

1851–2004 annual heat budget of the continental landmasses

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[1] Changing climate is accompanied by changing energy in various climate system components including the continental landmasses. When the temperature at ground surface rises, more heat will be deposited to the rocks beneath the ground subsurface, whereas when ground surface temperature falls, certain amount of heat will escape from the ground into the atmosphere. Based on the land-only global meteorological record, I analyze the annual heat budget of the world continents except for Antarctica. I show that between the period from 1851 to 2000 a total of 10.4 ZJ (Zetta-Joules or 10^{21} J) of thermal energy had been absorbed by Africa, Asia, Australia, Europe, North America, and South America landmasses. An additional 1.34 ZJ of heat has been stored beneath the ground surface of these continents over the first four years of the 21st century from 2001 to 2004. The recent global climate change has led to an intensified heating in the continental landmasses. **Citation:** Huang, S. (2006), 1851–2004 annual heat budget of the continental landmasses, *Geophys. Res. Lett.*, 33, L04707, doi:10.1029/2005GL025300.

1. Introduction

[2] The climate system of Earth is a dynamic system encompassing interactions among atmosphere, hydrosphere, lithosphere, biosphere, and cryosphere [Karl and Trenberth, 2003; Kiehl and Trenberth, 1997]. Understanding the energy budget of various climate components is of fundamental importance to our ability to predict future climate [Hansen et al., 2005; Meehl et al., 2005; Trenberth and Stepaniak, 2004; Wigley, 2005]. Oceans, atmosphere, and continental landmasses are three major reservoirs of heat in the energy budget of the climate system. Several efforts [Barnett et al., 2005, 2001; Beltrami, 2002; Beltrami et al., 2002; Fukasawa et al., 2004; Levitus et al., 2005, 2001] have been devoted to detect and attribute the heat content changes of these three climate system components, with a focus on the last half century or so. Levitus et al. [2005] recently offered the yearly heat content of world oceans for the period from 1955 to 2003. Based on the global database of borehole temperatures [Huang et al., 2000], previous geothermal studies [Beltrami, 2002; Beltrami et al., 2002] provide estimates of global continental heat content change at a 50-year temporal resolution. Here I estimate the annual heat budget of the continental landmasses over the period from 1851 to 2004 for Asia, Europe, North America, Africa, Australia, and South America.

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2. Method

[3] The heat content (thermal energy) of a substance is proportional to its temperature. The temperature and, therefore, the heat content of the uppermost layer of Earth's crust are influenced in part by the ground surface temperature variation which is ultimately determined by the solar energy flux the ground received, and in part by the flow of heat outward from the interior of the Earth, called terrestrial heat flow. The mean terrestrial heat flow [Pollack et al., 1993] over world-wide continental areas is about $65 \cdot 10^{-3} \text{ W/m}^2$, which is four orders smaller than the average solar energy flux at the ground surface [Lean, 2005]. Moreover, variation in terrestrial heat flow is significant only on a million-year time scale, whereas the temperature and solar energy flux at the ground surface change continuously all the time. Therefore, on annual to centennial time scales, the change of the heat content of the continental landmasses is controlled by the temperature at the ground surface.

[4] The heat flux at the ground surface is a state variable depending on the history of the surface temperature variation. If the ground surface temperature T changes with time t in the following fashion

$$T(t) = Ct^{k/2}, \quad (1)$$

where C is a constant and k is a positive integer, the ground surface heat flux function $q(t)$ can be described [Carslaw and Jaeger, 1959; Lachenbruch et al., 1982] as

$$q(t) = \frac{\Gamma(\frac{1}{2}k + 1)}{\Gamma(\frac{1}{2}k + \frac{1}{2})} \cdot \frac{\lambda}{\sqrt{\alpha \cdot t}} \cdot T(t), \quad (2)$$

where $\Gamma(x)$ is the gamma function of x ; λ and α are the thermal conductivity and thermal diffusivity of the rocks, respectively. Given an annual ground surface temperature anomaly time series (T_i , $i = 1, 2, \dots, n$) in the form of a series of ramps (i.e., $k = 2$ in equation (1) for each time step), the surface heat flux time series (q_i , $i = 1, 2, \dots, n$) can be estimated [Beltrami et al., 2002; Wang and Bras, 1998] by

$$q_i = \frac{2\lambda}{\sqrt{\pi \cdot \alpha \cdot \Delta t}} \sum_{j=1}^i [T_{j-1} - T_j] \cdot [\sqrt{i - (j-1)} - \sqrt{i-j}], \quad (3)$$

where Δt is one year. For a continental landmass of surface area A , the heat content change ΔQ over the period from the m th year to n th year would be

$$\Delta Q = \sum_{i=m}^n q_i \cdot A \cdot \Delta t. \quad (4)$$

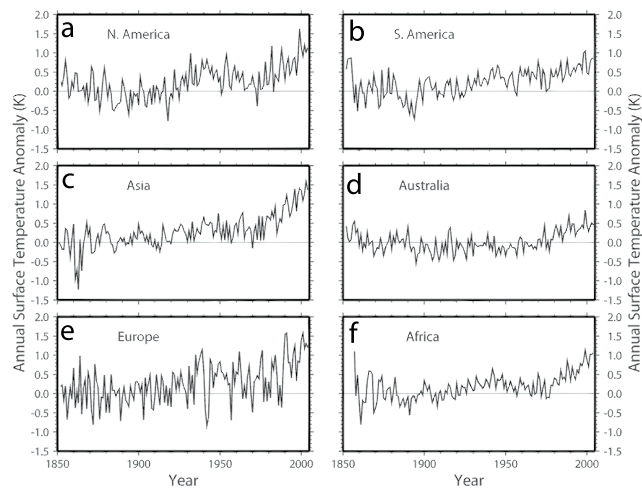


Figure 1. Annual time series of land surface air temperature anomaly assembled from the $5^\circ \times 5^\circ$ grid-box basis land-only temperature anomaly data set of the Climate Research Unit of the University of East Anglia. The temperature anomalies are referred to the pre-1900 mean of individual continental ensembles.

A similar method has been applied in the case studies of surface energy balance [Fitzmaurice *et al.*, 2004; Wang and Bras, 1998, 2001].

[5] In this study, I approximate the ground surface temperature anomaly with the instrumental record of the surface air temperature anomaly. Based on global climate modeling, a recent study [Mann and Schmidt, 2003] initially suggested that air and ground surface temperatures might be decoupled at regional scales due to snow cover. But a revisit [Chapman *et al.*, 2004; Schmidt and Mann, 2004] of the model shows that the original study [Mann and Schmidt, 2003] is indeed a confirmation of a good air and ground temperature coupling. Although the ground is usually warmer than the air above it, and there might be some phase shift in the diurnal and seasonal variations due to the insulation effect of land covers, observational studies and numerical modeling [Bartlett *et al.*, 2004; Chapman *et al.*, 2004; González-Rouco *et al.*, 2003; Smerdon *et al.*, 2004] show that ground surface temperature tracks the surface air temperature variation very well at annual and longer temporal scales.

3. Surface Temperature Data

[6] I assemble continental surface temperature anomaly time series from the variance adjusted version of the $5^\circ \times 5^\circ$ grid-box basis land-only air temperature anomaly data set of the Climate Research Unit (CRU) of the University of East Anglia [Jones and Moberg, 2003]. I take an area-weighting approach when averaging the annual $5^\circ \times 5^\circ$ grid-box means for the continent-wide temperature time series for Africa, Asia, Australia/Oceania, Europe, North America, and South America. All the continental annual time series except for Africa span the period from 1851 to 2004 (Figure 1). The African time series starts in 1856.

[7] There are very limited long-term meteorological records available in Antarctica [Jones and Moberg, 2003].

Additionally, the Antarctica landmass is widely covered by glacier where thermal energy storage is governed by different processes [Jeffries *et al.*, 1999] with different thermo-physical properties. Therefore, Antarctica is excluded from the heat content analysis of this study.

4. Results

[8] The ensembles of the meteorological records show that North America and South America share some common features in their surface temperature histories, with a late 19th century cooling and a two-phase warming in the 20th century (Figures 1a and 1b). But there are important differences in the detailed development of climate change over these two continents. Between the two 20th-century warming phases, there was a cooling period which is much more substantial in North America than in South America. The heat gains of the North America and South America landmasses are, respectively, 2.12 and 1.33×10^{21} J over the past 154 years (see Figure 2 and Table 1).

[9] Asia holds the largest continental heat gain over the last one and a half centuries. Despite an abrupt cooling of 1.5 K in the early 1860s which resulted in a substantial heat loss over a short period, there is a progressive and accelerated long-term warming trend over the record period. Not only is Asia the largest continent in terms of area, but it also experienced the greatest warming. The heat gain of Asia over the past 154 years sums up to 4.94×10^{21} J, more than double the heat gain of Africa, the next largest heat gainer among the six continents.

[10] Both Asian and African surface air temperature series suggest an abrupt cooling event around the early 1860s. However, little can be found in the climate research literature regarding any dramatic temperature change around 1860s in these two regions. It remains yet to be further investigated whether this is a significant climate event deserving more attention or whether this is just an artifact resulted from some unrepresentative records in the

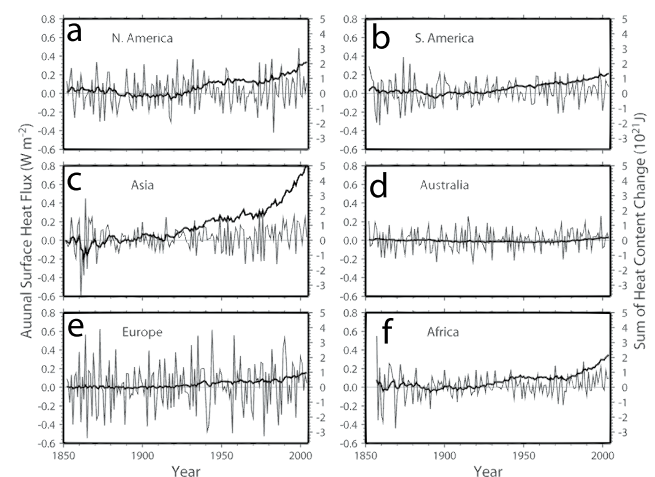


Figure 2. Annual time series of ground surface heat flux (thin line, left vertical scale) and cumulative heat content change (thick line, right vertical scale) for (a) North America, (b) South America, (c) Asia, (d) Australia/Oceania, (e) Europe, and (f) Africa. The thermal conductivity and thermal diffusivity are respectively taken to be 2.5 W/mK and 1.0×10^{-6} m²/s [Clauser and Huenges, 1995].

Table 1. Heat Content Changes of the Continental Landmasses^a

Continent	1851–1900	1901–1950	1951–2000	1901–2000	1851–2000	1851–2004
Asia	0.419	1.054	2.942	3.996	4.415	4.939
Africa	0.070	0.649	1.136	1.785	1.855	2.180
N. America	−0.250	1.006	1.168	2.174	1.924	2.120
S. America	−0.066	0.527	0.720	1.247	1.181	1.331
Europe	0.044	0.357	0.448	0.805	0.849	0.975
Australia	−0.052	−0.086	0.307	0.221	0.169	0.188
Sum	0.165	3.507	6.721	10.228	10.393	11.733

^aUnits measured in 10^{21} J.

global database. The more remote back in time, the fewer meteorological records are available in the CRU database, and the greater the uncertainty of a regional mean is [Jones and Moberg, 2003].

[11] The smallest cumulative change in the heat content over the 1851–2004 period is estimated for Australia. Meteorological record shows a long-term weak cooling trend followed by a moderate warming starting in the 1960s. Consequently, there was a small degree of long-term lithosphere cooling followed by a less than a half century of moderate lithosphere warming. Over the past one and a half centuries, the Australian landmass nearly made an even in its thermal energy budget. The cumulative change is a small net heat content gain of 0.19×10^{21} J.

[12] Among the six continents covered by this study, Europe demonstrates the greatest amplitude in the temperature and heat flux variations on annual to decadal time scales (Figure 1e). However, because of its relatively small size, the overall heat content change of Europe is moderate, 0.98×10^{21} J for the period between 1851 and 2004. Although the accumulative surface temperature change is significantly greater in Europe than in Africa, over the past one and a half centuries the heat gain of European landmass is less than half of that of the African landmass.

[13] Despite the regional variability in the continental surface air temperature, all six continents demonstrate a strong warming trend in the second half of the 20th century. With no exception, the mean 1951–2000 surface heat fluxes in all six continents are positive (Figure 3), indicating gains in heat content of the landmasses. The positive half-century heat flux in the Eurasia super continent extended through the entire one and a half century period. Africa, North America, South America, and Australia experienced moderate heat loss over the second half of the 19th century. The early heat loss extended into the first half of the 20th century in the Australian continent.

5. Conclusions and Discussions

[14] The analysis of the meteorological records shows that over the past 154 years from 1851 to 2004, the continental landmasses of Africa, Asia, Australia, Europe, North America, and South America had stored 11.7×10^{21} J of thermal energy with respect to the mean temperature of the second half of the 19th century. The heat content change of the six continents is 6.7×10^{21} J over the second half of the 20th century and 10.2×10^{21} J over the entire 20th century, respectively (Table 1). The recent global climate change has led to an intensified heating in the continental landmasses. In just four years from 2001 to

2004, there had been another 1.34×10^{21} J of thermal energy trapped beneath the ground surface of these continents.

[15] The current estimate of the would-wide continental heat content change is smaller than the previous estimate by Beltrami *et al.* [2002]. Assuming an average thermal conductivity of 3.0 W/m/K , Beltrami *et al.* [2002] estimates that a total of 15.9×10^{21} J thermal energy had been absorbed by global continents including Antarctica over the 20th century. The current study excludes the mostly ice-covered Antarctica landmass and uses a thermal conductivity of 2.5 W/m/K , which is more typical of the mostly sedimentary uppermost layer of the crust [Clauser and Huenges, 1995] directly influenced by the recent climate change. Additionally, the current study provides details of surface temperature, heat flux, and heat content changes at annual resolution for each of the continental landmasses.

[16] I emphasize that this study is based on the assumption that the continent-wide ground surface temperature anomalies can be approximated by the meteorological records of corresponding surface air temperature anomalies on an annual time scale. Although this assumption is strongly supported by recent climate model simulation and field data analyses [Bartlett *et al.*, 2004; Chapman *et al.*, 2004; González-Rouco *et al.*, 2003; Smerdon *et al.*, 2004], some degree of air-ground temperature decoupling in certain geographical settings on smaller spatial scales is a source of the uncertainty in the heat flux estimates.

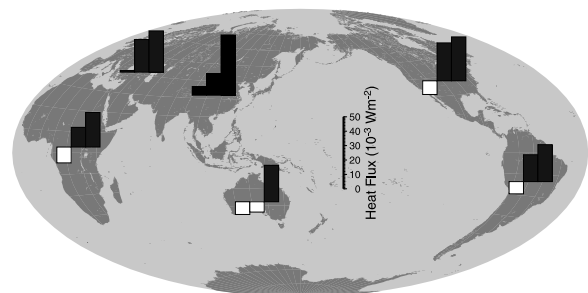


Figure 3. Comparison of the half-century continental heat fluxes over the 1851–2000 period. Each histogram represents the mean heat flux for the continent where it is located. In each histogram the three columns from left to right are for the second half of the 19th century, the first half of the 20th century, and the second half of the 20th century, respectively. Positive heat fluxes are shown in black to represent continental heat gain; while negative in white for heat loss.

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