GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L19707, doi:10.1029/2005GL023714, 2005

Long-term tracking of climate change by underground temperatures

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Received 8 June 2005; revised 18 August 2005; accepted 29 August 2005; published 6 October 2005.

[1] Underground temperatures contain a record of past changes in the energy balance at the Earth's surface, such that borehole temperature data can be used to reconstruct long-term trends of ground surface temperature (GST) changes. In addition to surface air temperature, however, GST is the response of the ground to other near surface processes that govern the surface energy balance. In order to compare GST histories constructed from geothermal data with surface air temperature (SAT) data, it is necessary to ascertain the relationship between these quantities. Here we jointly interpret four borehole temperature logs within a small area and SAT records from a nearby station. The subsurface temperature anomalies are consistent with the SAT data even in the presence of a variable snow regime, and different surface conditions. Our results indicate that borehole records are robust long-term paleoclimatological indicators. **Citation:** Beltrami, H., G. Ferguson, and R. N. Harris (2005), Long-term tracking of climate change by underground temperatures, *Geophys. Res. Lett.*, *32*, L19707, doi:10.1029/2005GL023714.

1. Introduction

[2] In the last decade our understanding of borehole climatology has improved and taken a place among other methods of paleoclimate reconstructions. Because the Earth's upper crust is in thermal equilibrium at periods larger than 10^5 years, the background temperature distribution in the upper kilometer is determined by the long-term surface temperature and the heat flowing from the Earth's interior. Under these conditions, subsurface temperature increases in a predictable way with depth. When the temperature at the Earth's surface changes, a quantity of heat is gained or lost by the ground in such a way that the energy balance across this interface is maintained. These changes appear as perturbations to the quasi-steady state thermal regime of the subsurface. The depths to which the temperature or heat anomalies penetrate depends on the thermal diffusivity of subsurface rocks such that surface temperature changes that occurred 100 and 500 years ago appear at depths of about 150 and 500 m, respectively. Analysis of these subsurface temperature anomalies allow borehole climatologists to reconstruct ground surface temperature (GST) changes that best explain the observed underground anomalies.

[3] Like all paleoclimatological techniques, the geothermal method has strengths and weaknesses. Unlike proxy methods where data are related to temperature through statistical correlations with SAT records, the geothermal method is a direct result of surface temperature change and is independent of SAT records. Geothermal data yield robust long-term temperatures trends, but with rapidly decreasing resolution in time due to the physics of heat diffusion. This characteristic makes the geothermal method better suited for estimated long-term temperature trends than short fluctuations [*Clow*, 1992].

[4] Although the Earth's response to the energy balance (or imbalance) at the surface is related to the surface air temperature, the ground temperature integrates the effects of other climatic variables that influence the energy balance. These variables may include vegetation, snow cover, phase changes (freezing and thawing) and solar radiation. The interaction of these effects governs the temperature of the ground in a complex (i.e. nonlinear) way. However, in spite of these processes several analyses of northern hemisphere borehole temperature profiles have yielded results consistent with meteorological records and some multiproxy reconstructions [*Huang et al.*, 2000; *Harris and Chapman*, 2001; *Beltrami and Bourlon*, 2004; *Pollack and Smerdon*, 2004]. These results indicate that on long time scales and over large areas, ground and air temperatures track each other. Nevertheless, recent studies have questioned whether processes operating at the Earth's surface bias the geothermal method thereby rendering them unsuitable for climatic reconstruction [*Mann and Schmidt*, 2003; *Mann et al.*, 2003]. In addition to the hemispheric studies cited above it is important to compare air and ground temperature records at a local scale, where biases may be more pronounced, and processes influencing energy exchanges at the air-ground interface might be better understood [*Beltrami and Kellman*, 2003; *Nitoiu and Beltrami*, 2005; *Kane et al.*, 2001; *Smerdon et al.*, 2004].

[5] Recently, several experimental air-ground stations have been established to monitor meteorological variables, soil thermal conditions, snow cover and vegetation cover with the objective of examining processes influencing energy exchanges within the first meter of the soil and at the air-ground interface [e.g., *Putnam and Chapman*, 1996]. These investigations are important for understanding the response of ground temperature to air temperature changes over annual and decadal time scales [*Beltrami and Kellman*, 2003; *Bartlett et al.*, 2004].

0094-8276/05/2005GL023714$05.00

[6] An alternative to waiting for the accumulation of sufficient decades of data at these stations, is analyzing meteorological data at locations where nearby high quality geothermal data exist. The consistency between the observed subsurface anomalies and the temperature anomalies generated using meteorological records of SAT as the upper boundary condition helps validate the use of temperature-depth profiles in climatic reconstructions. Here we analyze high-quality data measured in four boreholes in quasi-steady state from a small region in northern Quebec, to ascertain whether records of SAT collected nearby reproduce the subsurface temperature anomalies observed in the area. These results indicate that subsurface temperatures are consistent with nearly 70 years of SAT data even though snow cover effects and soil moisture phase changes are present. Our results show that the geothermal method provides a robust representation of long-term change in climate.

2. Theory

[7] In a homogeneous semi-infinite, source-free half-space the temperature, T, at depth z due to a time varying surface temperature change is governed by the one-dimensional unsteady heat diffusion equation.

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

$$T(z,t) = T_0 \operatorname{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right), \tag{1}$$

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

[9] The temperature anomalies generated from the changes in surface temperature are superimposed on the quasi-steady state geothermal profile. The time evolution of any arbitrary GST 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

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

[10] Equation (2) represents a general form of the forward problem, i.e. we know the boundary condition and seek to evaluate the subsurface perturbations. In contrast, the inverse problem, common in borehole climatology, consists of evaluating the boundary condition from the subsurface perturbations [*Beltrami et al.*, 1997].

3. Data and Analysis and Discussion

[11] We have chosen to analyze four borehole temperature logs from a small area near Belleterre (Quebec) (47.40°N, 78.71°W) measured by the GEOTOP-UQAM-MCGILL group in 1988 [*Pinet et al.*, 1991] (data available from the International Heat Flow Commission). These temperature logs contain stable and consistent climate signals [*Beltrami et al.*, 1997]. The sites are all located within an area of a few square kilometers, thus ensuring common underlying transient climatic signals, although they might exhibit different long-term static air-ground temperature offsets due to locally different surface conditions.

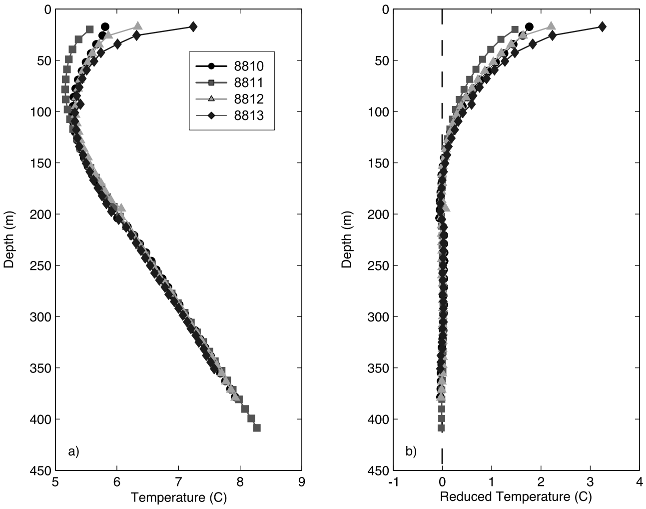

Figure 1. (a) Raw temperature versus depth profiles measured at Belleterre, Quebec. The four profiles were measured in 1988 by the GEOTOP-UQAM-MCGILL geophysics group. The borehole's temperature fields are stable and they are located within a few square kilometers. For precise location, see *Beltrami et al.* [1997, Figure 7]. (b) Reduced temperature-depth profiles. These subsurface temperature anomalies are obtained as the difference between the equilibrium geothermal profiles and the measured temperature profiles. See color version of this figure in the HTML.

[12] Temperature-depth profiles measured at four borehole sites at Belleterre are generally consistent with each other and show no conspicuous features (Figure 1a). The deeper portion of each profile shows a linear increase in temperature with depth consistent with the steady upward flux of heat from the Earth's interior to the surface. Above approximately 150 m, each profile shows temperatures increasing towards the surface. This deeper portion of each profile is used to estimate the background thermal regime and is parameterized in terms of the thermal gradient and surface temperature intercept, and estimated using data deeper than 160 m. This depth range is sufficient to avoid the near surface perturbation, and deep enough to give robust estimates of the parameters [*Harris and Chapman*, 2001]. The mean long-term surface temperature is 3.9°C. We subtract the background thermal regime from these temperature depth profiles and show reduced temperature profiles at an expanded scale (Figure 1b). Reduced temperatures are consistently positive near the surface with an amplitude between about 2 and 3 K, and a depth extent of about 150 m. These are the temperature perturbations that result from changes in GST and are consistent with ongoing surface warming. A simple ramp function jointly fit to the reduced temperature profiles indicates an amplitude of 3.0 K over the past 130 years.

[13] The closest Environment Canada operated meteorological station with a relatively long record is at Amos, Quebec (48.57°N, 78.12°W) located about 130 km from the Belleterre geothermal data site. Climatic data is relatively

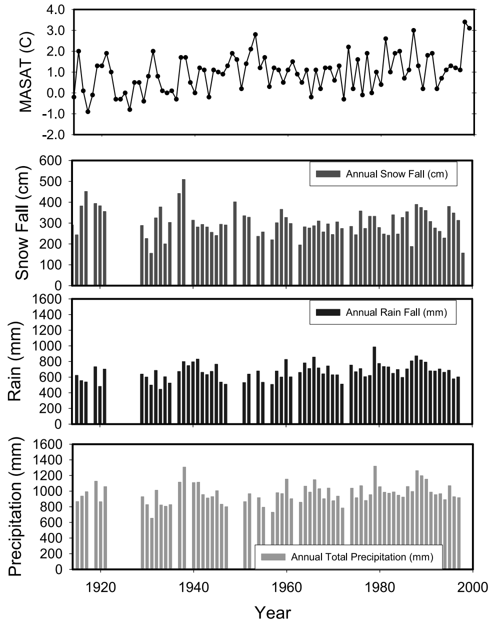

Figure 2. MASAT, snowfall, rainfall, total precipitation annual mean records for Amos, Quebec; about 130 km from Belleterre. See color version of this figure in the HTML.

complete, extends back in time to 1914 and shows that this area is subjected to large winter snow accumulation and summer precipitation (Figure 2). The mean annual temperature, snowfall and rainfall over the length of the record are 0.95°C, 302 cm and 670 mm respectively. The annual surface air temperature record shows a linear temperature increase of about 0.9 K in about 70 years. The offset between the mean SAT temperature and the surface temperature intercept (3.0 K) is attributable to a combination of incident solar radiation coupled with the greater heat capacity of ground relative to air, and snow cover in the winter [*Bartlett et al.*, 2004; *Beltrami*, 2001; *Beltrami and Kellman*, 2003].

[14] Because we are interested in the relationship between variations in ground and air temperatures we remove the offset such that ground temperature perturbations and SAT values are relative to a common reference temperature (Figure 3a). We compare air and ground temperatures by using the SAT record as the upper boundary condition to compute subsurface thermal perturbations (equation (2)) and compare them with the reduced temperature profiles. However, because of the short duration of the SAT record, a background initial long-term mean temperature prior to the beginning of the meteorological record must also be determined. In essence this parameter provides a baseline against which the SAT record represents warming or cooling. The best fitting baseline is 2.3 K below the mean SAT temperature and the root mean square (RMS) misfit to the average of the reduced temperature profiles is 28.5 mK (Figure 3b, inset). The sharp trough in the RMS misfit as a function of the pre-observational mean (POM) shows that this is a robust parameter, and the small magnitude indicates that this combination of POM and SATs provides an excellent match to the reduced temperatures. A step function having the same onset time and magnitude as the POM model (Figure 3a) isolates the subsurface effects of the SAT data [*Harris and Gosnold*, 1999; *Harris and Chapman*, 2001]. The RMS misfit for the step function is 57 mK, more than twice the misfit using the SAT data indicating the sensitivity of the average reduced temperature profile to the SAT data. Because the temperature anomalies extend to a depth of about 150 m, they are most sensitive to temperature variations over the past 175 years. Both the linear warming trends estimated from the reduced temperature profiles and the POM analysis indicates that this site has been warming over a period longer than the available meteorological records [*Beltrami et al.*, 1997; *Harris and Gosnold*, 1999].

[15] The transient component of the SAT penetrating into the underground explains the great majority of the anomalies' subsurface features. Candidate sources of misfit at these sites may arise from steady state effects due to differences in surface conditions arising from differences in soil moisture, forest floor organic matter mass [*Nitoiu and Beltrami*, 2005], latent heat exchanges at the ground surface and the insulating effect of snow cover [*Beltrami and Kellman*, 2003; *Bartlett et al.*, 2004]. Some discrepancies are due to an incomplete knowledge of the details of the underlying rock's thermal properties. There are only a few thermal conductivity measurements for each borehole. That is, we cannot discount that some of the high frequency variance might be due to unknowns in the subsurface thermal structure. High frequency climate-induced surface

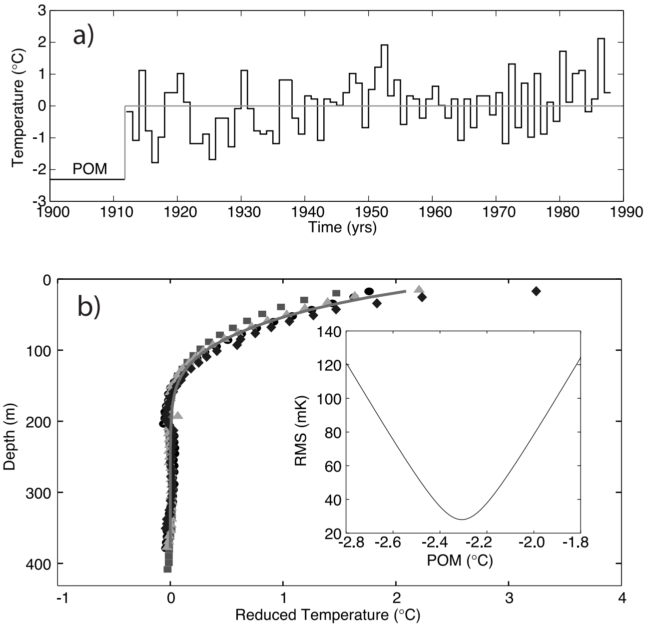

Figure 3. Comparison of SAT and reduced temperature data. (a) SAT data from Amos (1914 to 1988). Bold line shows POM, and shaded line shows step function. (b) Reduced temperature profiles. Line shows best fitting synthetic based on the combination of the POM and SAT data. The SAT data explains 98% of the variance in the reduced temperature profiles. Deeper discrepancies are due to the inability of SAT to yield information before 1920. Temperature anomalies however, do contain a recording of SAT previous to the beginning of the record of Figure 2. A thermal diffusivity value of 10^{-6} m^2 s^{-1} was used for the calculations. See color version of this figure in the HTML.

events, however, can be ruled out because they would be filtered by the ground which behaves as a low-pass filter.

[16] The Belleterre site and its high quality borehole temperature data contains subsurface information that represents the response of the ground to typical climatic conditions of large regions of central and eastern Canada [*Beltrami et al.*, 1992]. Our results show that the ground tracks the variations of the surface air temperature for at least seven decades, even though precipitation is large and variable. Therefore, under conditions of conductive heat transfer, borehole data can be considered as a robust and independent indicator of past climatic conditions. Borehole temperature profiles throughout the world contain a rich archive of the changes of the energy balance at the surface. In fact, borehole temperature data have been used in estimating the total heat absorbed by the continental areas and have been essential in showing that all climate subsystems are warming and that the warming of the Earth, in the last 50 years, has a global character [*Levitus et al.*, 2005; *Beltrami et al.*, 2002; *Intergovernmental Panel on Climate Change*, 2001]. The thermal regime of the shallow subsurface, in general, and borehole temperatures data, in particular, provide us with unique - largely unexplored - laboratories to be used in the verification of the long-term trends of climate predicted by general circulation models [*Beltrami et al.*, 2005].

4. Conclusions

[17] We analyzed high quality data measured in four boreholes in thermal quasi-steady state, in order to ascertain whether records of SAT collected nearby reproduce the observed subsurface temperature anomalies. Our results show that subsurface temperatures are consistent with 70 years of SAT data. This air-ground coupling is unaffected by snow cover and soil freezing effects present in this area at these long-time scales. Our results show that the geothermal method at this location provides a robust representation of long-term change in climate.

[18] **Acknowledgments.** This research was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), and the Atlantic Innovation Fund (AIF). R. H. was supported by NSF EAR0126029. We are grateful to F. Gonzalez-Rouco and an anonymous reviewer for their constructive comments.

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