Subsurface temperatures during the last millennium: Model and observation

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[1] General Circulation Models (GCMs) used to distinguish anthropogenic forcing of the Earth's past climate from its natural variability need to be validated by observations. The GCM ECHO-g was used to produce three millennial simulations of the Earth's climate. Two simulations include changes in anthropogenic and natural external forcing factors through the last millennium, differing only in their initial conditions, and a control run with constant external forcing representing internal variability. Since the ground contains a record of long-term trends in SAT, we use borehole temperatures in Canada, grouped into regions, as a record of past climate. The regional average SATs from ECHO-g were used to solve the forward subsurface thermal profile, and compared with the underground temperature anomalies observed at each region. In all cases simulated subsurface anomalies from the forced simulations are in better agreement with observations than those from the control simulation.
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1. Introduction

[2] For climate predictions from general circulation models to be interpreted with confidence, a robust record of past climatic changes is required. Without such a record, natural variability of the climate system cannot be separated from changes induced by anthropogenic activities and by individual forcing mechanisms [*Hansen et al.*, 2005]. Resolving this issue is essential for assessing political actions to address future climate change. Several methods have been applied to obtain global and hemispheric reconstructions of SAT changes in the last millennium [*Jones and Mann*, 2004]. However, underground temperatures are the only direct measurements of past surface temperatures [*Pollack and Huang*, 2000], in contrast to proxy data, that are indirect inferences of climate change [*Briffa and Osborn*, 2002]. Reconstructions of past climate from borehole data assume that the Earth's upper crust is in thermal equilibrium, such that the temperature distribution in the upper few kilometers is determined by the long-term surface temperature and the internal heat flow. If those boundary conditions are constant and the thermal properties of the subsurface are known, then the temperature increases predictably with depth. If the Earth's surface warms (cools), heat is gained (lost) by the ground. These changes in the surface energy balance propagate and are recorded in the subsurface as perturbations to the equilibrium thermal regime. Analysis of these anomalies are the essence of borehole climatology. Other surface factors, such as changes in vegetation cover, snow cover trends etc., can all potentially affect the underground thermal regime independently of climate. Therefore, borehole temperatures (BT) are carefully screened before they are analyzed for climate signatures [*Pollack and Huang*, 2000; *Beltrami and Bourlon*, 2004; *Pollack and Smerdon*, 2004].

[3] Preliminary comparisons of proxy and BT reconstructions [*Briffa and Osborn*, 2002] showed important differences in the timing and magnitude of climate change. In particular, borehole temperatures appeared much cooler from 1500 to 1800. This discrepancy was the subject of debate in the literature [*Trenberth and Otto-Bliesner*, 2003; *Beltrami*, 2002; *Mann and Schmidt*, 2003; *Mann et al.*, 2003; *Rutherford and Mann*, 2004; *Pollack and Smerdon*, 2004; *Chapman et al.*, 2004; *Schmidt and Mann*, 2004; *González-Rouco et al.*, 2003; *Beltrami et al.*, 2005; *González-Rouco et al.*, 2006], and it is in the process of being settled with the work of *Esper et al.* [2002, 2004], *Moberg et al.* [2005], and *Harris and Chapman* [2005].

[4] Since the underground climatic signal is attenuated with depth and time, the resolution of borehole data decreases with time. Thus climate reconstructions from BT cannot be directly compared with model output. To compare results from models and BT climatic reconstructions, we use the model output as an upper boundary condition and solve the forward problem. In other words, we propagate the simulated SAT into the ground, calculate the expected underground temperature perturbation, and compare it to the measured temperature subsurface perturbation. Here we present the first attempt to jointly interpret the results of GCMs with underground temperatures. We have chosen the Canadian boreholes because nearly half of all borehole data available for climate interpretation in the global database are from Canadian sites.

2. Data Set and Model Description

[5] Model data were extracted from long paleoclimate simulations made with the ECHO-g atmosphere-ocean GCM [*Legutke and Voss*, 1999]. The main components in ECHO-g are the atmospheric and ocean GCMs ECHAM4 and HOPE-g, respectively. ECHAM4 is integrated with T30 (ca. 3.75°) horizontal resolution whereas HOPE-g is used with T42 (ca. 2.8°) with gradual meridional refinement reaching 0.5° in the tropical regions between 10°S and 10°N. Vertical discretization incorporates 19 (20) levels

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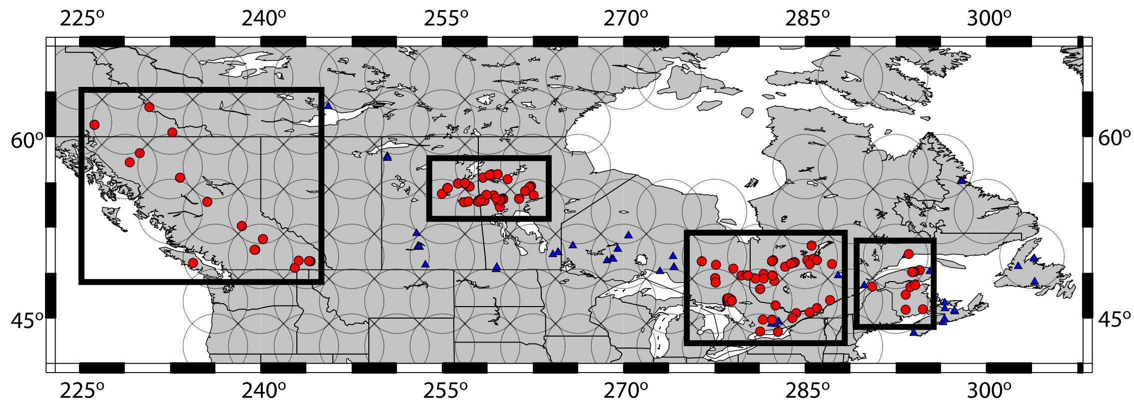

Figure 1. Borehole data distribution in Canada. Dots show the location of sites used in this work. Triangles show sites excluded from the analysis. The centers of the circles show the grid point output from ECHO-g simulations over the continental area considered.

for the atmosphere (ocean). Flux corrections, constant with time and with null global contribution are considered. Simulated temperatures at 2 m represent SAT. Ground temperatures are estimated from a five layer soil model with the deepest level at 9.83 m depth. Vegetation effects on evapotranspiration, snow fall, snow accumulation, melting, infiltration and run-off are simulated. Vegetation distribution is fixed to present day conditions [*Deutsches Klimarechenzentrum*, 1993]. ECHO-g has been extensively used and validated in numerous studies [*Min et al.*, 2005a, 2005b].

[6] A 1000 year long control run (CTRL) with present external forcing and two forced simulations of the period 1000 to 1990 AD incorporating identical external forcing but different initial conditions were considered. Both forced simulations (FOR1 and FOR2) were driven by identical estimates of natural and anthropogenic forcing (solar irradiance, radiative effects of stratospheric volcanic aerosols and greenhouse gas concentrations) based on the reconstructions provided by *Crowley* [2000]. Further description of external forcing as well as results from these simulations are given by *von Storch et al.* [2004], *González-Rouco et al.* [2003, 2006], and *Zorita et al.* [2003, 2005].

[7] The data set includes 210 temperature-depth profiles. Most of these logs were recorded by the Earth Physics Branch, and by GEOTOP at the University of Québec in Montréal [*Mareschal et al.*, 2000, and references therein]. The data used in this study can be found at the World Data Bank. Figure 1 shows the borehole data distribution in Canada along with the ECHO-g grid points for Canada. The center of the circles show the grid point output from ECHO-g simulations. The four regions shown within the boxes were chosen because of their BT data spatial density. The spatial distribution of the BT sites is uneven because measurements are carried out in holes of opportunity. Figure 2a shows an example of the set of subsurface temperature anomalies along with their average underground anomaly for Atlantic Canada. Underground anomalies exhibit a large variability within each region; some of this variability is due to local surface effects at the site of the borehole that may contribute to site specific noise [*Shen et al.*, 1995]. Interpreting ensembles of BT profiles reveals more easily the common underlying regional climatic response [*Beltrami and Mareschal*, 1992; *Beltrami et al.*, 1992, 2005; *Harris and Chapman*, 2005].

3. Theory

[8] The variation and distribution of the ground temperature, $T(z)$, as a function of depth z, is the result of the bottom (internal heat) and upper (ground surface temperature, GST) boundary conditions. Internal heat determines the long-term steady state component, and the changes in GST, assumed to be related to climate, determine the subsurface temperature deviations from steady state. In the absence of non-conductive processes, the temperature field is governed by the one-dimensional unsteady heat diffusion equation.

[9] The temperature anomaly at depth z, due to a step change, ΔT, in surface temperature is obtained from the forward model:

$$T(z,t) = \Delta T \operatorname{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right), \tag{1}$$

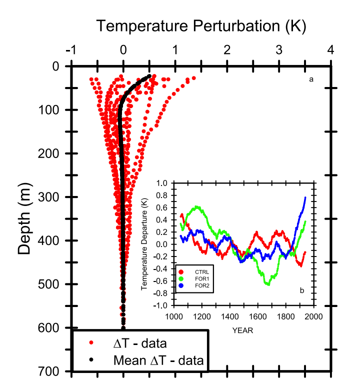

Figure 2. (a) Temperature anomaly spread for Atlantic Canada showing significant variability. The dark line represents the average temperature anomaly for this region. (b) The 1000-years ECHO-g simulation mean SAT for Atlantic Canada for the forced and control simulations as departures from the mean of the period.

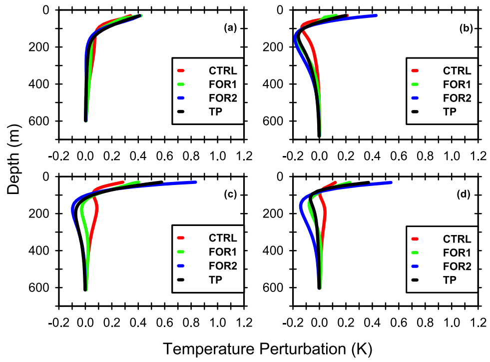

Figure 3. The resulting temperature anomalies for each region from the forward modelling of the ECHO-g control (red), FOR1 (green), FOR2 (blue) runs, and the mean temperature anomaly (black) for each region: (a) British Columbia/Yukon, (b) Manitoba/Saskatchewan, (c) Quebec/Ontario, (d) Atlantic Canada.

where erfc is the complementary error function, κ is the thermal diffusivity, t is time and z is depth, positive downward.

[10] The temperature anomalies generated from each of the past changes in surface temperature are superimposed on the quasi-steady state geothermal profile. The time evolution of any arbitrary ground surface temperature history can be approximated by a series of step temperature changes at the surface, such that the induced temperature anomalies at depth z are given by

$$T_t(z) = \sum_{k=1}^{K} T_k \left[\operatorname{erfc}\left(\frac{z}{2\sqrt{\kappa t_k}} \right) - \operatorname{erfc}\left(\frac{z}{2\sqrt{\kappa t_{k-1}}} \right) \right]. \qquad (2)$$

[11] Equation (2) represents a general form of the forward problem; that is, we know the boundary condition and need to evaluate the subsurface perturbations. The inverse problem, common in borehole climatology, consists of evaluating the boundary condition from the subsurface temperature anomalies [*Mareschal and Beltrami*, 1992; *Beltrami et al.*, 1997].

4. Analysis

[12] Due to the uneven spatial distribution and clustering of BT data in Canada, we divided Canada into four geographical regions containing sufficient numbers of boreholes to allow for a robust average, and also to be able to illustrate the significant spatial variability usually found in BT data. Within these regions, each temperature-depth profile was inverted individually using singular value decomposition (SVD) in order to remove each steady state component, and to obtain each subsurface temperature perturbation. The average temperature anomaly was also determined for each region.

[13] For each of the 1000-year ECHO-g forced and control simulations, and for each of the four regions of Canada considered, we used the forward model approach described above to calculate average grid-point subsurface perturbations to a depth of 600 m using ECHO-g SAT spatially averaged yearly anomalies as the upper boundary condition. Figure 2b shows the SAT anomalies with respect to the 1000-year mean output from FOR1, FOR2 and CTRL ECHO-g simulations for Atlantic Canada.

[14] A part of the standard test to compare field based observations of BT subsurface anomalies with those generated from SAT or, as in this case, numerical realizations of the Earth's climate of the last 1000 years, is to bring the subsurface anomalies to a common reference temperature and at the same time attempt to minimize their discrepancies [*Beltrami et al.*, 2005]. This is because the equilibrium temperature determination in a given borehole is dependent on thermal events at the surface that took place before the beginning of the meteorological records. This is the case for SAT-subsurface anomalies comparison, or before 1000 CE for the present comparison. The effect consists of a shift in the long-term reference temperature, commonly known as the pre-observational mean (POM) [*Harris and Chapman*, 2001]. Due to the nature of heat diffusion, the shifts for the numerical simulations examined here are much smaller then those commonly found for SAT. This is because the simulations cover a much larger time period and also, surface changes earlier than 1000 CE exert a very small influence for the borehole depth ranges considered here [*Beltrami et al.*, 2005].

[15] Figure 3 shows the comparison of the average subsurface anomaly for each region of Canada, and the average FOR1, FOR2 and CTRL simulation-generated subsurface anomalies. It is clear from this figure that, in all cases, the closest forward profiles to the observations are those simulated subsurface anomalies obtained from the forced simulations rather than from the CTRL. This implies that the observed subsurface temperature anomalies do not appear to be originating solely from internal variability of the climate system as modelled by the ECHO-g CTRL simulation. It appears that inclusion of realistic changes in forcings, as those of FOR1 and FOR2, are required to explain the observed subsurface anomalies in all four regions. In the BC/Yukon region subsurface temperature anomalies show smaller amplitudes than those in the other regions of Canada. Both forced simulations appear to better explain the region's mean subsurface anomaly than the CTRL simulation as shown in Figure 3. The control simulation does not explain the observed depth of the positive curvature of the temperature anomalies, nor the recent warming recorded by the ground. ECHO-g forced simulations seem to perform well in this region of Canada.

5. Discussion and Conclusions

[16] For the implementation of the forward problem and the generation of subsurface anomalies from ECHO-g, we have treated the output from the numerical simulations in the same way as we treat SAT from observations. We are aware that numerical simulations represent only a possible climate scenario, internally consistent, and consistent with current climatology, but with an internal variability which could potentially be of the same order of magnitude as the POM shifts encountered.

[17] Details of the agreement and disagreement between ECHO-g forward modeled SAT, and observed underground anomalies may be able to shed light on the understanding of

the internal dynamics of the model and the climate system. These sensitivities may allow for the improvement of the model's parameterizations to explain observations at regional resolution, as well as to improve model internal consistency in order to be able to use its output as a test base for proxy indicators of past climate reconstructions at regional levels [*von Storch et al.*, 2004].

[18] Because of the complexity of the climate system and the debate over paleoclimatic reconstructions it has become clear that a better picture of past climate will be obtained from integrated analyses in which all paleoclimatic reconstruction techniques are interpreted jointly. Inclusion of numerical models into this analysis is as fundamental as are interdisciplinary approaches and collaborations across fields in the resolution of past climate uncertainties [*Trenberth and Otto-Bliesner*, 2003; *Beltrami et al.*, 2005; *González-Rouco et al.*, 2006; *Beltrami*, 2002; *Hansen et al.*, 2005].

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