Ground surface temperatures in Canada: Spatial and temporal variability

Hugo Beltrami
Environmental Earth Sciences Research Laboratory, St. Francis Xavier University, Antigonish, Nova Scotia, Canada

C. Gosselin and J. C. Mareschal
GEOTOP-UQAM-McGill, Centre de Recherche en Géochimie et Géodynamique, Université du Québec à Montréal, Canada

Received 17 February 2003; revised 25 March 2003; accepted 16 April 2003; published 17 May 2003.

[1] Past changes in the Earth’s surface energy balance are recorded in the ground as perturbations of the subsurface thermal regime. Here we reconstruct ground surface temperature histories (GSTH) from temperature versus depth profiles measured at 246 sites distributed across Canada. We show that the ground has warmed about 0.7 K in the last 100 years. Spatial variability is significant and indicates that the largest warming is in the southern areas of Canada. The apparent signal for the “Little Ice Age” (LIA) does not appear to be homogeneous across Canada. INDEX TERMS: 1645 Global Change: Solid Earth; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3309 Meteorology and Atmospheric Dynamics: Climatological (1620); 1610 Global Change: Climatic and Atmospheric Dynamics: Climatology (1620); 3325 Global Change: Atmosphere (1620). This is an important issue in the evaluation of the magnitude and extent of climate change as energy balance variations at the land atmosphere interface, covering almost 30% of the Earth’s surface, are important for determining radiative forcing changes and for interface, covering almost 30% of the Earth’s surface, are important for determining radiative forcing changes and for interface, covering almost 30% of the Earth’s surface, are important for determining radiative forcing changes and for interface, covering almost 30% of the Earth’s surface, are important for determining radiative forcing changes and for interface, covering almost 30% of the Earth’s surface, are important for determining radiative forcing changes.

[2] Determination of the past changes of the Earth’s surface temperature inferred from geothermal data have shown that the study of perturbations to the Earth’s energy balance is possible [Lewis, 1992; Beltrami and Harris, and the references therein, 2001]. This is an important issue in the evaluation of the magnitude and extent of climate change as energy balance variations at the land atmosphere interface, covering almost 30% of the Earth’s surface, are important for determining radiative forcing changes and for providing a boundary condition to surface land models [Koster and Suarez, 1992]. This part of the energy balance budget at the Earth’s surface is difficult to measure from meteorological data because of high frequency noise [Karl et al., 1989] and also because of the large number of energy exchange processes taking place simultaneously at the air-ground boundary. Geothermal data bypass this limitation because they contain useful information about the long term surface energy balance variations. The Earth filters out high frequency energy fluctuations and retains only the long-term trends of surface energy imbalance, recording surface changes as perturbations of underground temperature as a function of depth. These changes in the energy balance at the Earth’s surface are reflected in geothermal records whenever the underlying physical processes are sustained.

[3] Previous work on the determination of ground surface temperature histories (GSTHs) and surface heat flux histories from geothermal data in Canada [Beltrami et al., 1992; Lewis, 1992; Beltrami, 2001; Majorowicz et al., 2002], and other regions [Pollack and Huang, 2000; Huang et al., 2000; Harris and Chapman, 2001; Beltrami, 2002a, 2002b; Beltrami et al., 2002] has been substantial. However, less emphasis was put on the determination of temporal and spatial variations in the GSTHs. Here we present the results from the analysis of the Canadian geothermal database. The Canadian average GSTH based on the analysis of 246 temperature logs is consistent with other records [Gallett and Skinner, 1992]. The spatial and temporal patterns in ground temperature reveal significant spatial variability in the timing and magnitude of the ground temperature changes in the recent past. We also find that a cold period in the recent past, which might be associated to the “Little Ice Age”, does not appear to be evenly distributed across the country.

1. Introduction

[4] We solve the inverse problem using a singular value decomposition (SVD) method described previously in Mareschal and Beltrami [1992]. The temperature at depth z, \( T(z) \), is the superposition of the quasi-equilibrium temperature and of \( T_L(z) \) the temperature perturbation due to variations in ground surface temperature:

\[
T(z) = T_{ref} + q_{ref} R(z) + T_L(z)
\]

(1)

where \( T_{ref} \) is a reference ground temperature, \( q_{ref} \) is the reference surface heat flow density, \( R(z) \) is the thermal depth,

\[
R(z) = \int_0^z \frac{dz}{\lambda(z)}
\]

(2)

and \( \lambda(z) \) is the thermal conductivity.

[5] The thermal conductivity is usually measured in core samples and/or estimated from the lithology. The inverse problem consists in determining \( T_{ref} \), \( q_{ref} \), and the ground surface temperature history (GSTH) from \( T_L(z) \). The steady state geothermal heat flux can be approximately determined from the deepest part of the profile, least affected by recent surface temperature variations, or it can be retrieved from the inversion. The GSTH can be approximated by a series of step temperature changes.
such that the temperature at depth $z$ is given by

$$T_i(z) = \sum_{k=1}^{K} T_k \left[ \text{erfc} \left( \frac{z}{2 \sqrt{K_d k}} \right) - \text{erfc} \left( \frac{z}{2 \sqrt{K_d (k-1)}} \right) \right]$$  \hspace{1cm} (3)$$

$$T_0(t) = T_k; \ t_k \leq t \leq t_{k+1}, k = 1, \ldots, K; \ t_0 = 0.$$  \hspace{1cm} (4)

Equation (1) is evaluated at each depth where data exist, forming a system of linear equations with $K + 2$ unknowns which is solved by SVD to yield the geothermal steady state heat flux $q_{\text{ref}}$, the surface reference temperature $T_{\text{ref}}$, and a series of $K$ surface temperature model parameters representing the GSTH at the site.

### 3. The Canadian Data Set

[6] The data set includes 246 temperature-depth profiles deeper than 300m that were measured before 2000. Most of these temperature logs were recorded by the Geological Survey of Canada (GSC), formerly the Earth Physics Branch, and by GEOTOP at the University of Québec in Montréal, in collaboration with the Institut de Physique du Globe de Paris (IPGP). Most of the GSC data are included in the compilation by Jessop et al. [1984] and have been filed with the International Heat Flow Commission. We also used data collected throughout the Canadian Shield by IPGP and GEOTOP. These data are described in details in several papers [Rolandone et al., 2002, Mareschal et al. and the references therein, 2000]. The spatial distribution of the sites in the data set is uneven because measurements are carried out in holes of opportunity.

#### 3.1. Results

[7] Each temperature log of the Canadian data set was inverted for the quasi-steady state geothermal heat flux $q_{\text{ref}}$ and the GSTH. The model for each individual inversion consists of a series of twenty average ground surface temperatures over 50-year intervals. The singular value cutoff was set at 0.3 for each GSTH inversion. In order to obtain average GSTH for the area, all inversions of individual temperature-depth profiles must be carried out with the same singular value cutoff if the geometry is the same, or, at least, the number of retained singular value should be the same. Otherwise, the average GSTH is based on individual inversions with different resolutions. This requirement implies that the maximum resolution is determined by the noisiest temperature versus depth profile included in the analysis [Beltrami et al., 1997]. Individual GSTHs were averaged over the whole region. The average GSTH obtained from the 246 temperature logs is shown in Figure 1.

[8] Because spatial and temporal variations of the ground surface temperature are well documented [Beltrami and Mareschal, 1992], the Canada-wide average ground surface temperature history is given only as reference to compare against local records. The Canadian average GSTH shows a marked increase in the energy stored in the shallow subsurface since about 1800. Average ground surface temperature increase between 1800 and 1900 is 0.44 K and 0.71 K since 1900. These values are consistent with the predicted warming due to increased levels of greenhouse gases since the onset of the industrial revolution [Houghton et al., 2001], and are in agreement with the meteorological records collected across Canada in the last 100 years [Gullett and Skinner, 1992].

[9] The collection of panels in Figure 2 shows the spatial variability of the ground surface temperature changes for each 50-year period since 1500 across Canada. Because the resolution of the geothermal records decrease with time, it is impossible to resolve climatic events shorter than 50 years 200 years ago [Beltrami and Mareschal, 1995]. Although the data distribution is uneven, the interpolation algorithm is smooth and preserves the long wavelengths trends. One robust conclusion of this work is that the recent climatic warming is quite variable reaching more than 2 K in some areas.

#### 3.2. “Little Ice Age” Spatial Variations

[10] Some indication of spatial variability of the so called “Little Ice Age” cold period in this temporal sequence is apparent. The recovery of the LIA is clearly visible as well as the onset of the recent warming. Note that the recovery of the LIA is not synchronous across the country and because of these results, the existence of the LIA across all of Canada is now in question. This is a remarkable finding since the global or synchronous existence of the LIA is far from being established. In fact, there is considerable discussion [Jones and Briffa, 2001] regarding the timing of onset, duration, and magnitude of the so called “Little Ice Age” or cold period between years 1200 and 1850 [Grove, 2001; Ogilvie and Jonsson, 2001; Luckman, 1995]. The analysis presented here confirms earlier inferences of the LIA in Canada [Nielsen and Beck, 1989; Beltrami et al., 1992; Beltrami and Mareschal, 1992].

### 4. Discussion and Conclusion

[11] In the SVD inversion for surface temperature history and quasi steady-state geothermal heat flux, data errors are...
amplified for the very small singular values, such that in order to reduce the impact of noise it is usually necessary to eliminate the singular values which are smaller than a cutoff value. Although the choice of cutoff is dependent on the problem in question, the GSTHs obtained by retaining only a few principal components always reproduce the gross features of the real energy balance changes at the ground surface [Menke, 1989]. The largest contribution to the standard error in the estimated model parameters is that of the empirical orthogonal function (EOF) associated with the smallest retained singular value.

Spatial analysis then requires that all temperature profiles must have comparable sampling and depth range and must be inverted with the same parameterization and singular value cutoff [Beltrami et al., 1997]. Although this requirement allows for spatial variability to be estimated, it lowers the resolution since the inversion and thus comparison of GSTH at the large scale will be limited by the results from the noisiest temperature-depth profile.

It appears that the cold period, between 1500 and 1850, prevailed in vast regions of Canada. More interesting, perhaps is the observation that this cold period is not found synchronously across the country.

Figure 2. Temporal variability of the surface ground temperature for 50-year time intervals from year 1500 to 2000. The recovery of the LIA is apparent as well as the onset of the past century’s warming. Note that the recovery and even existence of the LIA is not synchronous across the country.
at all locations and that it did not occur simultaneously in all regions. Detailed records at each of the sites in this study may serve as a constraint for models of the causes of the LIA. Furthermore, geothermal reconstructions complement analyses of proxy data and should allow a fuller investigation of climate change in Canada.

[14] Acknowledgments. This research was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC)(H.B. and J.C.M), and the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)(H.B.).

References


H. Beltrami, Environmental Earth Sciences Laboratory, St. Francis Xavier University, P.O. Box 5000, Antigonish, Nova Scotia, Canada, B2G 2W5. (hugo@stfx.ca)
C. Gosselin and J. C. Mareschal, GEOTOP-UQAM-McGill, Université du Québec à Montréal, C.P. 8888, Succ. Centre-Ville, Montréal, QC, H3C3P8, Canada.

6 - 4 BELTRAMI ET AL.: SPATIAL VARIATION OF SURFACE TEMPERATURE