconstruction is more difficult [*Huang et al.,* 2000].

One curve in Figure 1 not included in the *NRC* [2006] report represents an independent analysis of the borehole temperature reconstruction [*Harris and Chapman,* 2001]. This is a hybrid reconstruction utilizing both borehole and surface air temperature (SAT) information. The hybrid method yields a baseline temperature prior to the instrumental record, suggesting warming of about 1.1°C (Figure 1) since ~1750.

The borehole temperature archive serves yet another purpose in testing multicentury- to millennium-scale surface temperature reconstructions. Any surface temperature history can be used to generate a synthetic borehole temperature profile by computing the transient perturbation using surface temperatures as a boundary condition. The process requires a constant initialization temperature for the subsurface as a reference for temperature perturbations. All the temperature reconstructions based on proxies in Figure 1 produce fits within 0.05°C of the Northern Hemisphere observed borehole temperature anomaly (Figure 2). The reconstruction of *Esper et al.* [2002] yields a particularly good fit. It is possible that borehole temperature profiles could be used to pick winners in the temperature reconstruction stakes, but it would require a greater number of deep boreholes collocated with proxy sites.

Furthermore, the initialization temperature for each proxy, computed by minimizing the misfit between the synthetic profile and the global borehole observation, provides additional confirmation that current

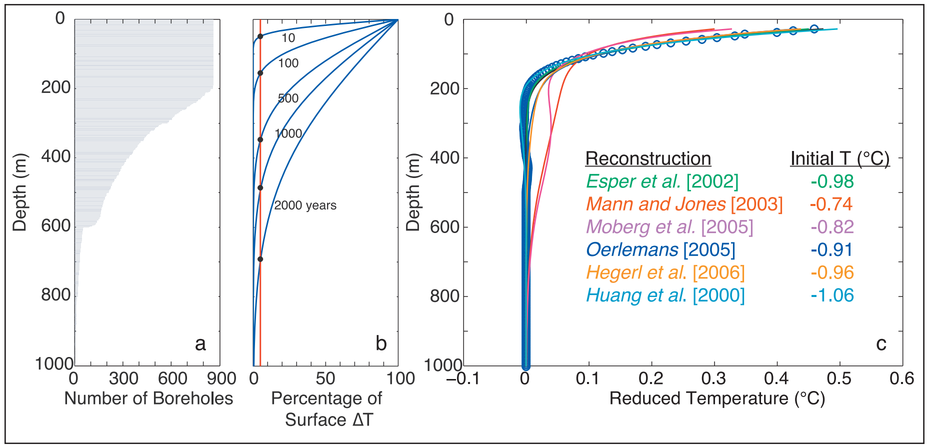

*Fig. 2. Geothermics of climate change. (a) Cumulative number of boreholes in the global climate borehole database with temperature observations to a given depth (shaded region). (b) Temperature versus depth at times following a step change (Δ*T*) in surface temperature. Solid dots mark depths where the signal is 5% of the surface change, a rough estimate of the noise level (red line) for a Δ*T* of 1°C. Climate change in the past 100 years is seen primarily in the uppermost 150 meters of a borehole; the past millennium is recorded down to depths of nearly 500 meters. (c) Average transient temperature from borehole observations (circles; see* Harris and Chapman *[2001] for details). Curves show various synthetic profiles derived from diffusing multiproxy temperature reconstructions (Figure 1) into the ground. The legend shows the initialization temperature to obtain the synthetic profiles. Those reconstructions with relatively warm ninth to thirteenth centuries (the Medieval Warm Period) produce a positive excursion in temperatures in the synthetic profile between 200- and 600-meter depth. A greater number of deep boreholes from geographically dispersed sites would assist in resolving whether this climatic warm period was a global or a regional phenomenon.*

surface temperature trends and future projections are unusual. All four proxy studies have initialization temperatures from –0.74°C to –0.98°C relative to the year 2000 reference temperature (Figure 2). All indicate that the twentieth-century warming is superimposed on centuries of considerably lower temperatures.

Surface Temperature in the Future

The *IPCC* [2007] assessment refines how global temperature might change in the future. The predictions are based on greenhouse gas emission scenarios and a link between greenhouse gas concentration and temperature through modeling.

The four scenarios shown in Figure 1 for future temperature trends combine different factors that influence how our atmosphere and surface temperature will change in this century. The factors include population growth, economic development, and technological change as well as cultural and social interaction among groups and countries. Differences between scenarios are considerable. For example, in scenario A2, population increases at current growth rates to 15 billion in 2100 accompanied by a heterogeneous economic theme of self-reliance and preservation of local identities. Global temperature increase with scenario A2 approaches 4°C by 2100. In contrast, the A1B story line has a population that grows from a current level to a peak at 8.7 billion at midcentury and decreases toward 7 billion at the end of the century. This scenario entertains efficient technologies and in particular a balanced technology emphasis between fossil fuel and non–fossil fuel energy sources. Global temperature increase in scenario A1B is ~2.5°C. B1 population follows A1B, but countries come together to use both technology and general environmental controls to decrease emissions, leading to a temperature increase of less than 2°C above the year 2000 level.

There is also a thermal consequence of the long response time of atmospheric carbon dioxide (CO_2). Curve C3 demonstrates that even if CO_2 concentrations are held at year 2000 levels, temperatures will increase throughout the century. This behavior is due to the lengthy response time of the climate system, both in the thermal inertia of the oceans, where it takes a long time to reach a new equilibrium state, and with unrealized warming due to the energy imbalance in the atmosphere as a result of current greenhouse gas concentrations. Holding CO_2 concentrations constant would allow for climate equilibration to occur; however, the complexity of the climate system, with the combination of inertial, memory, and feedback processes inherent in the system, means that equilibration would take an extended period of time.

The Path Forward

All of the emissions scenarios considered by the IPCC yield global warming in the 21st century that dwarfs warming seen in the past millennium. Immediate change to near-zero CO_2 emissions is required to restrict global temperature increases to less than the constant composition commitment, C3 [*Matthews and Weaver,* 2010].

Two additional points should be made. Whereas the most likely temperature increase is about 2°–3°C in the global average above levels in 2000, warming in high-latitude regions may be 3 times as much. Thus, the global average should be considered for what it is: a global average.

Second, the reconstructed temperatures for the past millennium indicate that temperatures for large regions, at least at the hemisphere scale, vary significantly at the multidecadal time scale. For example, all periods in the past millennium show temperature variations of up to 0.5°C that last for 1–4 decades. Thus, similar natural fluctuations in the future should be expected [*Easterling and Wehner,* 2009; *Lean and Rind,* 2009].

One major challenge in formulating climate mitigation and adaptation policies is first convincing a skeptical public that global warming is real, that it exceeds in magnitude and pace the natural changes over the past millennium, and that it is rapidly moving into an uncharted future fraught with serious consequences.

Having the temperature history of the past thousand years displayed together with various future scenarios of a warming climate (Figure 1) provides the benefit of both hindsight and foresight simultaneously and makes the warnings of climate scientists ever more persuasive. Seeing where society is headed in terms of where it has been may help policy makers worldwide choose a sensible path into the future.

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NEWS

Goals for Near-Earth-Object Exploration Examined

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With Japan's Hayabusa space probe having returned a sample of the Itokawa asteroid this past June, and with NASA's Deep Impact spacecraft impactor having successfully struck comet Tempel 1 in 2006, among other recent missions, the study of near-Earth objects (NEOs) recently has taken some major steps forward. The recent discovery of two asteroids that passed within the Moon's distance of Earth on 8 September is a reminder of the need to further understand NEOs. During NASA's Exploration of Near-Earth Objects (NEO) Objectives Workshop, held in August in Washington, D. C., scientists examined rationales and goals for studying NEOs.

Several recent documents have recognized NEO research as important as a scientific precursor for a potential mission to Mars, to learn more about the origins of the solar system, for planetary defense, and for resource exploitation. The October 2009 Review of Human Space Flight Plans Committee report (known as the Augustine report), for example, recommended a "flexible path" for human exploration, with people visiting sites in the solar system, including NEOs. The White House's National Space Policy, released in June, indicates that by 2025, there should be "crewed missions beyond the moon, including sending humans to an asteroid." In addition, NASA's proposed budget for fiscal year 2011 calls for the agency to send robotic precursor missions to nearby asteroids and elsewhere and to increase funding for identifying and cataloging NEOs.

Multiple Benefits From NEO Exploration

At the August workshop, speakers focused on the current status of our understanding of NEOs, mission results, and planetary defense. Damon Wells, assistant director for space and aeronautics at the White House Office of Science and Technology Policy, commented on the 2009 Augustine report's flexible path approach, saying it would allow travel to deep-space destinations "without the trips down the gravity well, to the surface of a solar system body." He said that there are "several very interesting deep space destinations that have lower overall energy demands than would be required for a landing on the Moon."

Wells said, "The bottom line is [that] an asteroid mission leads to many useful and interesting outcomes in its broader context. That is why it's a key element of the president's plan. That is why it's in the National Space Policy. It's going to be important to think through how best to achieve those outcomes as we pursue our plans."