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# Energy Balance at the Earth's Surface: Heat Flux History in Eastern Canada

Hugo Beltrami

**Department of Geology, St. Francis Xavier University**

Jingfeng Wang and Rafael L. Bras

**Department of Civil and Environmental Engineering, M.I.T.**

**Abstract.** The heat exchange at the air/ground interface is determined by many complex processes making the energy balance at the earth's surface extremely difficult to quantify and model. A new methodology allows heat flux at the Earth's surface to be estimated using ground surface temperature history reconstructed from geothermal data. We found that over a large region in eastern and central Canada, the average heat flux into the ground during the last 1000 years was on the order of 2.8 $\mathrm{mWm^{-2}}$. Our results suggest that significant change in the ground heat flux occurred in the last two centuries. The 200 years averaged heat flux since 1765 is 17.0 $\mathrm{mWm^{-2}}$, while the average heat flux over the latest 100 years is 74.0 $\mathrm{mWm^{-2}}$. The sensitivity of the subsurface to very small energy imbalances makes these type of data and analysis useful complements to the paleoclimatic record; they also provide constrains for general circulation model land-surface parameterization over a wide range of spatial-temporal scales.

## Introduction

Retrieval of long-term surface heat flux is a challenging issue in the study of climate change as energy balance at the land atmosphere interface is critical to the general circulation models (GCMs) simulation of global climate system (e.g. Koster and Suarez, 1992). According to the IPCC report (e.g. Houghton et al., 1990), the contribution of radiative forcing associated with greenhouse gases emission due to anthropogenic activities to the energy balance at the surface should be on the order of 3 W $\mathrm{m^{-2}}$ over the last two centuries. Such a small yet important component in the energy balance of the earth's surface is difficult to measure accurately from meteorological data with conventional means owing to the uncertainties in the measurements of atmospheric variables (Gieger, 1965). On the other hand, geothermal data contain useful information about the signatures of long term climatic scenarios since the Earth behaves as a low pass filter retaining the long-term trends of climate recorded as variations of ground temperature. For example, a temperature change of 1°K in the course of 100-year period is detectable 100 m down into the ground (Lettau, 1951). Several approaches have been developed to reconstruct ground temperature histories from borehole temperature profiles (e.g. Lewis, 1992 and references therein. See Beltrami and Chapman, 1994 for a general introduction to this subject).

In this paper we apply a method proposed by Wang and Bras (1999) to estimate the ground heat flux history using the reconstructed ground surface temperature history (GSTH) from simultaneous inversion of borehole temperature records (Beltrami et al., 1992) over a large region in eastern Canada. Although earlier efforts to reconstruct a paleoclimate record from geothermal data have been successful, reconstruction of ground heat flux histories from GSTH has remained unexplored. Contrary to classic temperature gradient algorithms, this method only requires GSTH at the surface and thermal inertia of rock materials.

## Method

A recently proposed method (Wang and Bras, 1999) will be applied for the estimation of the heat flux history in this study. This method, unlike the traditional approaches that require temperature measured at multiple levels, allows the heat flux to be derived from a time series of temperature measured at a single depth level where heat flux is desired. The rationale behind the new method is that diagnostic relationships can be established between the history of temperature and that of heat flux under rather general initial and boundary conditions assuming that the heat transfer in a one-dimensional column of media is described by

$$\begin{aligned} \frac{\partial T}{\partial t} &= \kappa \frac{\partial^2 T}{\partial z^2} && (1)\\ T &= T_0, \quad \text{for} \quad t = 0, \ z < 0, && (2)\\ T &= T_0, \quad \text{for} \quad t > 0, \ z \to -\infty && (3) \end{aligned}$$

where $T$ is temperature at time $t$ and depth $z$, and $\kappa$ is a constant thermal diffusivity. With the help of fractional calculus (e.g. Miller and Ross, 1993), the vertical gradient of temperature can be related to a weighted average

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(an operator referred to as half-order time derivative) of the time history of temperature at the same spatial location. That is, the heat flux (positive into the ground), $Q(z,t)$, can be expressed in terms of

$$\begin{aligned} Q(z,t) &\equiv \lambda \frac{\partial}{\partial z} T(z,t) \\ &= \lambda \frac{1}{\sqrt{\kappa}} \frac{\partial^{\frac{1}{2}}}{\partial t^{\frac{1}{2}}} [T(z,t) - T_0] \\ &= \sqrt{\frac{\lambda C_0}{\pi}} \frac{d}{dt} \int_0^t \frac{T(z,s)ds}{\sqrt{t-s}} \qquad (4) \end{aligned}$$

where $s$ is the integration variable. The thermal diffusivity $\kappa$ relates to the thermal conductivity $\lambda$ (W $\mathrm{m}^{-1}$ $\mathrm{K}^{-1}$) and the heat capacity $C_0$ (J $\mathrm{m}^{-3}$ $\mathrm{K}^{-1}$) of rock materials through $\kappa = \lambda / C_0$. Note that the derivation of the solution given in (4) does not require boundary conditions at the surface. When a temperature history consists of a series of steps temperature changes, the classic solutions (e.g. Carlslaw and Jaeger, 1959; Lachenbruch et al., 1982) can be retrieved from Eq (4).

We first test Eq (4) in estimating ground heat flux with high resolution soil temperature measurements, and compare it with the heat flux obtained from the conventional gradient method,

$$Q(z,t) = -\lambda \frac{\Delta T}{\Delta z}. \qquad (5)$$

The data for the purpose of testing Eq (4) was from a continuous record of soil temperature over a period of one year (Beltrami, 2000) collected from an experimental air-ground station (45°39'27"N; 61°51'25"W) located in a flat open field in Pomquet, Nova Scotia, Canada. Temperature at six depths of 0, 2.5, 10, 20, 50 and 100 cm were measured using CS107b soil temperature probes with a post-calibration accuracy of ±0.1 K. Surface (skin) temperature (Fig. 1(a)) measured by a probe placed at the surface just below the grass sod to avoid direct radiation will be used in Eq (4) to estimate the ground heat flux. Additional temperature measurements at 2.5 cm depth are needed to compute the ground heat flux using Eq (5).

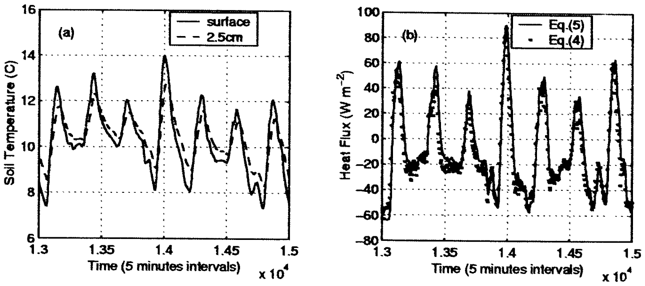

**Figure 1. a.** Soil temperature records at the surface and at 2.5 cm depth. **b.** Heat fluxes estimated using Eq (5) (solid) and using Eq (4) (dotted) from soil surface temperature data shown in (**a**). The time intervals are in units of five minutes from September 1, 1997

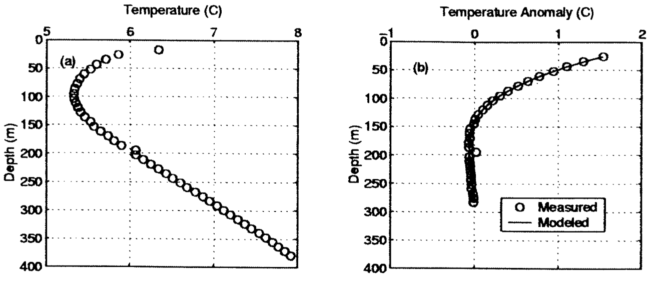

**Figure 2. a** Temperature-depth profile at Belleterre. **b** Temperature anomaly as the difference between steady state and the measured profile.

Figure 1(b) shows the comparison of ground heat fluxes estimated by Eqs (4) and (5) at the Pomquet station site. In general, the heat flux estimated from the new method through Eq (4) agrees well with that from the temperature gradient method through Eq (5).

## Application to Geothermal Data

### Geothermal Data

Borehole geothermal data have been collected at 53 locations within a large region 2000km by 500km in area in southeastern and central Canada (Beltrami et al., 1992). More than 200 depth profiles of borehole temperature were measured using calibrated thermistors with a precision of 2 mK. Thermal conductivity measurements exists for most of the boreholes. For those locations where the thermal conductivity measurements were not available near the surface, it was estimated from the lithological logs. Thermal conductivity data are used to correct temperature-depth data to compensate for subsurface inhomogeneities using a standard Bullard plot (Bullard, 1939)

### Local Heat Flux History

A heat flux history over the last 1000 years was retrieved from the reconstructed ground temperature at a mining exploration borehole drilled in 1985 (Beltrami et al., 1992) near the town of Belleterre (47°24'N,78°43'W) in Quèbec. The mean thermal conductivity was found to be 3.7 W $\mathrm{m}^{-1}$ $\mathrm{K}^{-1}$ with no systematic trend within the borehole. The heat capacity of the rock material is estimated as $3.565 \times 10^6$ J $\mathrm{m}^{-3}$K. The equilibrium profile (Figure 2a) extrapolated from the deeper part of the temperature log yields a surface temperature of 4.05°C, and a temperature gradient of 10.3 mK $\mathrm{m}^{-1}$ near the surface. The temperature anomaly (Figure 2b), defined as the difference between observed and equilibrium temperature profiles, is proportional to the cumulative heat flux into the ground. The vertical profile of the temperature anomaly, depending on the history of

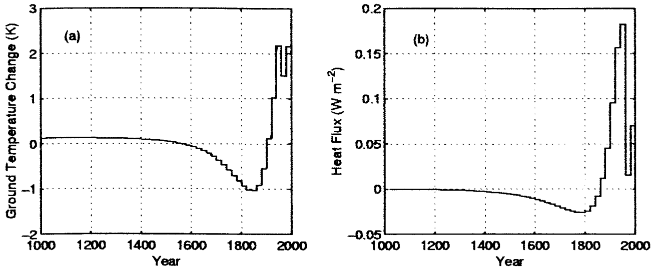

**Figure 3. a.** GSTH at Belleterre, consisting of 50 20-year step temperature changes. **b.** Estimated ground heat flux from the temperature in **(a)** using Eq (4).

energy balance at the surface (see Beltrami et al., 1997 for a description of these data and the inversion procedure), provides a rough estimate of the magnitude of averaged ground heat flux, $\tilde{Q}$,

$$\tilde{Q} = \frac{C_0}{\Delta t} \int_0^{z_{max}} \delta T(z) dz \qquad (6)$$

where $\delta T$ is the temperature anomaly, $\Delta t$ is the time interval, and $z_{max}$ is the maximum depth of temperature profile. The value of $\tilde{Q}$ is found to be 4.6 mW m$^{-2}$ for $\delta T$ given in Figure 2b, $\Delta t$ is 1000 years, and $z_{max}$ is 283 m.

The ground temperature histories (Fig. 3a) for this borehole at Belleterre was reconstructed with Singular Value Decomposition (SVD) inversion model covering the last 1000 years with fifty 20-year equal time intervals. The character of heat conduction implies that the resolution of past ground surface temperature changes from subsurface temperatures decreases in time, as such, GSTH have better resolution in the most recent period. This lack of resolution is also present in the heat flux estimates. A singular-value cutoff of 0.025 was selected to optimize the estimation based on the variance-resolution trade-off criterion (Beltrami et al., 1995). The ground temperature history (Fig. 3a) leads to a ground heat flux history shown in Fig. 3b using Eq (4). The ground heat flux followed the trend of ground temperature change, which reached a minimum around 1830 and has continued to recover ever since. The averaged heat flux over the 1000 years period was found to be $5 \pm 0.8 mWm^{-2}$, consistent with the rough estimate, 4.6 mW m$^{-2}$, according to Eq (6).

## Regional Heat Flux History

Previous studies (Beltrami et al., 1992, 1997) have found that the GSTH records from an ensemble of boreholes over a large region of central and eastern Canada have similar characteristics, suggesting that the region was under the influence of the same climatic conditions during the last few centuries. Efforts to analyze these borehole temperature data have resulted in site-averaged GSTHs (Beltrami et al., 1997). The GSTH's from simultaneous inversion at local or regional scales are more reliable than those from single boreholes since the large sample size tends to reduce the uncertainty of model parameter estimation and improve the stability of the inversion (see Beltrami et al., 1997). The encouraging result of ground heat flux retrieval from a single borehole GSTH suggests that regional ground energy balance history is expected to be derived from the borehole temperature records over an area covering a significant portion of Canada.

Figure 4a shows the (spatial) mean GSTH over a large region in eastern and central Canada from the simultaneous inversion of 21 temperature logs (Beltrami et al., 1992). The magnitude of ground warming in the last 100 years ( $1K$) agrees with the trends indicated from meteorological records ($1.1K$) for the area (Gullett and Skinner, 1992). Figure 4b shows the domain-mean ground heat flux reconstructed from the mean GSTH using Eq (4). The averaged heat flux into the ground for this case is $2.8 \pm 0.06 mWm^{-2}$ over the last 1000 years. A significant change in the flux occurred in the last two centuries. The magnitude of the mean ground heat flux is $17 \pm 0.06 mWm^{-2}$ since 1765 AD, and $74 \pm 0.06 mWm^{-2}$ over the latest 100 years in the eastern Canada.

The cold period between 1500 and 1800 A.D. indicated by a negative temperature anomaly (Fig. 3a and 4a) has been identified as the Little Ice Age (LIA) (Beltrami *et al.*, 1992). The estimated ground heat fluxes (Fig. 4b and 4b) are consistent with the LIA during which the warmer ground released heat into the colder atmosphere. We notice that the warming trend since 1800 A.D. in the ground heat flux history is correlated closely with historical $CO_2$ record. The ice core data (e.g. Etheridge *et al.*, 1996) show that the atmospheric $CO_2$ concentration started to increase from around 1800 A.D. This fact further supports the argument that change in atmospheric $CO_2$ concentration affects the surface energy balance or vice versa, presumably through radiative processes. The preliminary results presented here seem to suggest that the warming trend in the climate (whatever cause it is) since the end of the LIA around 1800 A.D. could be partially responsible for the global warming in this century, as augued

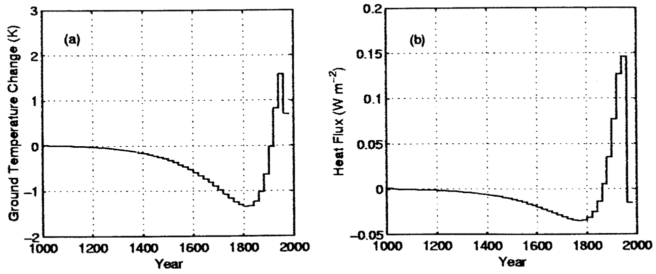

**Figure 4. a** GSTH from simultaneous inversion of 21 temperature profiles in eastern Canada. **b.** Estimated ground heat flux from **(a)** using Eq (4) Average error estimates for heat flux are $\pm 0.06 mWm^{-2}$.

by many. The release of $CO_2$ by burning fossil fuel may strengthen the global warming that has already been existing regardless anthropogenic activities. Certainly, more research needs to be done to arrive at a definite conclusion.

## Summary and Discussion

Ground heat flux histories were reconstructed from borehole ground temperature records for the last 1000 years over a large region in Canada using the half-order time derivative method. The (time) mean ground heat flux at a single borehole location, 5 mW $m^{-2}$, is in close agreement with 4.6 mW $m^{-2}$ obtained from the heat balance relationship. The method also produces a reasonable estimate of the regional ground heat flux history from the regional ground temperature history averaged over a number of borehole measurements. The results suggest that the method is potentially applicable to greater spatial scales using, for instance, the global geothermal data set currently being assembled by the International Heat Flow Commission (Pollack et al., 1998), to reconstruct global ground heat flux history. The analysis presented here is not only essential in assessing the long-term energy balance at the Earth's surface, but also valuable in detecting and modeling regional and global climate change over a wide range of time scales. These results have immediate implications on the study of the impact of increasing emission of greenhouse gases due to anthropogenic activities on the radiation budget at the earth's surface (Houghton et al., 1990). Heat fluxes determined from geothermal data are most sensitive to the change in energy balance at the land atmosphere interface in the last 300 years (Beltrami and Mareschal, 1995). This is the time window when radiative forcing for the climate might have been affected by human activities. At present grid resolutions of GCM's ( 300 x 300 km), regional heat flux averages from geothermal data may also be well suited to constrain the dominant features of surface process parameterization in the "big leaf" type of models (Koster and Suarez, 1992; Henderson-Sellers and Pitman, 1992)

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Hugo Beltrami, Department of Geology, St. Francis Xavier University, P.O. Box 5000, Antigonish, Nova Scotia, Canada, B2G 2W5. email: hugo@stfx.ca

Jingfeng Wang and Rafael L. Bras, Department of Civil and Environmental Engineering, M.I.T.,Cambridge, MA 02139, U.S.A.

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