Ground temperature changes in eastern Canada: borehole temperature evidence compared with proxy data

Hugo Beltrami[1] and Jean-Claude Mareschal[1,2,*]
[1]*GEOTOP, Université du Québec à Montréal, PO Box 8888, Station A, Montréal H3C 3P8, Canada.* [2]*Laboratoire de Dynamique de Systèmes Géologiques, Institut de Physique du Globe, 4 Place Jussieu, 75252, Paris Cedex 05, France*

ABSTRACT

Borehole temperature logs have been inverted to infer ground temperature histories (GTH) in eastern and central Canada. Regional ground temperature histories were obtained by simultaneous inversion of several temperature profiles from the same areas. Simultaneous inversion of 21 temperature logs sampled across all of eastern and central Canada yielded an average solution for this region. All but three of the studied sites show signs of warming in the last 150 years. This period of warming, which started after 1800 AD, was found throughout this part of Canada. The warming followed a cooler period corresponding to the little Ice Age. The inferred ground temperature histories exhibit long-term trends similar to those obtained from tree-ring growth indices in nearby regions and stable isotope data in the southern hemisphere. The modern warming appears correlated with the atmospheric concentration of CO_2 as measured in ice cores.

Terra Nova, 5, 21–28, 1992.

INTRODUCTION

Analyses of meteorological records (Hansen and Lebedeoff, 1987; Jones *et al.*, 1986) indicate that global surface air temperatures have been rising steadily in the last century. The evaluation of possible effects of anthropogenically induced changes of the Earth's climate has been hampered by a lack of long-term records of climatic variations and by problems with the existing meteorological data (Karl *et al.*, 1989; Elsner and Tsonis, 1991; Ghil and Vautard, 1991; Willmott *et al.*, 1991). It is possible, however, to determine long-term changes of the ground surface temperature by studying the perturbations to the equilibrium temperature profiles commonly measured for heat flow density determination (e.g. Beck, 1977; Shen and Beck, 1983; Lachenbruch and Marshall, 1986; Beltrami and Mareschal, 1991; Wang, 1992).

This note summarizes the results of analysis of a large set of geothermal data in central and eastern Canada. Evidence was found for the existence of the Little Ice Age in these regions and a deeper borehole indicates the existence of an earlier warm period that might be associated with the climatic optimum reported by several historical and proxy data in Europe (Lamb, 1972, 1977). Finally, these results are compared with an 802-year long tree-ring index time series in Québec, a tree-ring temperature reconstruction for the northern part of the North American continent, the $\delta^{18}O$ ratios measured in the Quelccaya summit ice core and the atmospheric CO_2 concentration as determined in a Greenland ice core. It appears that ground temperature histories (GTH) inferred by inversion of geothermal data provide a good estimate of the *long-term* trends in past climatic variations and their spatial variability.

DATA

Borehole temperature data, covering an irregular extension of about 2000 by 500 km in southeastern and central Canada, have been assembled. The distribution of the data in this region, which extends from Saskatchewan to Newfoundland, is displayed in Fig. 1.

The data set consists of more than 200 temperature profiles, distributed among 53 sites. Temperature measurements were carried out using calibrated thermistors with a precision of about 2 mK. Thermal conductivity measurements are available for most of the boreholes, although not always in the upper-most section, where the temperature perturbations are largest. When thermal conductivity measurements are not sufficient, the lithological logs have been consulted in order to check for variations of thermal conductivity; if such variations do not appear likely, an average value of the thermal conductivity has been assumed for this temperature log.

Several criteria have been used to select the final data-set to be analysed and interpreted. First, the temperature profiles were examined to visually identify obvious disturbances due to ground-water flow. The boreholes located in or near urban centres have also been discarded since it is expected that the 'natural' recent climatic signals would be masked by the urban heat island effect or by man-made disruptions of the surface environment, which can result in 1–2°C surface temperature increase. Secondly effects of topography have been taken into account in order to

*Corresponding author.

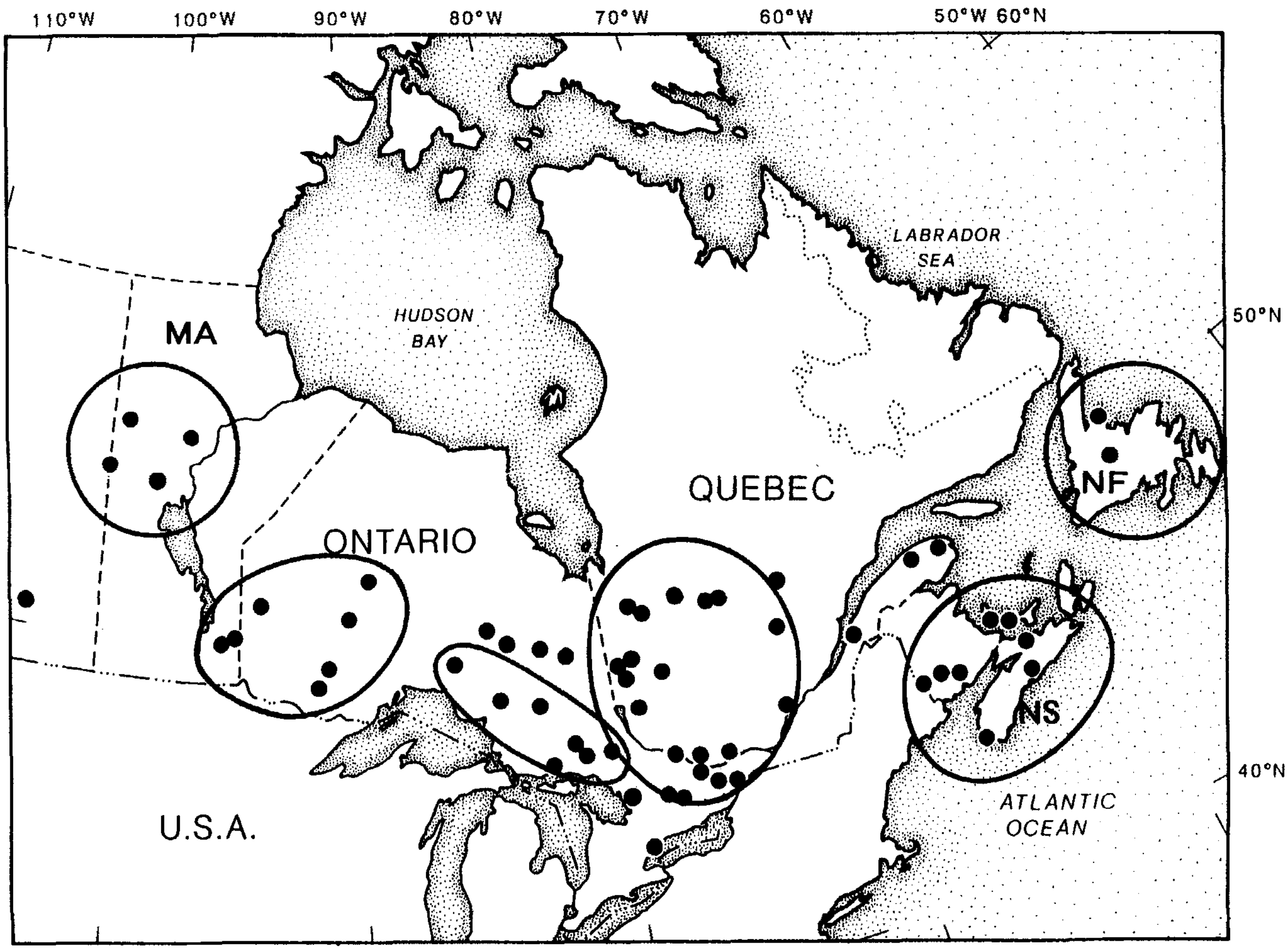

Fig. 1. *Locations of sites and data used in this study. Solid lines surround the regions for which an average ground temperature history was calculated.*

avoid biasing the results; care has been taken to discard boreholes located in S-facing and N-facing slopes (Blackwell *et al.*, 1980), which can give rise to different snow-cover regimes. Boreholes located near or under bodies of water have not been used in the analysis since the effects of lateral heat conductions are not easily eliminated and often exceed the effect of recent surface warming. Finally, care has been taken to identify and avoid temperature logs from boreholes located near mining shafts since they are usually affected by ground water flow and drop of the water table level resulting from mine water pumping. A total of 120 temperature logs have been retained for analysis.

The geothermal data have been published elsewhere (see Jessop *et al.*, 1984; Mareschal *et al.*, 1989 and Pinet *et al.*, 1991 and references therein).

INVERSION

The temperature at depth z, $T(z)$, can be written as the superposition of the equilibrium temperature and the perturbation $T_t(z)$ included by the time-dependent surface temperature condition:

$$T(z) = T_0 + q_0 R(z) + T_t(z) \quad (1)$$

where T_0 is the equilibrium surface temperature, q_0 is the surface heat flow density and $R(z)$ is the thermal depth between the surface and depth z, given by:

$$R(z) = \int_0^z \frac{dz'}{k(z')} \quad (2)$$

where $k(z)$ is the thermal conductivity.

The present subsurface temperature perturbation $T_t(z)$ in a semi-infinite solid with surface temperature history $T_s(t)$, where t is time before present, is given by (Vasseur *et al.*, 1983):

$$T_t(z) = \frac{z}{2\sqrt{\pi\kappa}} \int_0^\infty T_s(t) t^{-3/2} \exp\left(-\frac{z^2}{4\kappa t}\right) dt, \quad (3)$$

where κ is the thermal diffusivity.

Equation 3 can be evaluated for various surface temperature history model functions. A series of instantaneous changes of the surface temperature ΔT_k at times t_k before present yields the expression (Carslaw and Jaeger, 1959):

$$T_t(z) = \sum_{k=1}^{N} \Delta T_k \operatorname{erfc} \frac{z}{2\sqrt{\kappa t_k}} \quad (4)$$

where erfc is the complementary error function. Such perturbations are attenuated with depth and their depth of penetration depends on the duration of the temperature change. For the daily and annual temperature cycles, the subsurface perturbation decays to 1/e of the surface amplitude in about 0.2 and 3 m, respectively.

Because short-period variations are filtered out by the Earth, the surface temperature can be approximated by the average surface temperature over K time intervals of equal duration Δ, i.e.

$$T_0(t) = T_k(k-1)\Delta \leq t \leq k\Delta, k = 1,\ldots,K.$$

Equation 1 can then be written as:

$$\Theta_j = A_{jk}X_k \quad (5)$$

where Θ_j is the measured temperature at depth z_j, X_k is a vector containing the unknowns $\{T_0, q_0, T_1,\ldots, T_k\}$ and A_{jk} is a matrix each row of which contains 1 in the first column, the thermal resistance to depth z_j in the second column, and K elements formed by evaluating the difference between complementary error functions at times $t_{k-1} = (k-1)\Delta$ and $t_k = k\Delta$:

$$A_{jk+2} = \operatorname{erfc}\left\{\frac{z_j}{2\sqrt{\kappa t_{k-1}}}\right\} - \operatorname{erfc}\left\{\frac{z_j}{2\sqrt{\kappa t_k}}\right\} \quad (6)$$

The system of linear equations obtained is usually ill-conditioned. It cannot be solved for all the unknowns and some of the unknowns are too sensitive to small variations in the data (i.e. noise and errors). One of the standard solution techniques is the singular value decomposition (SVD) (Lanczos, 1961; Jackson, 1972; Menke, 1989) which consists of determining the linear combinations of unknown parameters most sensitive to the data. The application of SVD to the analysis of climatic signals in borehole temperature data is described by Mareschal and Beltrami (1992).

The inversion scheme used in this analysis performs well for the quality of the existing data. Figure 2 shows a simple example of the robustness of the inversion. The solid line shows an artificial GTH consisting of a 1 K ground surface temperature increase occurring 300 yr BP. The dashed line represents the GTH recovered by inversion for a model of fifty 10-yr constant temperature intervals with noise-free data and the dotted line represents the GTH recovered from the same artificial surface history with a 0.02 K noise level added to the subsurface temperature profile. Tests of the robustness of this inversion and comparison with other methods are reported by Wang *et al.* (1991), Shen *et al.* (1992) and Beck *et al.* (1992).

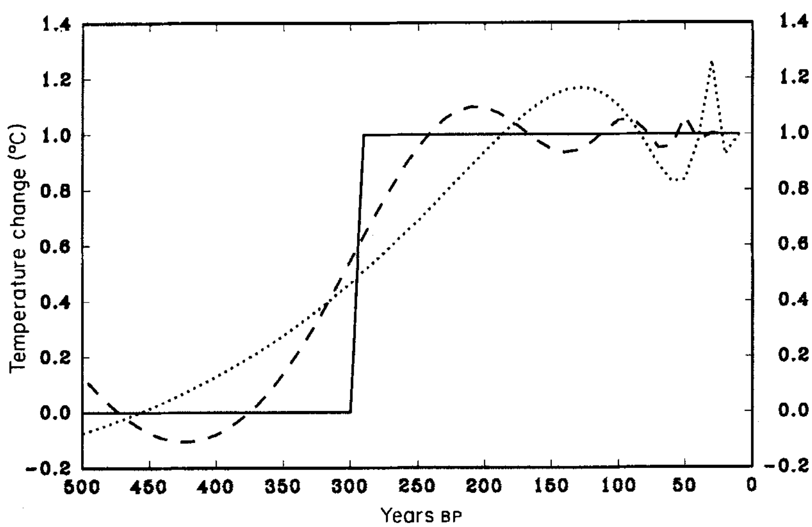

Fig. 2. *Reconstructed GTH (long dash line) from artificial noise-free and artificial noisy (dotted line) and true (solid line) ground temperature history consisting of 1°C temperature increase 300 yr before present. The absolute value of the cutoff for singular values was set at 0.000001 and 0.01 for the noise-free and noisy data, respectively.*

RESULTS FROM INVERSION

The model chosen for reconstructing ground temperature histories by inversion of single and multiple temperature logs consists of 50 equally spaced 20-yr time intervals. The absolute value of the singular-value cutoff has been set at 0.025. A high singular-value cutoff reduces the resolution (Jackson, 1972). The singular value cutoff was selected by finding the optimal variance-resolution trade-off.

The great majority of the boreholes deeper than 500 metres analysed in this area show a clear signal interpreted as a cold period with a minimum at *c.* 1800 AD, commonly identified as the Little Ice Age (Grove, 1988). Temperature logs from individual boreholes were analysed and site-average solutions were obtained by Beltrami *et al.* (1992). From the 25 sites with deep boreholes that were analysed, 20 contain a signal of the Little Ice Age and 5 remain inconclusive.

Since all these sites yielded qualitatively and quantitatively similar solutions, it can then be assumed that the same forcing factors were responsible for similar behaviour over wide areas. That is, the region as a whole has been under the influence of similar climatic conditions for at least the last five centuries. Therefore, it is appropriate to invert the temperature perturbations from several boreholes, over a large area, simultaneously. This procedure is equivalent to averaging the temperature perturbation at each depth. If the noise is not coherent, this approach improves the signal-to-noise ratio and thus the stability of the solution.

The results of several such regional averages are shown in Fig. 3. The average solution for Newfoundland was obtained by the simultaneous inversion of two temperature logs; Québec, 8 logs; western Ontario, 8 logs; northwestern Ontario, 3 logs; and northern Manitoba 6 logs. The solution for Nova Scotia was calculated from the inversion of the single available deep temperature log in that area. Although shallower Nova Scotia boreholes indicate the same recent warming as that inferred from the deep boreholes, they are not sufficiently deep to reveal temperature variations before the last 200 years and are not included in the regional average.

These solutions appear similar, with

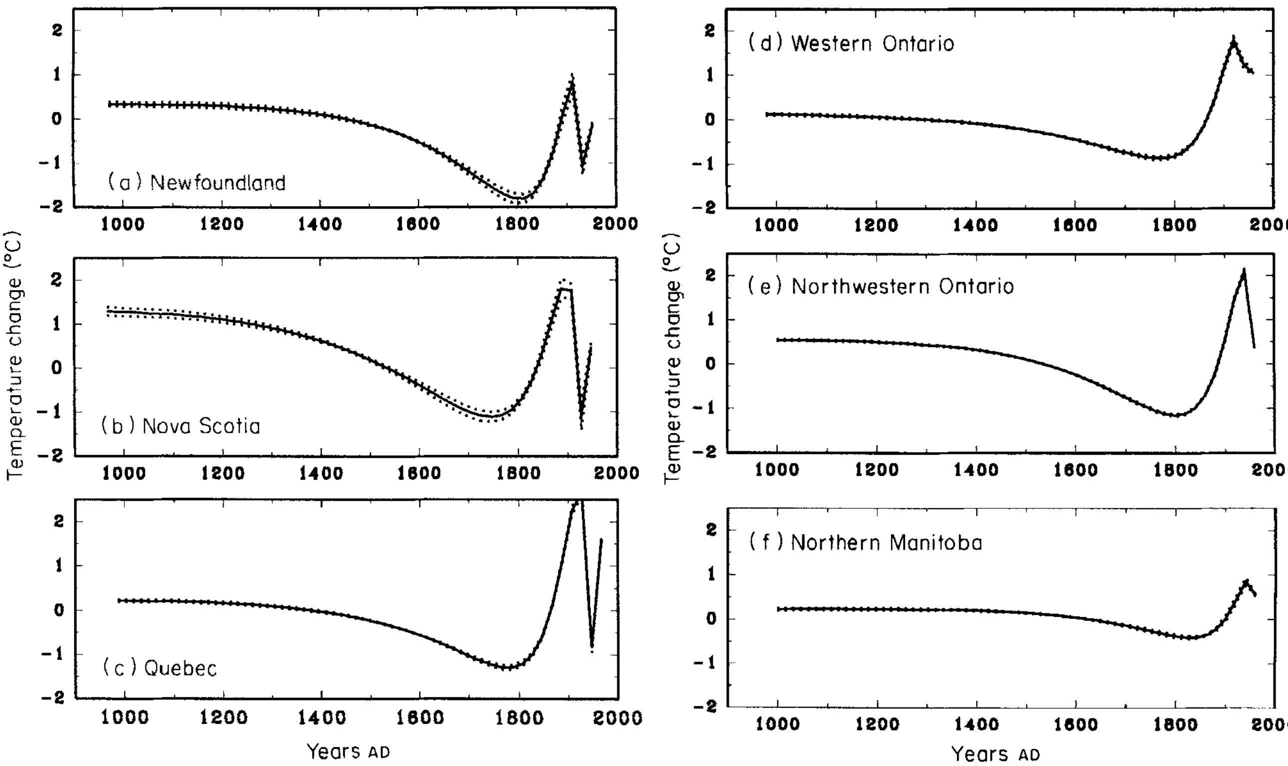

Fig. 3. *Average ground temperature histories for several regions of Canada. (a) Newfoundland (2 logs), (b) Nova Scotia (1 log), (c) Québec (8 logs), (d) Western Ontario (7 logs), (e) Northwestern Ontario (3 logs), (f) Northern Manitoba (6 logs).*

the exception of northern Manitoba. These similarities suggest that a common forcing has acted upon a large area of southeastern Canada. Accordingly, 21 temperature logs from all regions except northern Manitoba were inverted simultaneously to yield an estimate of the average ground temperature history for a wider area. The resulting average GTH for southeastern Canada is shown in Fig. 4.

The approximate timing (beginning of the 20 year period) and magnitude of the temperature at the minimum of the Little Ice Age and the 'modern' maximum as inferred from each regional inversion are shown in Table 1. The temperature change ranges are about 3°C for most regions and 1°C in northern Manitoba. Most of these changes occurred within 140 years; only Newfoundland and northern Manitoba show a temporal interval between minimum and maximum of 100 years. While the cooling at the beginning of the Little Ice Age appears to have been gradual (this is, in part, due to decreasing resolution of geothermal data) the warming after recovery from the Little Ice Age minimum shows an amplitude much larger than the former. This leaves pending the question of the role of anthropogenic activities after this time.

All solutions shown above have in common a significant warming during the last 200 years. This is confirmed by *all but three* of the 54 (shallow and deep) sites analysed in Canada, which show a

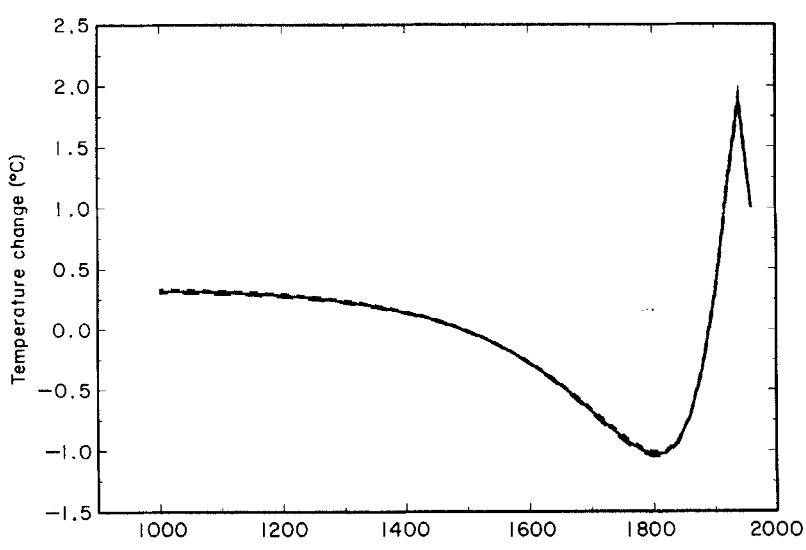

Fig. 4. *Average ground temperature history for all regions of eastern Canada below 50°N latitude. This solution was obtained from the simultaneous inversion of 21 temperature logs.*

Table 1. Timing of maxima and minima for the regional and total average ground temperature histories as inferred from inversion. Times given indicate the beginning of the 20-yr time interval.

Region	Minimum		Maximum		Range	
	t (yr)	T (°C)	t (yr)	T (°C)	ΔT (°C)	Δyr
Newfoundland	1822	−1.8	1922	0.8	2.6	100
Nova Scotia	1757	−1.1	1897	1.8	2.9	140
Québec	1797	−1.3	1937	2.7	4.0	140
Western Ontario	1790	−0.9	1930	1.8	2.7	140
N. West Ontario	1810	−1.2	1950	2.1	3.3	140
N. Manitoba	1830	−0.3	1930	0.8	1.1	100
Eastern Canada	1810	−1.0	1950	1.9	2.9	140

clear indication of warming starting some 150–200 yr BP (Beltrami and Mareschal, 1991, 1992; Beltrami *et al.*, 1992). It should be borne in mind, however, some of the inferred warming, from boreholes of various depths, corresponds to a 'recovery' from the earlier cold period.

DISCUSSION

The different GTH for northern Manitoba has been confirmed by the solutions found by inverting each temperature log individually (Beltrami *et al.*, 1992). It is clear that the cold period *c.* 1850 AD is less pronounced in magnitude and in temporal length than are the other regional averages. Thus, this regional solution appears unmistakably different from the rest of the regional GTHs. The gross features of this curve are in agreement with temperature reconstruction carried out by Jacoby and D'Arrigo (1989) and D'Arrigo and Jacoby (1992) from dendrochronological data in northern North America. Figure 5a shows the regional solution for northern Manitoba from the period 1600 AD to the present, together with air temperature reconstruction for the northern part of North America (Fig. 5b) from seven dendrochronological series by D'Arrigo and Jacoby (1992). The gross features of the temperature record are recovered by the GTH although the comparison cannot at this point be carried out further since the quantities represented by this curve are different (i.e. reconstructed *air* temperature and inferred *ground* temperature). Other single-site air temperature reconstructions from tree-rings in lower latitudes in Canada or northern United States show rather different histories in agreement with the ground surface temperature histories found here for near-by regions. For example, Fig. 6 shows part of the regional solution for northwestern Ontario (a) and two single-site annual air temperature reconstructions from tree-rings (Fritts, 1991) for (b) Marquette and (c) Alpena. Although these temperature reconstructions show differences among themselves, they are clearly closer to each other than to the northern North America temperature reconstruction. These relations point to different kinds of air temperature histories – and maybe climate – for different areas as indicated by the ground temperature histories inferred here. Ground temperatures are (in regions with snow cover) determined mainly by the number of days with snow on the ground in Spring and Fall and by the air temperature regime (Beltrami and Mareschal, 1991); ground temperature is a climatic change indicator since it integrates the effects of the surface air temperature and the precipitation regime. Thus the comparison suggested in Fig. 5 and Fig. 6 must be made with caution, particularly where single-site air temperature reconstruction is concerned since its representativity might be local.

Figure 7 shows the average ground temperature history for eastern Canada (7a), the tree-ring indices 20-year running mean with 10-year shifts for a 802-year time series from southern Québec (7b) (Archambault and Bergeron, 1992), the atmospheric CO_2 concentration as determined by Wahlen *et al.* (1991) from a Greenland ice core (7c), and the bi-decadal $\delta^{18}O$ ratios found by Thompson *et al.* (1986) in a southern hemisphere ice core (7d).

The agreement between the growth

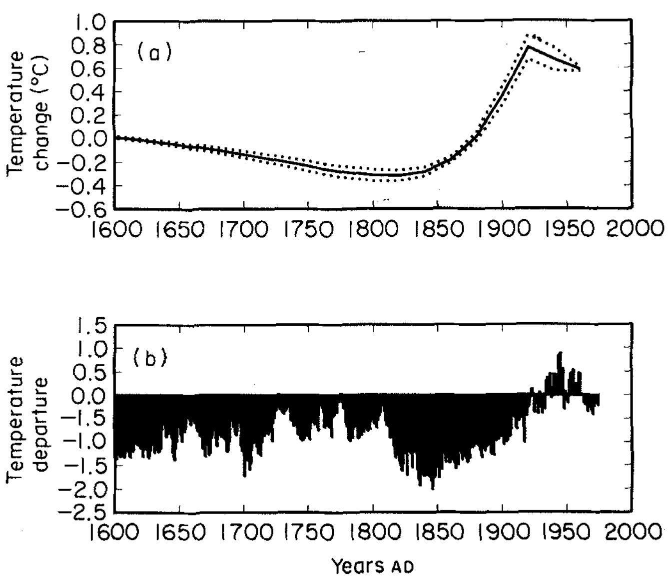

Fig. 5. *(a) GTH for northern Manitoba; part of the GTH in Fig. 3f. (b) Air temperature reconstruction for northern North America from 7 dendrochronological series (D'Arrigo and Jacoby, 1992).*

index and the average GTH for the last five centuries is good; both curves show similar trends for long-term changes. Earlier features and short-term variations recorded in the tree-ring data, are not expected to be resolved by the geothermal data because of their decreasing resolving power. This agreement is not surprising since ground temperatures might have an important effect on tree-ring widths (Archambault and Bergeron, 1992). Dendrochronology would thus provide an appropriate tool for verification of the gross features of GTHs determined from the geothermal measurements.

The ground temperature changes inferred by this study appear to be correlated with the atmospheric CO_2 concentration (Beltrami and Mareschal, 1992). Measurements of methane concentration in an antarctic ice core follow the carbon dioxide trends (Etheridge *et al.*, 1988). The timing of the temperature minimum during the Little Ice Age (*c.* 1800 AD) coincides with the increase in the concentration of atmospheric CO_2 (*c.* 1810 AD). The causality relation cannot be clarified at present, but it is clear that the atmospheric CO_2 before 1800 AD was lower than present. The apparent lack of significant change in the atmospheric concentration of this greenhouse gas before 1800 AD, if confirmed by new ice core data could imply that global temperature changes can occur without a change in the atmospheric content of this gas. If atmospheric CO_2 concentration variations have accompanied the Little Ice Age one would expect this phenomenon to have had a worldwide character, as suggested by climatic data (Lamb, 1977; Thompson *et al.*, 1986) (i.e. changes would occur simultaneously) and would significantly complicate the quantitative identification of anthropogenic influences on climate. More data are needed to verify whether atmospheric CO_2 was higher before 1500 AD. Finally, the increase in ground temperature in northern Manitoba lags the atmospheric CO_2 increase.

The GTH for eastern Canada also appears to be correlated with the $\delta^{18}O$ record in the southern hemisphere. Although this proxy indicator does not directly translate into air-temperature variations since it represents the temperature at the time that precipitation actually occurred (Grootes and Steig, 1992), the similarities of these curves is surprising and furthermore, they suggest that the factors affecting the temperature changes have acted worldwide.

The results shown here have not been compared with meteorological records of air temperature, since the ground temperature cannot be readily translated into air temperature variations, and since the meteorological records in these areas hardly covers 100 years. Nonetheless, the western Ontario GTH obtained from geothermal data recovers the magnitude of this century's warming in eastern Canada (≃ 1°C) according to the only rural station with a long, usable record (Parry Sound) (data from Environment Canada).

A solution from a deeper borehole indicates, in addition to the Little Ice Age, that a warm period existed around 1000 AD (Fig. 8). Such a warm period, the Climatic Optimum, has been extensively documented in Europe (Lamb, 1977). The timing and magnitude of the warm event remains uncertain since this GTH was obtained from the inversion of data from a single, isolated borehole temperature log with no thermal conductivity measurements in the first 200 m, but a similar warm event has been inferred from two deep boreholes in France (Mareschal and Vasseur, 1992), and in a deep borehole in Canada (Wang, 1992).

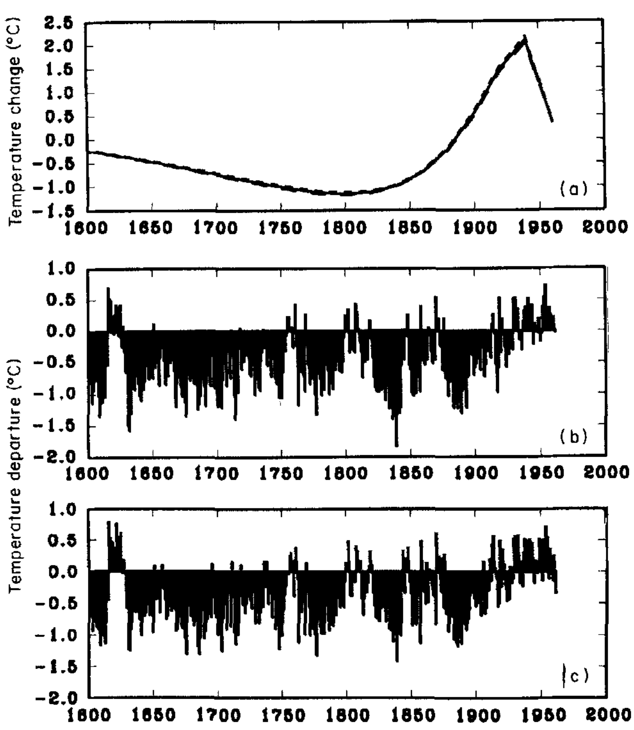

Fig. 6. *(a) GTH for western Ontario; part of the GTH in Fig. 3d. (b) Single-site air temperature reconstruction from tree rings at Marquette (46°33N, 87°24W). (c) Single-site air temperature reconstruction from tree rings at Alpena (45°04N, 83°26W).*

CONCLUSIONS

The regional ground temperature histories presented here and their agreement with nearby tree-ring indices, stable isotope records from the southern hemisphere and the atmospheric concentration of CO_2, give support to the use of geothermal data for the inference of past climatic changes.

The agreement between two 'types' of GTH obtained in this work with treering temperature reconstruction and tree-ring indices indicate that GTH are also useful for recovering the spatial variation of past climate and confirm the regional variation in timing of the Little Ice Age.

The period of warming that started in the early 1800s (1830 AD in northern Manitoba) appears correlated with the

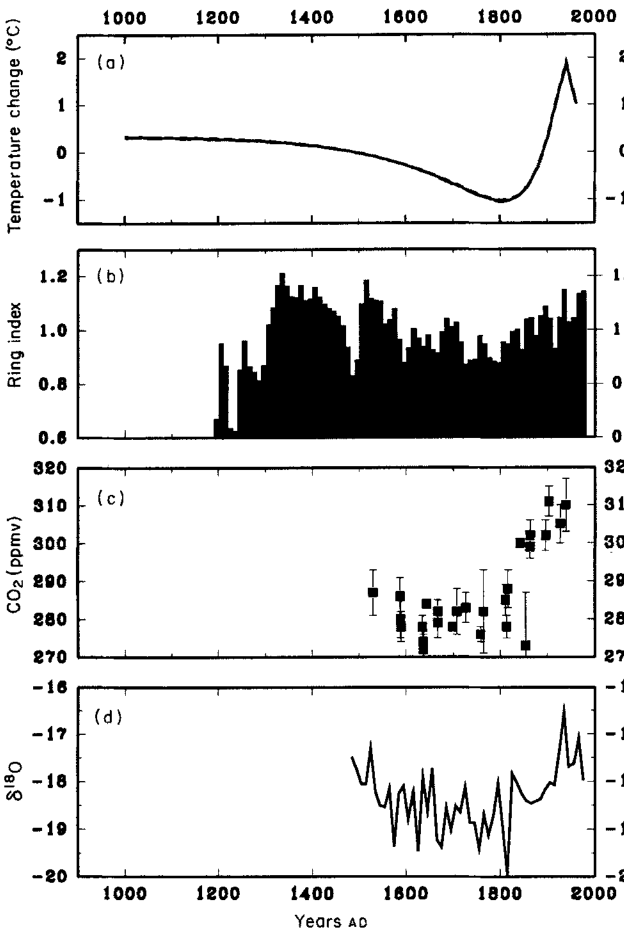

Fig. 7. *(a) Ground temperature history for Canada. This solution was obtained by simultaneous inversion of twenty-one (21) temperature logs in the area. The standard deviations of the estimated parameters for an assumed data standard deviation of 0.02 K are included in the solid line. (b) Tree-ring growth index for a 802-yr time series at Rouyn (Québec) (48°28N, 79°17W). The figure shows the 20-yr running mean starting in 1200* AD *with 10-year shifts. (c) Atmospheric CO_2 concentrations as obtained from a Greenland ice core. (d) Radio of $\delta^{18}O$ (bi-decadal averages) in an ice core from the Quelccaya summit ice core.*

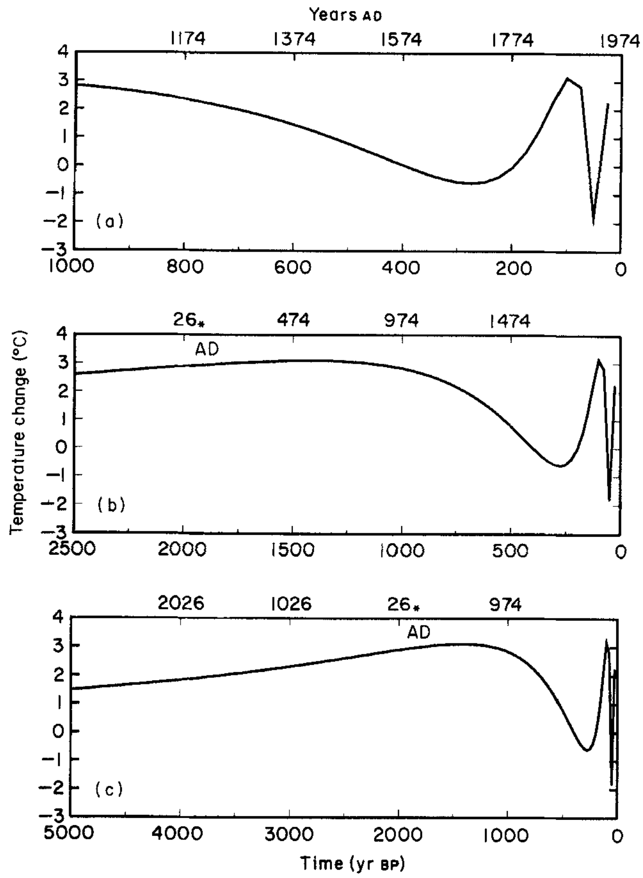

Fig. 8. *Ground temperature history from a deep borehole in Gaspé (Québec) with different parameterizations and time scales. The inversion indicates a warm event before the LIA but the timing of this event remains poorly resolved because of the insufficient depth of the borehole. Note that the timing of the temperature minimum is not affected by the parameterization.*

atmospheric concentrations of carbon dioxide and methane. Results also indicate that the climate has been subjected in the past to natural oscillations; whether or not these variations have always been accompanied by changes in the atmospheric CO_2 concentration remains to be determined. This question could be answered by measurements of atmospheric CO_2 before 1500 AD. This would open the door for the investigation of the role of the ocean in short-term (100–1000 yr) climatic change and could reconcile biotic CO_2 sources with ice-core data (Enting, 1992).

Results suggest that temperature measurements in well-located drill holes could be used to complement the information on recent climatic changes. Continuous monitoring with permanent facilities would improve resolution, as well as remove transient effects from surface temperature changes and promote further understanding of air-ground temperature relations. A worldwide record of thermal history of the ground could be useful for the validation of general circulation models predicting climatic evolution and as a complement to the meteorological record and other proxy climatic indicators.

ACKNOWLEDGEMENTS

We are grateful to Alan Jessop at Geological Survey of Canada for providing part of the data used in this study, and to Dr Yves Bergeron and Dr Gordon Jacoby for providing their tree-ring data. We thank Drs Paul Shen and Kelin Wang for innumerable discussions while this work was carried out, and Dr J. Graham and L. Kellman for comments on an earlier version of this paper and discussions at the SUIAS (Montréal) workshops. JCM is grateful for the generous and continuous support of the Natural Sciences and Engineering Research Council (Canada) and of the fonds pour la Formation de Chercheurs et l'Aide à la Recherche (Québec). HB received fellowships from PFACC (UQAM) and the Chaire de Recherche en Environnement (HydroQuébec–NSERC–UQAM).

REFERENCES

Archambault S. and Bergeron Y. (1992) A 802-year Tree-Ring Chronology from Quebec Boreal Forest, *Can. J. For. Res.*, in press.

Beck A.E. (1977) Clinically Perturbed Temperature Gradients and their Effects on Regional and Continental Heat-Flow Means, *Tectonophys.*, **41**, 17–39.

Beck A.E., Shen P.Y., Beltrami H., Mareschal J.C., Safanda J., Sebagenzi S., Vasseur G. and Wang, K. (1992) A Comparison of 5 Different Analyses of Interpreting 5 Data Sets. *Global Planet. Change, in press.*

Beltrami H. and Mareschal J.C. (1991) Recent Warming in Eastern Canada: Evidence from Geothermal Measurements, *Geophys. Res. Lett.*, **18**, 605–608.

Beltrami H. and Mareschal J.C. (1992) Ground Temperature Histories for Central and Eastern Canada from Geothermal Measurements: Little Ice Age Signature, *Geophys. Res. Lett.*, **19**, 698–692.

Beltrami H., Jessop A.M. and Mareschal J.C. (1992) Ground Temperature Histories in Eastern and Central Canada from Geothermal Measurements: Evidences of Climatic Change. *Global Planet. Change, in press.*

Blackwell D.D., Steele J.L. and Brott C.A. (1980) The Terrain Effect on Terrestrial Heat Flow, *J. Geophys. Res.*, **85**, 4757–4772.

Carslaw H.S. and Jaeger J.C. (1959) *Conduction of Heat in Solids*, 2nd edn. Oxford University Press, Oxford, 510 pp.

D'Arrigo R.D. and Jacoby G.C. (1992) Dendrochronological Evidence from Northern North America. In: *Climate since* AD *1500* (ed by R.S. Bradley and P.D. Jones). Routledge, London.

Elsner J.B. and Tsonis A.A. (1991) Comparison of Observed Northern Hemisphere Surface Air Temperature Records, *Geophys. Res. Letts.*, **18**, 1229–1232.

Enting I.G. (1992) The Incompatibility of Ice-Core CO_2 data with Reconstruction of Biotic CO_2 Sources (II). The influence of CO_2-Fertilized Growth, *Tellus*, **44B**, 23–32.

Etheridge D.M., Pearman G.I. and de Silva F. (1988) Atmospheric Trace-Gas Variations as Revealed by Air Trapped in an Ice Core from Law Dome, Antarctica, *Ann. Glaciol.*, **10**, 28–33.

Fritts H.C. (1991) *Reconstructing Large-Scale Climatic Patterns from Tree-ring Data: A diagnostic Analysis.* University of Arizona Press, Tucson.

Ghil M. and Vautard R. (1991) Interdecadal Oscillations and the Warming Trend in Global Temperature Time Series, *Nature*, **350**, 324–327.

Grootes P.M. and Steig E.J. (1992) Uncertainties in the Isotope-Temperature relationship in Ice Cores, *Eos, Trans. Am. Geophys. Un.* **73**, Spring Mtng Suppl. 107.

Grove J.M. (1988) *The Little Ice Age.* Methuen, London, 498 pp.

Hansen J. and Lebedeff S. (1987) Global Trends of Measured Air-Surface Temperature, *J. Geophys. Res.*, **92**, 13,345–13,372.

Jackson D.D. (1972) Interpretation of Inaccurate, Insufficient, and Inconsistent Data, *Geophys. J. R. astr. Soc.*, **28**, 97–110.

Jacoby G.C. and D'Arrigo R. (1989) Reconstructed Northern Hemisphere Annual Temperature Since 1671 Based on High-Latitude Tree-Ring Data from North America, *Clim. Change*, **14**, 39–59.

Jessop A.M., Lewis T., Judge A.S., Taylor A.E. and Drury M.J. (1984) Terrestrial Heat Flow in Canada, *Tectonophys.*, **103**, 239–261.

Jones P.M., Wigley M.L. and Wright P.B. (1986) Global Temperature Variations between 1861 and 1984, *Nature*, **322**, 430–434.

Karl T.R., Tarpey J.D., Quayle, R.G., Diaz H.F., Robinson D.A. and Bradley R.S. (1989) The Recent Climate Record: What it Can and Cannot Tell Us, *Rev. Geophys.*, **27**, 405–430.

Lachenbruch A. and Marshall B.V. (1986) Changing Climate: Geothermal Evidence from permafrost in the Alaskan Arctic, *Science*, **234**, 689–696.

Lamb H.H. (1972) *Climate: Present, Past and Future. Volume I: Fundamentals and Climate Now.* Methuen, London, 613 pp.

Lamb H.H. (1977) *Climate: Present, Past and Future. Volume II: Climatic History and the Future.* Methuen, London, 853 pp.

Lanczos C. (1961) *Linear Differential Operators.* D. van Nostrand, New York, 564 pp.

Mareschal J.C., Pinet C., Gariépy C., Jaupart C., Bienfait G., Dalla Coletta G., Jolivet J. and Lapointe R. (1989) New Heat Flow Density and Radiogenic Heat Production Data in the Canadian Shield and the Quebec Appalachians, *Can. J. Earth Sci.*, **26**, 845–852.

Mareschal J.C. and Beltrami, H. (1992) Evidence for Recent Warming from Perturbed Geothermal Gradients: Examples from Eastern Canada, *Clim. Dyn.*, **6**, 135–143.

Mareschal J.C. and Vasseur G. (1992) Ground Temperature History from Two Deep Boreholes in Central France. *Global Planet. Change, in press.*

Menke W. (1989) *Geophysical Data Analysis: Discrete Inverse Theory* International Geophysical Series, Vol. 45, Academic Press, San Diego, 289 pp.

Pinet C., Jaupart C., Mareschal J.C., Gariépy C., Bienfait G. and Lapointe R. (1991) Heat Flow and Structure of the Lithosphere in Eastern Canada, *J. geophys. Res.*, **96**, 19,941–19,963.

Shen P.Y. and Beck A.E. (1983) Determination of Surface Temperature history from Borehole temperature Gradients, *J. geophys. Res.*, **88**, 7385–7493.

Shen P.Y., Wang K., Beltrami H. and Mareschal J.C. (1992) A Comparative Study of Inverse Methods for Estimating Climatic Histories from Borehole Temperature Data, *Global Planet Change, in press.*

Thompson L.G., Mosley-Thompson E., Dansgaard W. and Grootes P.M. (1986) The Little Ice Age as Recorded in the Stratigraphy of the Tropical Quelccaya Ice Cap, *Science*, **234**, 361–364.

Vasseur G., Bernard Ph., Van de Meulebrouck J., Kast Y. and Jolivet J. (1983) Holocene Paleotemperatures Deduced From Geothermal Measurements, *Paleogeogr. Paleoclimtol. Paleoecol.*, **43**, 237–259.

Wahlen M., Allen D., Deck B. and Herchenroder A. (1991) Initial Measurements of CO_2 Concentrations (1530 to 1940) in Air Occluded in the GISP 2 Ice Core from Central Greenland, *Geophys. Res. Letts.*, **18**, 1457–1460.

Wang K., Shen P.Y., Beltrami H. and Mareschal H.C. (1991) *A Comparative Study of Inverse Methods for Estimating Climatic History from Borehole Temperature Data.* IUGG General Assembly Vienna, August 1991.

Wang K. (1992) Estimation of the Ground Temperature History from Borehole Temperature Data, *J. geophys. Res.*, **97**, 2095–2106.

Willmott C.J., Robeson S.M. and Feddema J.J. (1991) Influence of Spatially Variable Instrument Networks on Climatic Averages, *Geophys. Res. Letts*, **18**, 2249–2251.

Received 24 August 1992; revision accepted 25 August 1992