

Spatial patterns of ground heat gain in the Northern Hemisphere

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[1] Variations in the Earth's surface energy balance are recorded in the subsurface as perturbations of the steady state thermal field. Here we invert 558 temperature-depth profiles in the Northern Hemisphere (NH), in order to estimate the energy balance history at the continental surface from heat flux anomalies in the subsurface. The heat gain is spatially variable and does not appear to have been persistent for the last 200 years at all locations, but overall continental areas have absorbed energy in the last 50 years. Results indicate a mean surface heat flux of 20.6 mWm^{-2} over the last 200 years. The total heat absorbed by the ground is $4.8 \times 10^{21} \text{ J}$ and $13.3 \times 10^{21} \text{ J}$ for the last 50 and 200 years respectively. We suggest that our results may be useful for state-of-the-art General Circulation Model (GCM) validation and for land-surface coupling schemes. **Citation:** Beltrami, H., E. Boulton, L. Kellman, and J. F. González-Rouco (2006), Spatial patterns of ground heat gain in the Northern Hemisphere, *Geophys. Res. Lett.*, 33, L06717, doi:10.1029/2006GL025676.

1. Introduction

[2] The energy balance and its variation at the Earth's surface is important to help determine changes in radiative forcing, climate systems energy budgets, and for constraining climate and land surface models [Delworth and Knutson, 2000]. The radiative forcing associated with anthropogenic greenhouse gas emissions to the Earth's energy balance is about $2.0\text{--}2.5 \text{ W m}^{-2}$ since 1780 [Intergovernmental Panel on Climate Change (IPCC), 2001]. Approximately one third of this forcing goes to heating the surface; about 10% of this flows into the ground [Sellers, 1995]. The ground component of the energy balance of the Earth's surface is relatively small and difficult to measure due to uncertainties in the measurements of atmospheric variables, and also because of several processes taking place near the air-ground interface. However, recent analysis of the underground temperature field indicated that continents have absorbed as much energy as the whole atmosphere in the last 50 years [Levitus et al., 2001; Beltrami et al., 2002; Levitus et al., 2005].

[3] The underground temperature field at shallow depths is a direct response of the ground to past surface temperatures [Pollack and Huang, 2000, and references therein], in contrast to the analysis of other climate proxies, that are modelled as climate anomalies through the fitting of nu-

merical functions [Briffa and Osborn, 2002]. Because of heat diffusion underground, borehole temperature (BT) data yield robust information on long-term temperature trends. Although, as in the case of other methods for paleoclimatic inferences, BT based reconstructions have uncertainties.

[4] Recent attempts to reconstruct surface temperature variation for the last millennium using a variety of proxy data, have generated much controversy and have stimulated a large body of recent work. Within this debate, BT reconstructions tend to be much colder than some reconstructions based on tree-ring data or multiproxy data sets [Briffa and Osborn, 2002; Jones and Mann, 2004; Pollack and Smerdon, 2004; Beltrami and Boulton, 2004]. This initial discrepancy has raised concern about potential biases produced by changes in land-use, vegetation and snow cover among others, as factors that can affect the SAT and soil temperature coupling and may distort temperature reconstructions based on BT profiles [Mann and Schmidt, 2003; Mann et al., 2003; González-Rouco et al., 2003, 2006; Pollack and Smerdon, 2004; Chapman et al., 2004; Nitoiu and Beltrami, 2005]. In addition to BT reconstructions, new approaches aimed at preserving low-frequency information in tree-ring chronologies have recently provided comparable degrees of cooling in pre-industrial times [Esper et al., 2002, 2004; Moberg et al., 2005; Beltrami et al., 2005; Harris and Chapman, 2001; Harris and Chapman, 2005] lending support to the results obtained with BT profiles. The topic is still open for debate and though much progress has been made, considerable uncertainties hamper our understanding of the amplitude of temperature variations through the last millennium.

[5] Independent of this discussion and the uncertainties that affect BT profiles as a source of information for past SAT trends, subsurface temperatures record past changes in the energy budget at the surface of the ground. Whether related to climate or to other physical changes at the surface, subsurface temperature variations with depth record a history of heat storage and loss with time which can be used to analyse the contribution of continental areas to the Earth's energy balance [Levitus et al., 2005].

[6] In this note, we report on the results of the analysis of the NH borehole data set of 588 temperature-depth profiles, in order to estimate for the first time, the spatial variation of the ground surface energy balance during the last 200 years. We find that the ground heat flux in the NH has increased an average of 20.6 mWm^{-2} over the last 200 years. In the last 50 years the mean flux has been 29.6 mWm^{-2} implying that the NH continental surface has absorbed $4.8 \times 10^{21} \text{ J}$. This quantity of energy is of similar magnitude to that of the heat absorbed by the whole atmosphere ($6.6 \times 10^{21} \text{ J}$) and to that absorbed by all continental areas (except Antarctica) ($8.0 \cdot 10^{21} \text{ J}$) for the same time period [Levitus et al., 2001; Beltrami et al., 2002; Beltrami, 2002; Levitus et al., 2005].

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[7] This work contributes a step forward in the context of recent advances in Earth's energy balance [Levitus *et al.*, 2005; Hansen *et al.*, 2005] through updating quantities relating to continental heat storage and picturing the spatial distribution of these numbers for the NH. Results should be meaningful also in the context of climate model development, since evaluation of the ground surface heat flux variations from borehole data may prove useful for discriminating between different model schemes and parameterizations, which can be improved with information of realistic evaluations ground heat flux. This could be important since small differences between model parameterizations may lead to large differences in model results [Takayabu *et al.*, 2001].

2. Analysis and Data

[8] In the Earth, the heat flux at any depth is given by the addition of the quasi steady state geothermal heat flux, q_{eq} and the transient component, that is:

$$q(z, t) = q_{eq} + \Delta q_0(z, t) \quad (1)$$

[9] The surface heat flux history can be approximated by a series of step heat flux changes at the surface [Beltrami *et al.*, 1997]. Geothermal data are acquired as temperature-depth profiles such that it is possible to calculate the heat flux at each depth and the steady state geothermal heat flux can also be determined from the deepest part of the profile least affected by recent surface temperature variations. Then, under these conditions, subtracting q_{eq} , the heat flux anomaly at depth z and for thermal diffusivity κ , is given by:

$$\Delta q_t(z) = \sum_{k=1}^K q_k \left(\operatorname{erfc} \left(\frac{z}{2\sqrt{\kappa t_k}} \right) - \operatorname{erfc} \left(\frac{z}{2\sqrt{\kappa t_{k-1}}} \right) \right) \quad (2)$$

where equation (2) forms a system of linear equations in k unknowns when evaluated at each data depth. We solve by SVD inversion to retrieve a series of surface heat flux model parameters representing the surface heat flux history at the site [Beltrami, 2001, 2002].

[10] Figure 1 shows the set of BT anomaly data used in this study. The departures from the steady state situation are represented in this figure as departures from zero anomaly. Positive and negative departures represent ground heat gain

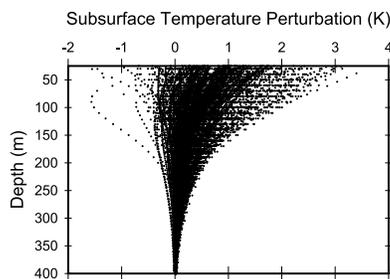


Figure 1. Subsurface temperature perturbations used in the determination of the long-term ground surface energy balance.

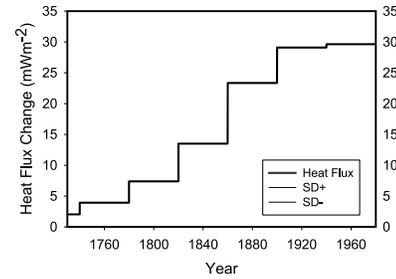


Figure 2. Mean surface heat flux history obtained from the NH subsurface heat flux anomalies. The dotted lines show the standard error of the estimated model parameters.

and loss, respectively. To avoid giving excessive weight to areas containing a large number of data, we used a gridding procedure. We filtered the data on a $5^\circ \times 5^\circ$ cell grid. A block average method was applied to compute a mean location and the L2 norm average Δt value in each cell. This is to suppress redundant data and avoid spatial aliasing [Smith and Wessel, 1990].

[11] Rather than a simple arithmetic average, we estimated the continental NH mean flux using a kilometric gridding, thus, cells are of the same size and no area-weighting is required. These sizes were chosen to avoid single borehole cells, and to have a density as uniform as possible. Grid size effects, however, are not important in the determination of the NH average [Pollack and Smerdon, 2004]. In addition, [González-Rouco *et al.*, 2006] have shown, using a comprehensive numerical experiment, that the spatial distribution of present day borehole data and their sampling frequency between 30° and 60°N yields a very good representation of the complete NH past climatic conditions.

3. Results

[12] Figure 2 shows the NH average heat flux history evaluated from all available temperature profiles shown in Figure 1. Although there are significant variations at regional scales, the average reveals an increasing trend in heat flowing underground in the recent past. The mean flux for the 1780–1980 period is of the order of 20.6 mWm^{-2} , while during the 1930 to 1980 period the estimate is 29.6 mWm^{-2} ; that is the NH continental surface has absorbed $4.8 \times 10^{21} \text{ J}$. The cumulative heat flux absorbed by the ground since industrialization is about 103 mWm^{-2} . This is about what is expected from the additional forcing due to industrial activities [IPCC, 2001]. The total heat absorbed by the continental areas of the NH since industrialization was estimated as $13.2 \times 10^{21} \text{ J}$. 36% of this heat gain occurred in the last 50 years of the 20th century. This amount of heat is of the same order of magnitude than previous estimates of the heat absorbed by the whole atmosphere ($6.6 \times 10^{21} \text{ J}$) and that gained by all continental areas (except Antarctica) ($7.0\text{--}9.0 \cdot 10^{21} \text{ J}$) for the last 50 year period of the 20th century based on measurements, analytical approximations and inversion methods [Levitus *et al.*, 2001; Beltrami *et al.*, 2002; Beltrami, 2002; Levitus *et al.*, 2005].

[13] Figures 3a and 3b display the spatial variability of the heat flux at the Earth's surface for 1930 to 1980 and the cumulative heat flux for the 1780 to 1980 period. Figure 3a

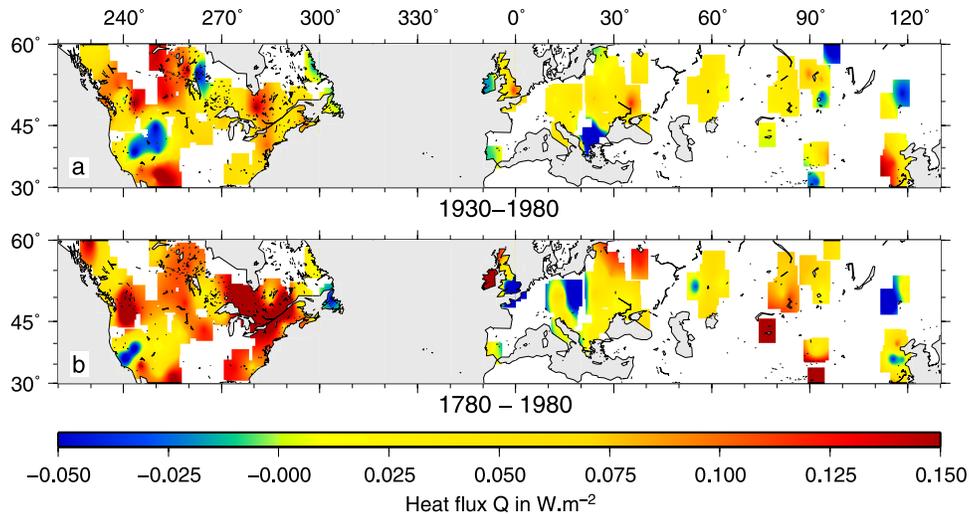


Figure 3. Spatial variation of the estimated ground surface heat flux. (a) Surface heat flux history for the 1930 to 1980 period. (b) Cumulative ground heat flux for a 200 year period from 1780 until 1980. This time interval would include most of the time since industrialization.

shows higher spatial variability at smaller scales over 50 years, but Figure 3b shows sustained heat gain trends over larger areas of the NH, with the most prominent areas showing the largest ground heat gain located in parts of inner continental North America. Areas in the eastern most coast of Canada, mainly Newfoundland, show signs of overall heat loss over the 1780–1980 period. Most of the heat loss observed in the midwest of N. America, is due to cooling between 1930 and 1980. Cooling observed at isolated locations in Asia should be interpreted with caution since they arise from the analysis of isolated BT data.

4. Discussion

[14] BT profiles exhibit significant variability (see Figure 1), not always fully explainable by climatic variation. The variability is sometimes the result of non-climatic influences such as deforestation, groundwater flow, etc., even after careful screening is carried out for such perturbations. The average perturbation, however, recovers the recent climatic change as recorded by meteorological data [Beltrami *et al.*, 2005; Harris and Chapman, 2005]. Nonetheless, our present calculations of the ground heat flux and heat content, do not depend on any of these surface effects, but are evaluated from the actual subsurface thermal regime and represent a real and robust measure of energy storage and energy balance at the Earth's surface.

[15] The spatial distribution of heat flux accumulated over the last 50 years and further back in the past 200 years shows considerable variability, the causes for which still remain uncertain. There are several reasons which, we can speculate, can contribute to this non uniform character of accumulated heat in the ground. Firstly, atmospheric dynamics play a role in shaping regional positive and negative surface temperature changes which translate to fluxes into or out of the subsurface. In the context of any change in the energy budget, the system can respond with changes in the main modes of circulation which would have effects on

the regional level [Zorita *et al.*, 2005]. Additionally, decadal variability in surface processes like vegetation or snow cover would be able to produce local to regional changes and decoupling between surface air temperature and ground surface temperature in the heat budget storage which would not necessarily relate to climate mechanisms. Recent results in large continental areas do not seem to support this possibility [Hu and Feng, 2005] but further work needs to be done. Finally, aerosol cooling can potentially produce regional cooling in areas of relevant aerosol load as discussed by Levitus *et al.* [2005].

[16] Determining the energy balance at the Earth's surface is important because of the potential incorporation of this information in climate and land-surface models [Koster and Suarez, 1992; González-Rouco *et al.*, 2006], and also because our results respond to recent calls for careful monitoring of key metrics for the planetary energy imbalance [Hansen *et al.*, 2005] to confirm that the present energy imbalance is not a fluctuation but, as recorded in the subsurface of the continental areas and shown here, appears to be a sustained effect.

[17] State of the art GCMs should yield similar values of heat fluxes over continental areas in simulations of the recent climate [Zorita *et al.*, 2005; Levitus *et al.*, 2005]. A realistic representation of the ground in terms of heat fluxes and capacity for heat storage is desirable in state-of-the-art climate models. Otherwise a quantity of heat of nearly identical magnitude to that of the heat absorbed by the atmosphere may remain poorly accounted for in the global energy balance, at the risk of making additional energy available for atmospheric dynamics, rather than being stored in the ground. The role of the ground in storing heat could be of relevance in climate change scenario simulations for which typically relatively shallow soil models (ca. 10 m) are used. The use of such thin models could lead to simulate accumulations of heat in the uppermost meters of the ground instead of distributing it to more realistic depths. As an illustration, the total heat storage which the upper

100 m of the N H crust can host for a 1 K long-term change at the surface (a very conservative amount in the pool of IPCC estimates) is four orders of magnitude higher than the numbers provided in this manuscript.

5. Conclusions

[18] Estimates of the energy balance at the Earth's surface were made for a series of 50-year average intervals for the NH. We find that, although there is a significant increase in surface heat flux from 1930 to 1980, the energy gain is not homogeneous but exhibits high variability. The energy imbalance estimated here does not appear to be a fluctuation [Hansen et al., 2005], but it appears recorded in the subsurface of the continental areas as a sustained effect. Results of this work could stimulate the inclusion of surface heat fluxes in GCMs and land surface models for a better representation of the components of the surface energy balance.

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