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GROUND TEMPERATURE HISTORIES FOR CENTRAL AND EASTERN CANADA FROM GEOTHERMAL MEASUREMENTS: LITTLE ICE AGE SIGNATURE

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Abstract. Deep borehole temperature profiles have been analyzed to determine ground temperature histories in central and eastern Canada. Clear signs of a cold period between 1500 and 1800 A.D., corresponding to the little ice age, have been found. A warming trend after 1800 A.D. was detected throughout eastern and central Canada. Temperature profiles from western Ontario are consistent and were inverted simultaneously to yield a regional ground temperature history. The recent warming appears to be correlated with the increase of atmospheric CO_2 reported for a Greenland ice core.

Introduction

Several analyses of world-wide meteorological records of surface air temperature indicate a global average increase of about 0.5°C in the last century (Hansen and Lebedeff, 1987; Jones et al., 1986; Gruza et al., 1988). However, meteorological records suffer from a number of limitations. Since measurements have been taken for societal purposes, they have uneven spatial distribution; their temporal coverage is rather short; the longest records available are usually the most contaminated by cultural noise and they are affected by variable standards and procedures (Karl et al., 1989). Furthermore, Elsner and Tsonis (1991) compared three analyses of Northern Hemisphere data that had identified definite increasing temperature trends and they showed that these three analyses yield statistically different conclusions. Ghil and Vautard (1991) have used singular spectrum analysis to show that the time series from meteorological records analysis for the Northern Hemisphere are not long enough to confirm the inferred trends. Therefore, it is important to find alternative or complementary records of temperature change for the recent past. Such information is important to determine whether -and to what extent- the anthropogenic input of greenhouse gases has affected the global climate and may also be useful to validate general circulation models used to predict climatic changes.

Method

It has been shown (e.g., Birch, 1948; Beck, 1977; Lachenbruch and Marshall, 1986) that the Earth' subsurface records variations of ground temperature. Furthermore, the Earth filters out short-lived temperature variations, effectively integrating the signal and recording only long term changes (Carslaw and Jaeger, 1959). These changes in ground temperature are recorded as perturbations of the equilibrium geothermal gradient, routinely measured for heat flow density determination.

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The temperature perturbation at depth z, T(z) is solution to the one-dimensional heat equation in a semi-infinite solid and has the form:

$$T(z) = \frac{z}{2\sqrt{\pi\kappa}} \int_0^\infty T_o(t) t^{-3/2} \exp\left(-\frac{z^2}{4\kappa t}\right) dt. \qquad (1)$$

where κ is the thermal diffusivity, $T_o(t)$ is the past surface temperature and t is time before present. This function can be calculated for several surface temperature models (Carslaw and Jaeger, 1959).

In the Earth the temperature perturbation appears superimposed on the equilibrium temperature which, for an homogeneous source-free half space, increases linearly with depth. The temperature perturbation is determined as the difference between the measured subsurface temperature and the equilibrium geotherm. The equilibrium heat flow, assumed undisturbed in the lowermost part of the profile, is found by standard methods (Bullard, 1939) and the equilibrium temperature profile is determined by upward continuation. The area between the measured temperature data and the upward continued equilibrium profile is proportional to the heat absorbed by the ground, and the shape of the perturbation is determined by the ground temperature history (GTH). This history can be obtained directly by inversion (e.g., Vasseur et al., 1983; Nielsen and Beck, 1989; Mareschal and Beltrami, 1992; Shen and Beck, 1991; Wang, 1992).

In a preliminary study of borehole temperature data from eastern Ontario and Québec, Beltrami and Mareschal (1991) have detected a definite warming trend on the order of 1°C over the past 150 years. Nielsen and Beck (1989) have found a signature corresponding to the little ice ages in four boreholes in Ontario. The objective of the present letter is to outline the results obtained by inverting the GTH of the past 1,000 years from all the suitable temperature profiles in eastern and central Canada. The temperature perturbation has been inverted by singular value decomposition. The inversion scheme and its robustness are discussed by Mareschal and Beltrami (1992).

Data

Over 200 temperature logs collected by the Geological Survey of Canada (Jessop et al., 1984) and by the Université du Québec à Montréal and the Institut de Physique du Globe de Paris (Mareschal et al., 1989; Pinet et al., 1991) were examined to infer a GTH. The boreholes are distributed over 80 sites in central and eastern Canada, covering a region extending from Manitoba to Newfoundland. Some sites contain only one temperature profile and others as many as six. The depth of the boreholes varies between 200 and 800 m. The distribution of the data is uneven since the majority of these measurements were carried out in holes of opportunity.

GTH's cannot be reconstructed from every borehole: care was taken to eliminate from the analysis all boreholes that might have been perturbed by anthropogenic activities (i.e.,

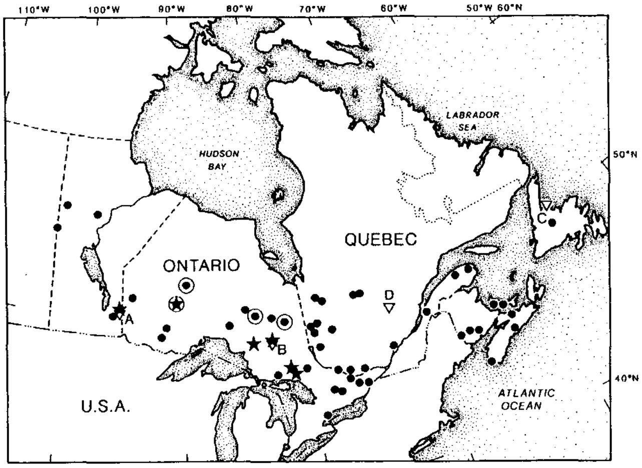

Fig. 1. Distribution of borehole temperature measurements in eastern Canada that were inverted for ground temperature history. Letters and triangles identify the selected examples shown in Fig. 2 and Fig. 3. Stars mark the sites used for simultaneous inversion of a GTH representative of western Ontario (Fig. 4). Circles mark the boreholes studied by Nielsen and Beck (1989).

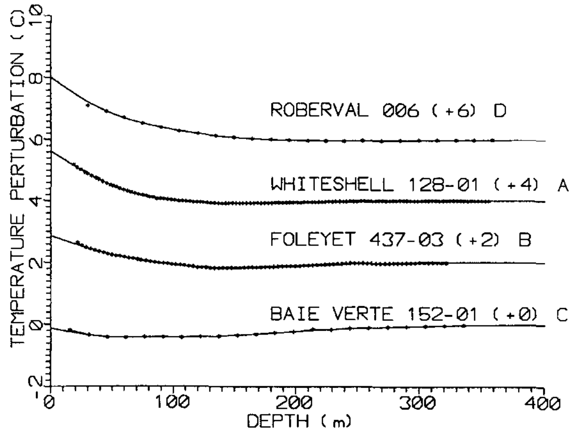

Fig. 2. Temperature perturbations (difference between measured and equilibrium temperatures) at four selected sites covering the study area. Location of sites are: Whiteshell, Manitoba (50°12 N, 95°55 W), Foleyet, Ontario (47°56N, 82°25W), Roberval, Quebec (48°32N, 72°15W), Baie Verte, Newfoundland (49°54N, 56°04W). Stars indicate the temperature data, the solid line shows the perturbation calculated from the GTH.

boreholes near urban centers or in areas where there has been landscape disruption). Temperature logs affected by topography and by ground water circulation were not retained for analysis. All the boreholes analyzed are located in flat land to avoid biasing effects (Blackwell et al., 1980) and are deeper than 400 m to allow determination of a GTH for the last 500 to 1000 years. One hundred and twenty (120) boreholes from a total of 200 were found suitable for analysis; they are located at 53 different sites. Figure 1 shows the location of the sites where boreholes were retained for analysis.

Results and Conclusions

Table 1 summarizes the information presently available from all the boreholes in eastern Canada. Recent warming was inferred for 50 sites while cooling was suggested for only 3. Twenty five sites with sufficiently deep boreholes were inverted to tentatively detect a signal from the little ice ages (LIA). The LIA signal is definitely present in 20 sites; for 5 sites, the study is not conclusive. Figure 2 shows four temperature logs selected as examples to cover the widest geographical area possible. For the inversion scheme, the ground temperature history is approximated by a series of fifty 20-years step changes. Figure 3 shows the GTH's obtained for these four boreholes. A period of cooling corresponding to the LIA is present in all these boreholes, but it is less pronounced at Roberval than at the other sites; the lack of changes of curvature in the temperature log is another indication of a weaker LIA signal at Roberval. This may be part of a regional trend since temperature logs in Nova-Scotia and New-Brunswick do not show conclusively a LIA signal (Beltrami et al., submitted to Global and Planetary Change). Figure 3 also shows a definite increase in ground temperature over the last 150 years for all four sites; this modern warming signal is confirmed by all but three sites in central and eastern Canada (Table 1). The inferred recent warming is in agreement with the meteorological records for the region, including the period of maximum around 1950 and the subsequent cooling.

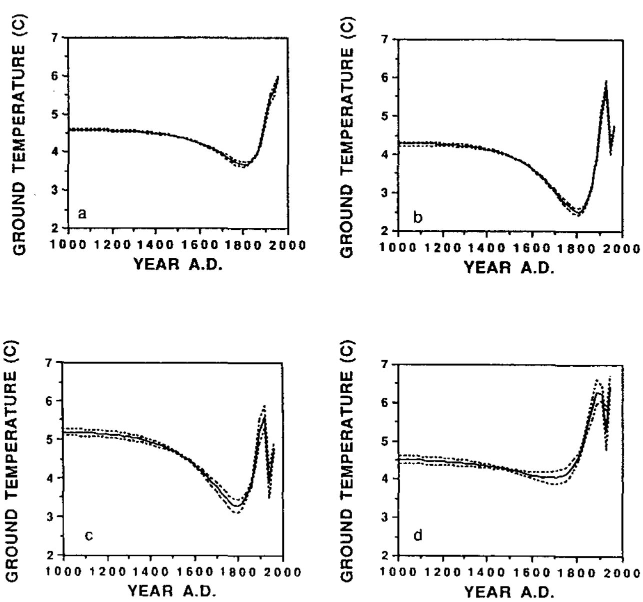

Fig. 3. Ground temperature histories determined by inversion of the data shown in Fig. 2. The dashed lines represent the model parameters standard deviation (data noise level standard deviation = 0.02 K, the eigenvalue cutoff is 0.025)

Table 1: Statistics on climatic signals detected in temperature logs of all the boreholes from eastern and central Canada suitable for analysis.

Total # boreholes	# Useful Boreholes	Total # Sites	Recent warming	Recent cooling	# Deep holes	LIA signal	LIA non conclusive
200	120	53	50	3	25	20	5

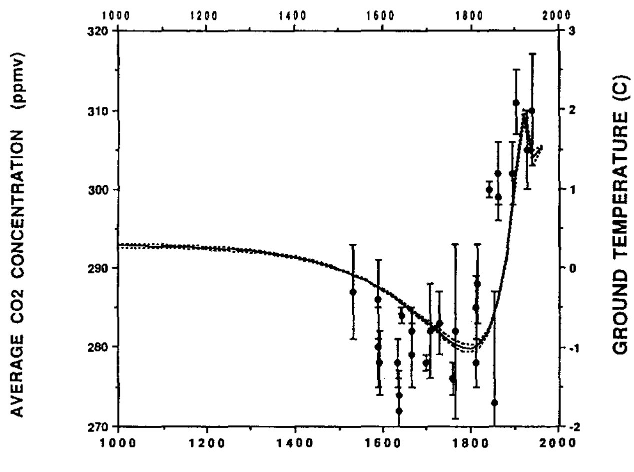

Fig. 4. Average ground temperature history for western Ontario. This GTH was obtained from the joint inversion of temperature data from six boreholes assumed to have experienced the same history. The circles represent the CO_2 concentration measured in a Greenland ice core.

However, temperature changes inferred from geothermal measurements should be compared cautiously with air temperature. For instance, Beltrami and Mareschal (1991) have shown that long term changes in the number of days with snow on the ground during spring and fall -April, October and November in Canada- can affect the ground/air temperature difference. Figure 2 shows how well the temperature perturbation calculated for the inferred GTH (solid line) fits the data (stars).

An average GTH for western Ontario was constructed by analyzing and inverting simultaneously data from several different boreholes with similar depth and sampling interval covering the area. Other regions do not have a sufficient number of deep boreholes to find a representative solution. The averaging was carried out assuming that, after thermal conductivity corrections, the temperature perturbation in each borehole is due to the same regional climatic forcing and the data from all boreholes can be inverted simultaneously. All the boreholes in Ontario and surrounding regions were analyzed individually to determine the widest area showing consistent GTH's. Several combinations of temperature logs were inverted jointly and yielded similar results over western Ontario. The example shown in Figure 4 was obtained by joint inversion of temperature perturbation data from 6 different boreholes. This procedure could not be extended to include boreholes from all of eastern Canada, such as those shown in Figure 3, because climatic variations have significant spatial variation as shown by the analysis of meteorological data for the last 100 years (Hansen and Lebedeff, 1987).

The regional GTH can be compared with the past atmospheric CO_2 concentration. The circles in Figure 4 correspond to atmospheric CO_2 concentrations found by Wahlen et al. (1991) in a Greenland ice core. The figure shows that a change in atmospheric CO_2 concentration has accompanied the modern warming. Changes in temperature appear correlated with the concentration of this greenhouse gas in the atmosphere, but the cause and effect relationship can not be ascertained.

The GTH is consistent with the paleoclimatic and historical records of the little ice ages (Grove, 1988) and with the meteorological record of the modern warming. This agreement supports the suggestion to use geothermal data as a record of ground temperature changes. Such approach has the advantage that it is possible to retrieve past ground temperatures in all the continental areas, even in regions where no meteorological records exist. However, because ground temperature is affected by several factors, this information is different and therefore complementary of past air surface temperature records.

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