Global Ground Surface and Heat Flux Histories from Geothermal Measurements: Inferences from Inversion of the Global Data Set

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Abstract

Past changes in the Earth's surface energy balance propagate into the subsurface and appear as perturbations of the subsurface thermal regime. Here I present results from a singular value decomposition (SVD) inversion method used to reconstruct surface heat flux histories (SHFH) and ground surface temperature histories (GSTH) from the heat flux and temperature anomalies detected in the shallow subsurface. Results from the analysis of Canada's geothermal database indicate that the ground heat flux has increased an average of 24 mW/m2 over the last 200 years. Application of this method to the global geothermal data base allowed for a quantification of the global ground energy balance at the Earth's surface for the past few centuries. Preliminary global ground surface temperature and surface heat flux histories indicate that the Earth's continents have warmed by about 0.5 K and received an additional 26 mW/m2 of energy in the last 100 years.

1 Introduction

The Earth's long-term surface heat flux is important in the study of climate change as energy balance variation at the land atmosphere interface is a fundamental quantity to help determine changes in radiative forcing and for constraining land surface models [1]. The total contribution of radiative forcing associated with greenhouse gas emissions from anthropogenic activities to the energy balance at the Earth's surface is estimated to be about 2.0-2.5 W m^{-2} since 1765 [2]. About one third of this forcing is direct radiative heating of the surface, and about 10 % of this flows into the ground [3]. This forcing is spatially and temporally variable and regional variations are expected. This small yet important component in the energy balance of the Earth's surface is difficult to measure accurately from meteorological data in both space and time, owing to the uncertainties in the measurements of atmospheric variables [4], and also because of the complex and complicated processes taking place at the air-ground interface [5]. Geothermal data, on the other hand, contain useful information about the signatures of long term energy balance variations. The Earth behaves as a low pass filter, retaining the long-term trends of surface energy imbalance recorded as variations of underground temperature and heat fluxes. For example, daily and annual temperature variations are detectable to depths of about 1 m and 20 m respectively; a temperature change of 1 K in the course of a 100-year period is detectable about 100 m into the subsurface. Several approaches have been developed to reconstruct ground surface temperature histories (GSTH) from borehole temperature profiles [6]. In the last decade, it has been learned that small changes in the energy balance at the earth's surface are reflected in geothermal records as long as the underlying physical processes are sustained and that it is possible to resolve the temporal evolution of the energy balance at the surface.

Although there is considerable work on the determination of ground surface temperature histories from geothermal data [6], the extraction of temporal and spatial surface heat flux variations from these data has remained unexplored. Beltrami et al. (2000)[7] presented the first attempt to estimate fluxes from existing GSTHs using an integral approximation derived using fractional Calculus and recently presented a preliminary inversion of subsurface heat flux anomalies [8]. Here I use SVD inversion to retrieve the heat flux history from temperature-depth profiles and simultaneously the quasi steady-state geothermal heat flow density. This inversion procedure allows full borehole temperature logs to be analyzed directly. When inverting temperature perturbation profiles, solutions are consistent with heat-flux history estimates as reconstructed by a discrete analytical approximation [7]. The methodology is used to obtain an average surface heat flux history (SHFH) for Canada, based on 112 temperature logs. Application of this method to reconstruct SHFH using a data sets at a global scale [9] shows that the Earth's surface has gained heat since about 1600. These result are consistent with other climatic records [11, 10].

1.1 Canadian Data Set

A heat flux inversion [8] was applied to 112 temperature logs across the country [13, 6]. Each temperature log was inverted individually, for the quasi steady-state geothermal heat flux and for the SHFH. The model for each individual inversion consists of a series of twenty 50-year step changes in surface heat flux. The eigenvalue cutoff was set at 0.1 for each inversion [13]. From each temperature log, a flux anomaly profile was generated using the mean the thermal conductivity for each of these sites.

Because the data were acquire in holes of opportunity, the spatial distribution of the sites is uneven. Thus, individual SHFHs were then averaged over the whole region. This average SHFH from 112 temperature logs is shown in Fig. 1a. Figure 1b shows the GSTH for the region obtained in a similar fashion from the same data attempting to maintain a parameterization between SHFH and GSTH inversions as close as possible (but not identical[8]). GSTH and SHFH for Canada show a marked increase in the energy stored by the ground since about 1800, consistent with the expectations due to increase levels of greenhouse gases since the onset of the industrial revolution [2]. Average heat flux into the ground (positive here) since 1765 is 23.5 mWm^{-2} and 37.7 mWm^{-2} for the last 100 years.

Spatial and temporal variations of the ground surface temperature in Canada are well documented [13], thus this average heat flux history for Canada should be considered with caution. A report with detailed analysis, results for regional variations and comparison with proxy data in Canada is in preparation.

1.2 Global Data Set

The global data set consists of 616 temperature-depth profiles in all continental areas ([9]. Figure 2 shows the global average heat flux history for the inversion of all data obtained from this analysis.

2 Conclusions

Application of this inversion to all temperature depth profiles in eastern Canada yielded a heat flux history for the last 1000 years. The heat flux since 1765 is 23.5 mWm^{-2} and 37.7 mWm^{-2} for the last 100 years. Application of this method to the analysis of the global data set [9, 6] yields an estimate of the global energy balance at the Earth's surface in its recent past. Inferred energy gained by the ground amount to 17 mWm^{-2} and 32 mWm^{-2} during the last 200 and 50 years respectively.

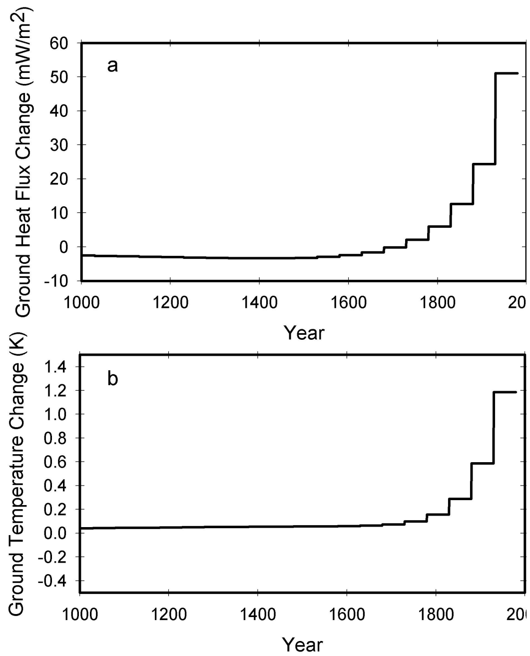

Figure 1: Heat flux (a) and Ground temperature (b) Histories in Canada inferred from geothermal data. One hundred and twelve temperature logs were used in calculation. Standard error of the model parameters are included within the lines shown.

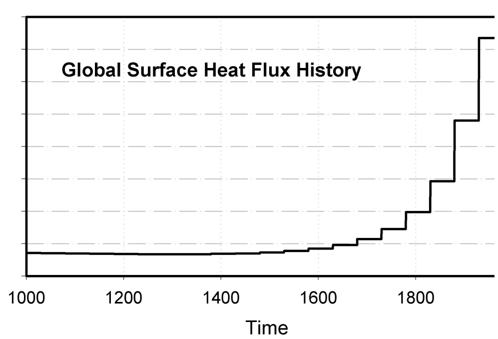

Figure 2: Global Heat Flux History inferred from geothermal data. Six hundred and sixteen temperature logs were used to calculate this average. Standard error of the model parameters are included within the line shown.

Acknowledgments

Discussions with H. Pollack, R. N. Harris and V. Cermak and I. Kukkonen are appreciated. This research was funded by The Natural Sciences and Engineering Research Council of Canada (NSERC)and sponsored by IGCP 428.

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