Recent warming in eastern Canada inferred from geothermal measurements

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RECENT WARMING IN EASTERN CANADA INFERRED FROM GEOTHERMAL MEASUREMENTS

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Abstract. Borehole temperature measurements from several sites in eastern Canada were analyzed to determine recent step changes in ground surface temperature. Inversion of the data suggests a warming by 1 to 2°C in the last 100 years for most of the sites analyzed.

Introduction

A study of worldwide continental meteorological, carried out by Hansen and Lebedeff (1987), pointed out a .5°C global average temperature increase in the last 100 years. This temperature change is unevenly distributed. Several regions show warming by 3 to 5°C, while others show no warming or even cooling. In North America, the warming trend appears well marked in Alaska, in central and eastern Canada, and northeastern United States.

These analyses must be considered with caution because meteorological data are biased towards the northern hemisphere, suffer from variable standards and procedures, and have been affected by changes in station location and by urbanization (Karl et al., 1989). Furthermore, continuous meteorological records are not available at all locations and usually the well documented areas are the most contaminated by urbanization.

Birch (1948) has shown that the past surface temperature of the Earth is recorded in the subsurface as a deviation from steady state conditions. Thus, past ground temperatures can be inferred by analyzing the perturbations to the equilibrium geothermal gradient. Temperature logs at several locations around the world appear perturbed for the few first hundred meters. Such perturbations have been interpreted as caused by recent surface temperature variations (e.g., Cermak, 1971; Beck, 1977; Lachenbruch and Marshall, 1986; Nielsen and Beck, 1989).

This paper reports on a study of temperature logs obtained in parts of eastern Canada. For most sites in the area, the analysis indicates that ground temperature increased by 1 to 2°C over the last 100-150 years.

Theoretical framework

The present temperature perturbation $T(z)$ in a semi-infinite solid with past surface temperature $T_0(t)$, where z is depth and t is time before present, is given by (e.g. Vasseur et al., 1983):

$$T(z) = \frac{z}{2\sqrt{\pi\kappa}} \int_0^\infty T_0(t) t^{-\frac{3}{2}} \exp\left(-\frac{z^2}{4\kappa t}\right) dt. \qquad (1)$$

where κ is the thermal conductivity. For a series of N instantaneous changes of the surface temperature T_k at times t_k before present, the integration yields:

$$T(z) = \sum_{k=1}^{N} T_k \operatorname{erfc} \frac{z}{2\sqrt{\kappa t_k}} \qquad (2)$$

where erfc is the complementary error function.

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In the Earth, the temperature perturbation is superimposed on the equilibrium temperature which for a homogeneous, source-free half space increases linearly with depth. In the deeper part of the profile, which is not affected by recent changes, the heat flow is constant. The equilibrium heat flow can be determined in the unperturbed section of the profile following standard methods (Bullard, 1939), and the equilibrium temperature is continued upward by assuming constant gradient over intervals of constant conductivity. The intercept of the extrapolated temperature profile at the surface gives the mean ground temperature before the onset of the present perturbation.

The shape of the perturbation profile is determined by the thermal history of the surface. This history can be determined directly by inversion (Vasseur et al., 1983; Shen and Beck, 1983; Nielsen and Beck, 1989). Analysis of the inversion and its robustness will be reported by Beltrami and Mareschal (submitted to Climate Dynamics).

Data and interpretation

For this study, more than 100 temperature logs collected for HFD determination in eastern Canada (Mareschal et al., 1989) were analyzed for detection of a recent surface temperature step change. Figure 1 shows the location of the sites, and a summary of results. Temperature measurements were made at 10 m intervals with a calibrated thermistor. However, the shallowest part of the log is often missing because measurements were made only below the water table.

A total of 61 borehole temperature logs, at about 20 sites, were retained for this preliminary study; data from water wells were not included because these wells are not deep enough to determine the equilibrium HFD and they are more likely to be affected by nonclimatic factors. The great majority of water wells logged are located in the region of Lac St. Jean (QC), where land development has caused some recent disruption of the landscape. These boreholes are discussed by Pinet et al. (submitted to J. Geophys. Res.). Other temperature profiles not used in this study are the ones with evidence of ground water flow.

The mining exploration boreholes retained for analysis are not located in cleared areas. It is not expected that the horizontal variations of surface temperature (trees cut for drilling) would have disturbed the temperature profiles. The wavelength of these variations is small (less than 5 m) and the effect is negligible below 20 m or so. Also, an apparent warming signal arising from biased borehole logging on cleared South facing slopes is of no concern in this study since the boreholes selected are located in flat land.

The classification of results was done considering sites showing negative temperature gradients in the upper 100-150 m - with no obvious alternative explanation - as a definitive sign of surface temperature increase. Sites exhibiting contradictory or highly distorted profiles are reported as inconclusive. Finally, sites showing no perturbation are reported as such.

Inversion for a single step-like variation of surface temperature was used to reconstruct surface temperature history at each location. For the inversion, the thermal diffusivity was assumed throughout to be 10^{-6} m^2s^{-1}, although it can be modified when measurements indicate different values.

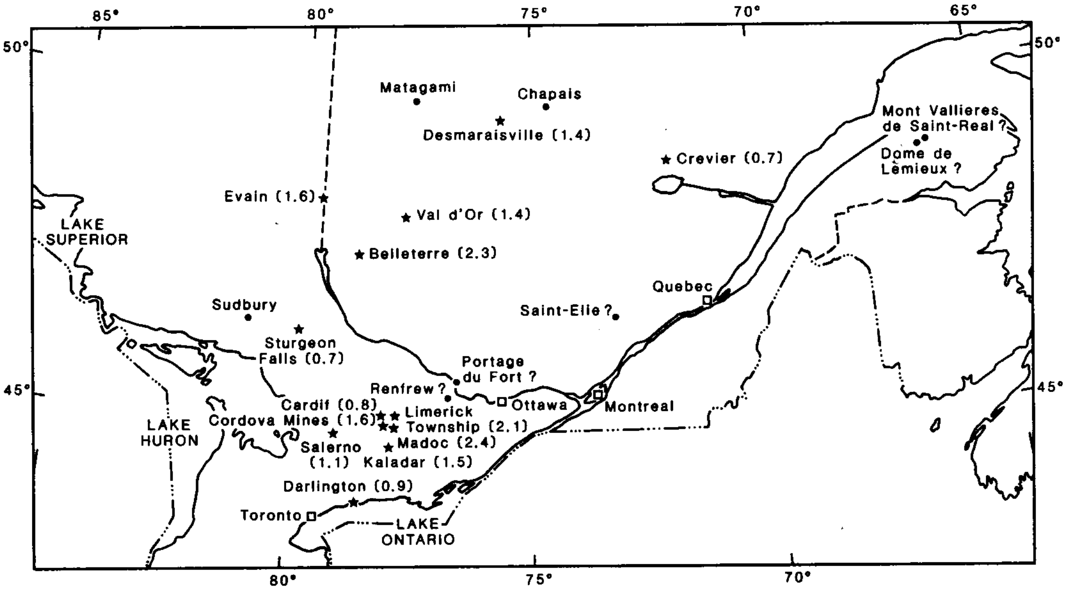

Fig. 1. Sites in eastern Canada. Stars mark sites with definite indication of warming (temperature change in brackets). Dots represent sites where no unequivocal sign of warming was detected. The perturbations at Chapais and Sudbury and Matagami are too small to be interpreted.

Table 1 summarizes the results for each site with error estimates for the inversion accounting for temperature measurements errors, uncertainty on the slope of the linear profile due to variations in thermal conductivity, and the uncertainty on the steady state temperature profile due to anterior temperature history.

Figure 2a shows the data for sites with evidence of warming, the linear profile extrapolated, and the calculated profile for the best-fitting step-like surface temperature model. Only one profile per site is shown.

Figure 2b shows data with no indication of warming. One borehole in Chapais exhibits a weak warming signal (0.2°C), starting approximately 500 years ago, but it is not confirmed by the other measurement. For Sudbury, another analysis of temperature measurements in different boreholes (Jessop, personal communication) does suggest a 2.3°C warming

TABLE 1. Location of sites, number of logs analyzed, number of logs showing warming, cooling, or no change, and results of inversion. ΔT gives the range of surface temperature increase from all logs at the site. Δt is the range for the time of the step. T_{air} (°C) is the annual mean air temperature at the closest station. T_{gr} (°C) is the present ground temperature determined by inversion.

Site	Latitude	Longitude	Logs	warmer	cooler	same	ΔT	Δt	T_{air}	T_{gr}
Val d'Or	48° 05' 57"	77° 33' 33"	3	3	-	-	1.1-1.7	65-79	1.3	5.5
Desmairaisville	49° 36' 23"	75° 50' 37"	3	2	-	1	1.6	120	-0.3	4.4
Belleterre	47° 24' 06"	78° 42' 37"	4	4	-	-	1.8-3.0	58-75	1.8	6.2
Cordova Mines	44° 32' 06"	77° 47' 09"	4	3	1	-	1.1-1.9	98-200	6.5	8.0
Evain	48° 16' 47"	79° 05'49"	2	2	-	-	1.6	240	1.3	5.5
Salerno	44° 51' 24"	78° 38' 09"	6	6	-	-	0.9-2.1	48-98	5.2	7.5
Sturgeon Falls	46° 26' 31"	79° 56' 51"	2	2	-	-	0.3-1.1	20-130	4.1	6.0
Kaladar	42° 43' 05"	77° 10' 49"	4	4	-	-	1.0-1.6	40-132	5.7	8.0
Limerick	44° 52' 15"	77° 43' 18"	2	2	-	-	1.2-4.0	48-109	5.7	7.3
Cardif	45° 00' 26"	78° 02' 03"	2	2	-	-	0.7-0.9	28-42	5.7	7.3
Crevier	49° 28' 01"	72° 46' 15"	1	1	-	-	0.7	102	1.7	3.8
Sudbury	46° 26' 24"	81° 03' 56"	3	-	-	3	0	-	3.3	8.0
Chapais	49° 47' 19"	74° 48' 34"	2	1	-	1	0	-	-0.3	4.5
Matagami	49° 42' 58"	77° 44' 03"	4	-	-	4	0	-	-0.9	3.2
St Elie	46° 29' 20"	72° 57'17"	4	1	3	-	-	-	4.7	-
Mt. Vallieres	48° 49' 50"	65° 57' 35"	3	-	-	2	-	-	1.3	-
D. de Lemieux	48° 47' 23"	66° 10' 54"	3	1	-	1	-	-	1.3	-
Renfrew	45° 25' 23"	76° 42' 17"	3	1	2	-	-	-	5.1	-
P. du Fort	45° 35' 59"	76° 39' 17"	4	2	2	-	-	-	5.1	-
Darlington	43° 52' 05"	78° 43' 00"	1	1	-	-	0.9	25	7.4	8.8
Madoc	44° 30' 14"	77° 47' 09"	1	1	-	-	2.4	150	6.5	9.0

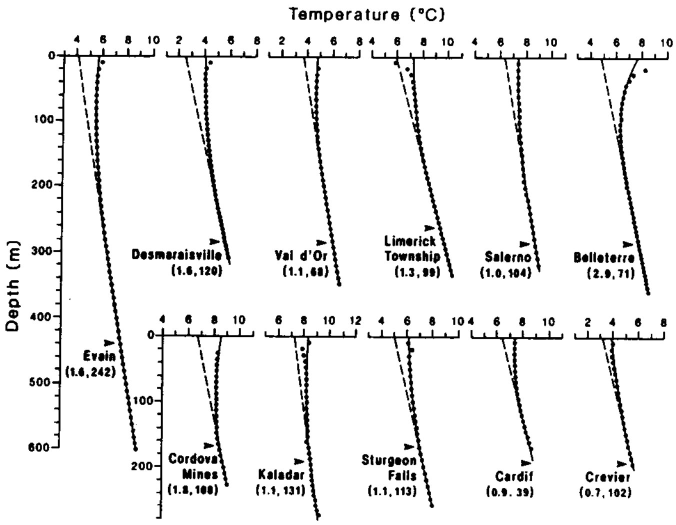

Fig. 2a. Selected data from eastern Canada. Sites showing surface temperature increase. The linear part of the profile has been superimposed on each log and extrapolated to the surface. The solid curve is calculated for the best fitting model.

starting around 1900. The boreholes used in the present study were less than 50 m from a lake and this proximity might explain the absence of warming signal. At Matagami, the apparent cooling signal is likely due to ground water flow observed at the site.

Figure 2c shows data with evidence of warming but not considered conclusive. The result at Madoc is considered inconclusive because the topmost 60 m of the temperature profile are missing. At Darlington, the detected warming is about 1°C during the last 25 years. The timing of this warming is suspect because this site is close to the cities of Oshawa and Toronto which have expanded considerably in the last 30 years.

At three locations, different temperature profiles yield inconsistent conclusions; some indicate warming and some cooling. This is the case at St Elie (QC), Portage du Fort (QC) and Renfrew (ON). More data and a better understanding of interaction between climate and the solid Earth are needed to clarify these phenomena. Temperature logs at the

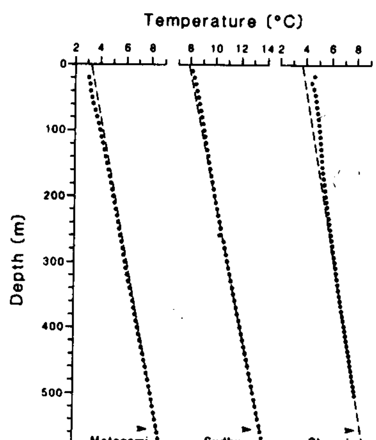

Fig. 2b. Sites exhibiting no perturbation or very small surface temperature changes over a very long time period.

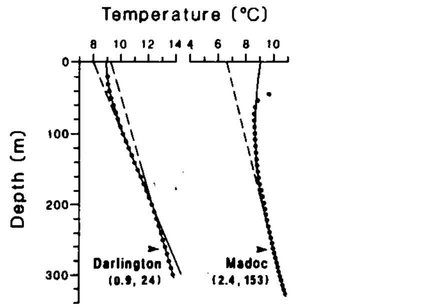

Fig. 2c. Sites showing a signal but still considered inconclusive.

nearby locations of Mont Vallieres (QC) and Dome de Lemieux (QC) were also inconclusive because of the topography.

Discussion and conclusions

This report confirms the warming trend suggested by studies in eastern and central Canada. Nielsen and Beck (1989) concluded to recent surface temperature increase from a study of 4 boreholes in Ontario. Preliminary analysis by Jessop (pers. comm.) shows surface temperature increase in eastern and central Canada. The warming trend detected in borehole temperature measurements in eastern Canada is corroborated by the meteorological data analysis of Hansen and Lebedeff (1987). The warming trend observed reflects local climatic variations, and does not necessarily have a global character.

The object of this report is not only to interpret a climatic signal, but also to discuss whether this signal is significant. Distorted temperature gradients can also reflect effects of topography and lateral temperature variations. An apparent warming signal can be caused by non climatic factors such as urban heat islands and recent deforestation.

To relate the ground temperature history to climate, it is important to elucidate the relationship between ground and air temperature. Measured mean annual air temperature and ground temperature calculated by inversion are compared in Table 1. The difference between air and ground temperatures in eastern Canada is between 1.5 to 6°C. The difference seems to be due mainly to the insulation of the ground by the snow during winter months. In Val d'Or, the mean air and soil temperatures for the period from 1972 to 1989, are 1.3°C and 6.5°C respectively. At this site, the temperature profile extrapolated to the surface gives a surface temperature of 5.5°C; this is 1°C less than soil temperature measurements over the last 15 years at a nearby location, but it is closer to mean soil than to mean air temperature. The difference is expected since the borehole data did not include the topmost 20 m and, therefore are not sensitive to changes over the last decade. Soil temperature measurements are, unfortunately, not available for other sites. Fig. 3a, shows measured monthly mean air and soil (5 cm) temperature at Val d'Or (QC) (data provided by Environment Canada). The insulating effect of snow, preventing ground temperature from reaching subfreezing values, is apparent during the winter. In eastern Canada, the number of days with snow on the ground appears as the main factor correlating with the difference between air and ground temperature. Figure 3b shows the relation between the annual mean ground-air temperature difference and the number of days with snow on the ground for the months of April, October and November of each year. The variation in the duration of snow cover over decades or greater time periods complicates the identification of the air temperature signal. A decrease (increase) in the number of days with snow cover may result in a net

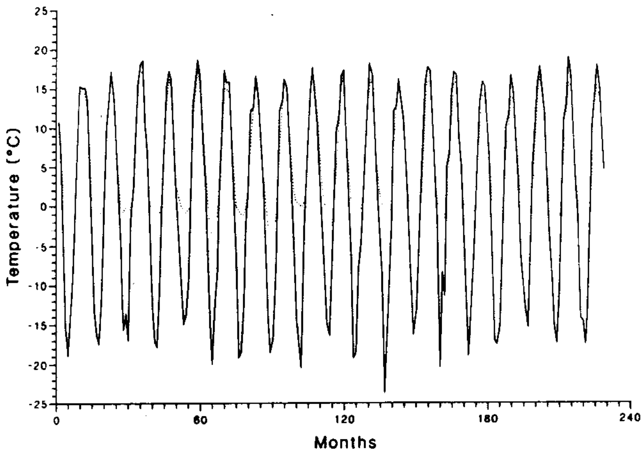

Fig. 3a. Monthly mean air temperature and soil temperature (5cm) at Val d'Or (QC) for the period between 1972 and 1989. The mean annual air/soil temperature difference for this location is 5.2°C.

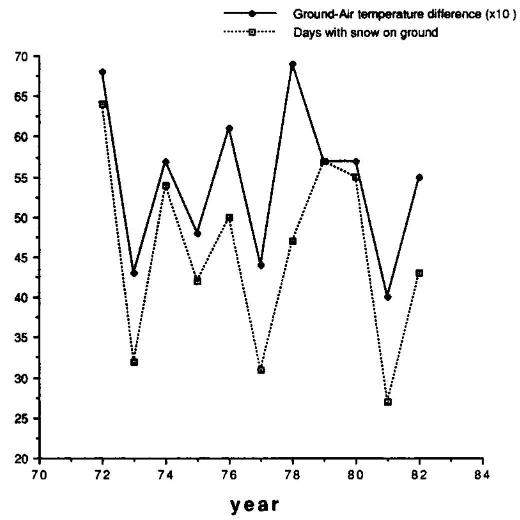

Fig. 3b. Relation between annual ground-air temperature difference and the number of days with snow on the ground for April, October and November at Val d'Or. Snow cover during December, January, February and March shows no variation on the record since 1955.

decrease (increase) of mean annual soil temperature, and thus hide a warming (cooling) trend in the air temperature. Snow accumulation records should be studied, whenever available, to detect variations that could affect mean ground temperature.

The resolution of the climatic signal from the data is good. Although the temperature history remains ambiguous in its details, the total increase in surface temperature is robust and does not depend on the details of the surface temperature history. Improved resolution of the climatic signal can be achieved by measuring the time rate of change of the temperature perturbation or by simultaneous inversion of temperature profiles taken at suitable time intervals (Lachenbruch and Marshall, 1986; Nielsen and Beck, 1989). These measurements also permit the identification and elimination of stationary perturbations of the geothermal gradient.

The analysis of temperature measurements in boreholes has the advantage that the Earth filters out short-lived climatic variations, leaving only long-term trends of surface temperature change. Most importantly, this analysis can be carried out in regions where meteorological records do not exist and in areas untouched by human intervention. This approach could thus complement the meteorological record on the recent climatic regime of the continents.

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