

Author's Response (including a point-by-point response to the reviews, a list of all relevant changes made in the manuscript, and a marked-up manuscript version)

Response to the reviews, February 20, 2015

“Late Pleistocene-Holocene ground surface heat flux changes reconstructed from borehole temperature data (the Urals, Russia)” by D. Y. Demezhko and A. A. Gornostaeva

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We are grateful to J.-C. Mareschal for the recommending publication. The following is our reply to questions raised by Referee #2.

The revised version would still have to be edited by a native speaker. I include below a few corrections that I spotted in the first two pages, but this really goes through the whole manuscript. This, being a revised version, is annoying for a reviewer, because it distracts from focusing on the content of the manuscript.

We will improve the language aspect of the final revised paper using the help of Editor and copy-editing.

The authors responded that recalibration is usually introduced in many glacial-interglacial records. Closer to the truth is that it was routinely used decades ago, but now it is much contended.

In our paper we cited both well known works on the orbital tuning and recent published. There also exist a lot of the newest publications (e.g. Grant et al., 2012 - Nature, Nowaczyk et al., 2013 - Climate of the Past, Torres et. al, 2013 - Quaternary Science Reviews). We already pointed out shortcomings of conventional orbital tuning and advantages of our approach in previous version of the paper (P8 L3-8) in the final revised text).

...it is not clear to be how the recalibration is done? and then ...How is the optimal value found and what is the uncertainty in the change of the diffusivity?

If the thermal diffusivity value (a) changes the time scale of geothermal reconstructions changes too. An optimal diffusivity value is determined from the maximum of cross-correlation $R(a)$ between the surface heat flux (SHF) and insolation (I) time series. In our case the interval of uncertainty for the optimal diffusivity value under $R \geq 0.95$ is $(0.71 \pm 0.06) \cdot 10^{-6} \text{ m}^2/\text{s}$.

We included correspondent speculation into the Section 4.

...is the recalibration achieved just by changing the value of the diffusivity i.e. replacing one single constant value by another single constant value ?

Exactly.

I nor sure whether the diffusivity is assume to be a function of time, which offers many more possibilities to tune any curve to the desired result.

In our study we considered the thermal diffusivity as a constant over time. This assumption is physically correct for such a long time intervals and depths. At that the value of this constant is

uncertain. The effective thermal diffusivity may be strongly affected by different factors like hydrogeological processes, thermophysical inhomogeneities of rocks, thawing-freezing processes and so on.

We included correspondent speculation into the Section 4.

The manuscript should also stress that the correlation between the SHF and solar insolation (0.99) is achieved only after 'tuning' and this it cannot be directly interpreted as an 'observed' physical relationship between both. The estimation of the 'climate sensitivity' is thus probably biased high and its uncertainties are too optimistic. The authors acknowledge these aspects in their response, but I cannot find them in the revised version.

We included correspondent speculation into the final revised version.

The authors also compare the GST and SHF to the reconstructions of CO₂ concentrations and conclude that the GST is much closer to the CO₂ concentrations, but not so much to the SHF. How is this physically possible?

Hereafter the reviewer answered this question: ... ***the radiative forcing first changes the heat flux and later the temperature. If they conclude that CO₂ is not having an affect on the heat flux, it should have no physical effect on temperatures either.***

We found this explanation very good and included it into the Section 5.

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- Torres, V., Hooghiemstra, H., Lourens, L., & Tzedakis, P. C.: Astronomical tuning of long pollen records reveals the dynamic history of montane biomes and lake levels in the tropical high Andes during the Quaternary, *Quaternary Science Reviews*, 63, 59-72, 2013.

List of all relevant changes

P6, L7 after words "...and therefore the time scale of geothermal reconstructions" we added:

The effective thermal diffusivity may be strongly affected by different factors like hydrogeological processes, thermophysical inhomogeneities of rocks, thawing-freezing processes and so on.

P6, L9 after words "...to maximize the correlation between them" we added:

The correlation maximum points to an optimal value of thermal diffusivity, which determines the degree of expansion/compression of SHF and GST time scale.

P6, L16 after words "...A maximum correlation" we added: ($R=0.99$)

P6, L19 after words "It corresponds to the thermal diffusivity decrease from initial value of $a = 1.0 \cdot 10^{-6} \text{ m}^2/\text{s}$ to $0.71 \cdot 10^{-6} \text{ m}^2/\text{s}$ " we added:

The interval of uncertainty for the optimal diffusivity value under $R \geq 0.95$ is $(0.71 \pm 0.06) \cdot 10^{-6} \text{ m}^2/\text{s}$.

P6, L21-23 following text "(the linear correlation coefficient $R = 0.99$). So, at least until 6 kyr BP the reconstructed heat flux variability was almost completely determined by orbital forcing." is removed.

P7, L16 after words "... of CO_2 forcing to climatically caused heat flux" we added: and thus to the temperature increase.

P8, L23 after words "... Urals: $(1 \pm 0.3) \times 10^{-6} \text{ m}^2/\text{s}$ (Demezhko, 2001)" we added: Therefore a hypothesis on the orbital factor as the main cause of the surface heat flux variability is quite justified.

P9, L14-16 following text "The reconstructed SHF variations are almost completely coincides with changes in insolation of Northern Hemisphere on the scale of the last glacial-interglacial cycle" is removed.

Marked-up manuscript version

Late Pleistocene-Holocene ground surface heat flux changes reconstructed from borehole temperature data (the Urals, Russia)

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Abstract

We use early obtained in the Middle Urals geothermal reconstruction of the ground surface temperature (GST) history to determine the surface heat flux (SHF) history over the past 35 kyr. A new algorithm of GST-SHF transformation was applied to solve this problem. The time scale of geothermal reconstructions has been corrected by comparing the estimated heat flux and annual insolation at the latitude of 60° N. The consistency of SHF and insolation changes on the interval 35-6 kyr BP (the linear correlation coefficient $R = 0.99$) points to orbital factors as the main cause of climatic changes during the Pleistocene-Holocene transition. The amplitude of SHF variations is about 1.3% of the insolation changes amplitude. The increase of carbon dioxide concentrations lagged by 2-3 kyr from the SHF increase and occurred synchronously with GST changes.

1 Introduction

The role of orbital factors in Pleistocene climatic variations has been studied more than 100 years since Joseph Adhemar, James Croll and Milutin Milankovitch. A popular approach is comparing paleotemperatures reconstructed from proxy data (oxygen isotopes, palynological or others) with theoretically calculated insolation. Some investigators (Peixóto and Oort, 1984; Pielke, 2003; Douglass and Knox, 2012) criticized this approach. They noted that temperature field is not an optimal parameter for climate attribution, particularly for evaluation of climatic reaction on the external radiative forcing. There is a lag between external radiative flux and temperature changes, which is disappeared if we consider the heat content or the surface heat flux changes. The advantage of heat flux estimation over temperature one was not realized in full up to date. Wang and Bras (1999) proposed the integral relation to estimate surface heat flux (SHF) changes from ground surface temperature (GST) variations. A finite-difference approximation of the relation between the GST (represented by a piecewise linear function of temperature), and the SHF was proposed by Beltrami et al. (2002). SHF history reconstructions

based on borehole temperature data were made in timescales from several centuries to millennium (Beltrami et al., 2002, 2006; Huang, 2006). Another approach was used in (Majorowicz et al., 2012). Subsurface temperatures were calculated from solar irradiance change using information about climate sensitivity.

In the paper we first present the SHF history for the past 35 kyr obtained from GST early reconstructed on the basis of temperature-depth profile logged in the Urals superdeep borehole (Demezhko and Shchapov, 2001). The recently developed improved algorithm of GST-SHF transformation (Gornostaeva, 2014) was applied to estimate the SHF history.

2 The method

The GST-SHF transformation algorithm is based on the relation between surface heat flux and surface temperature changes according to the Fourier's equation in one dimension:

$$q(0,t) = -\lambda \left. \frac{\partial T(z,t)}{\partial z} \right|_{z=0} \quad (1)$$

where q is SHF, t is time, λ is thermal conductivity, $T(z, t)$ is temperature anomaly at a depth z .

If GST is represented by an expression (Carslaw and Jaeger, 1959, Lachenbruch et al., 1982)

$$T(0,t) = D(t)^{\frac{n}{2}} \quad (2)$$

where D is a constant, n is positive integer (or 0) determining the shape of temperature changes, the transient temperature anomaly at any depth is

$$T(z,t) = 2^n \Gamma\left(\frac{1}{2}n+1\right) i^n \operatorname{erfc} \frac{z}{\sqrt{4at}} T(0,t) \quad (3)$$

where $a = \frac{\lambda}{\rho C}$ is thermal diffusivity, ρ is density, C is specific heat capacity, $i^n \operatorname{erfc}(\alpha)$ is the n -

th repeated integral of the error function of α and $\Gamma(\beta)$ is gamma-function of argument β . Differentiation of (3) yields SHF

$$q(0,t) = \frac{\Gamma\left(\frac{1}{2}n+1\right)}{\Gamma\left(\frac{1}{2}n+\frac{1}{2}\right)} \cdot \frac{\lambda}{\sqrt{at}} \cdot T(0,t) \quad (4)$$

Note that the ratio $E = \lambda(a)^{-1/2}$ represents the rock's thermal effusivity (thermal inertia) characterizing the rate of heat exchange at the surface.

We approximate GST history by a sum of temperature changes corresponding to Eq. (2):

$$T_i = T_0 + \sum_{j=1}^i D_j (i-j+1)^{\frac{n}{2}} \quad (5)$$

where i, j are positive integers related with the real time by the equations $t = i \cdot \Delta t$, $t = j \cdot \Delta t$, Δt is uniform time interval. For each addend of this sum

$$T_i = D_i i^{n/2}, \quad q_i = k_n \frac{E}{\sqrt{\Delta t}} D_i i^{\frac{n-1}{2}}, \quad k_n = \frac{\Gamma\left(\frac{1}{2}n+1\right)}{\Gamma\left(\frac{1}{2}n+\frac{1}{2}\right)}. \quad (6)$$

Using a recurrence equation

$$D_1 = T_1 - T_0$$

$$D_i = (T_i - T_0) - \sum_{j=1}^{i-1} D_j (i-j+1)^{\frac{n}{2}}, \quad i > 1 \quad (7)$$

one can estimate D_i for each interval of temperature curve and then by the equation

$$q_i = k_n \frac{E}{\sqrt{\Delta t}} \sum_{j=1}^i D_j (i-j+1)^{\frac{n-1}{2}} \quad (8)$$

one can calculate heat flux instantaneous values at the end of interval. The SHF history reconstruction will be more accurate if we calculate the average value of heat flux on the interval and refer it to the midpoint of the interval ($i-0.5$)

$$\overline{q_{i-0.5}} = q_{i-1} + \frac{2}{n+1} (q_i - q_{i-1}). \quad (9)$$

The GST-SHF transformation algorithm was tested by applying it to a harmonic function of surface temperature change with amplitude A , frequency ω , and initial phase φ :

$$T(0,t) = A \sin(\omega t + \varphi), \quad (10)$$

the propagation of temperature waves in a homogeneous half-space with thermal diffusivity a is described by the expression

$$T(z,t) = A e^{-kz} \sin(\omega t - kz + \varphi), \quad k = \sqrt{\omega/2a}. \quad (11)$$

Differentiating (11) with respect to z , we find the ground surface heat flux change $q(0,t)$:

$$q(0,t) = -\lambda \left. \frac{\partial T(z,t)}{\partial z} \right|_{z=0} = AE \sqrt{\omega} \sin\left(\omega t + \varphi + \frac{\pi}{4}\right) = E \sqrt{\omega} T\left(0, t + \frac{\pi}{4\omega}\right). \quad (12)$$

The relationship between the amplitudes of GST and SHF changes is determined by thermal diffusivity E and frequency ω . The heat flux changes are ahead of temperature changes by $\pi/4$, i.e., one-eighth of the oscillation period.

The relative error of SHF estimation was calculated as the ratio of the standard error of the SHF estimation to the real amplitude of SHF variations. The test showed that approximation of temperature history by the Eq. (5) with $n = 2, 3$ provides the most accurate results (Fig. 1). When GST discretization is 6 points per period we obtain the relative error of SHF history estimation equals to 3%, and given 10 points per period the relative error is less than 1% (Gornostaeva, 2014). For comparison, the algorithm proposed by Beltrami et al. (2002) under the same discretization conditions provides relative errors equals to 8% and 3.5% respectively.

3 GST data and SHF estimation

We used the temperature history (Demezhko and Shchapov, 2001) early reconstructed from temperature-depth profile logged in the Urals superdeep borehole SG-4 (58° 24' N, 59° 44' E, Middle Urals, Russia) as initial data (Fig. 2). We analysed only the last 35 kyr of the GST history for the SHF reconstruction, while the paper mentioned above presents 80 kyr temperature history. Because of the decrease of the GSTH resolution with time the interval from 35 to 80 kyr BP does not contain any noticeable GST variations. The SHF may be considered as a constant on this time interval.

The reconstruction of the surface heat flux history was conducted using the algorithm described above with $n = 3$ (see Fig. 2). GST and SHF curves are different in shape. The temperature increase started about 15 kyr BP and after a short break it continued to 1 kyr BP, while the heat flux increase began about 3 kyr earlier. The heat flux reached its maximum of 0.08 W/m² about 8 kyr BP and then it began to decline.

4 The comparison of the SHF with solar insolation

The reconstructed SHF changes are similar to the Northern Hemisphere solar insolation changes that are determined by the variations of the Earth's orbital parameters like eccentricity, inclination and the Earth's axis precession (Fig. 3). It is admissible to assume that insolation changes cause the surface heat flux changes. This assumption for the Middle Urals is also supported by the absence of Late Pleistocene ice sheets here (see Velichko et al., 1997, Svendsen et al, 2004 and references therein). However, there is some shift between insolation and SHF changes. The observed shift can be explained by several reasons. The first one is the influence of internal climatic factors and feedbacks translating the external heat flux on the Earth's surface with a certain delay and amplitude attenuation. The second reason is an overestimation of the effective thermal diffusivity that determines the rate of climatic signal propagation into the depth and therefore the time scale of geothermal reconstructions. **The effective thermal diffusivity may be strongly affected by different factors like hydrogeological processes, thermophysical inhomogeneities of rocks, thawing-freezing processes and so on.** To synchronize SHF and insolation (ΔI) time series it is necessary to correct the initial value of thermal diffusivity (and time scale respectively) to maximize the correlation between them. The correlation maximum points to an optimal value of thermal diffusivity, which determines the degree of expansion/compression of SHF and GST time scale. Note that the direct comparison of these series is not so correct. The insolation temporal resolution is constant while SHF resolution power decreases back in time. A minimal resolved interval of geothermal reconstruction is approximately $2 \cdot t^*/3$ where t^* is time before present (Demezhko and Shchapov, 2001). The procedure of averaging in uneven running windows was proposed (Demezhko and Solomina, 2009) to modify the curve to a form comparable with the geothermal one. The insolation curve for the latitude of 60° N smoothed according to the resolution power of geothermal method is presented in Fig. 3b. A maximum correlation ($R=0.99$) between SHF history and smoothed insolation is achieved by increasing SHF dates by 1.4 times. It corresponds to the thermal diffusivity decrease from initial value of $a = 1.0 \cdot 10^{-6}$ m²/s to $0.71 \cdot 10^{-6}$ m²/s. **The interval of uncertainty for the optimal diffusivity value under $R \geq 0.95$ is $(0.71 \pm 0.06) \cdot 10^{-6}$ m²/s.**

Linear regression analysis of q and ΔI from 35 to 6 kyr BP showed that change of insolation on 1 W/m² produces an additional surface heat flux equals to 0.013 W/m² ~~(the linear correlation coefficient $R = 0.99$). So, at least until 6 kyr BP the reconstructed heat flux variability was almost completely determined by orbital forcing.~~ At that only a small portion of insolation

changes (about 1.3%) was spent to the increase of the lithosphere heat content. The ratio $\Delta q/\Delta I$ may be considered as a dimensionless measure of climate sensitivity of the region under study to long-term orbital forcing variations.

Taking the climatically caused SHF before 35 kyr BP equals to 0 W/m^2 and integrating it with respect to time we estimate changes in heat content. This value characterizes the additional amount of heat adsorbed in a rock column having a cross-sectional area of 1 m^2 and limited by the depth of thermal anomaly penetration (i.e. by a few kilometers). Until 15 kyr BP a total heat balance was negative. A minimum value of heat content of -3.5 TJ/m^2 with respect to the reference value at 35 kyr BP was found about 20 kyr BP. From this moment the heat flux became positive. For the next 14 kyr (20-6 kyr BP) the heat content increased to 22.0 TJ/m^2 . For comparison, during the period of modern warming (1765-2000), heat content of the continental lithosphere increased by 0.1 TJ/m^2 (calculated using data from Beltrami, 2002).

5 The comparison of the SHF with CO₂ changes

Another source of the additional radiative forcing during the Pleistocene-Holocene transition could be greenhouse effect caused by the increase of carbon dioxide concentration in the atmosphere (see Shakun et al., 2012 and references therein). An additional downward heat flux necessarily would contribute to SHF changes. Figure 4 shows geothermal reconstructions of surface temperatures and heat fluxes from the borehole SG-4 (on the time scale corrected after SHF-insolation synchronization) and carbon dioxide concentration changes in Antarctic ice cores (Blunier et al., 1998; Indermühle et al., 1999; 1999b; Smith, 1999; Barnola et al., 2003; Pedro et al., 2012). Despite the substantial dispersion of CO₂ estimations, a character and a chronology of CO₂ concentration changes are much closer to temperature changes rather than to heat flux variations. It may mean no significant contribution of CO₂ forcing to climatically caused heat flux [and thus to the temperature increase](#) during Pleistocene-Holocene warming.

About 10 kyr BP the increase of carbon dioxide concentration was replaced by its fall which ended about 8 kyr BP. This local minimum is not consistent with either GST or SHF histories. It is possible that the CO₂ decrease was associated with a sharp increase of vegetation absorbing its excess.

6 Discussion and conclusions

The reconstruction of the surface heat flux history using data on the past surface temperature changes represents a new instrument for climate analysis. The reconstructed SHF variations and radiative forcing changes may be compared directly because they are expressed in the same units of energy flux (W/m^2).

Time synchronization of heat flux and orbital insolation series is similar to the orbital tuning of glacial or marine sediments isotope records (Imbrie et al., 1984, Martinson et al, 1987; Waelbroeck et al., 1995, Shackleton, 2000; Bender et al., 2002; Parrenin et al, 2007). However, it has some special features.

First. Since the concentration of $\delta^{18}\text{O}$, δD in the ice cores or marine sediments associated with paleotemperature fluctuations, the time shift between the orbital insolation and temperature reaction can be estimated only from independent absolute markers. Because of the rarity of such markers it is generally considered that the shift is a constant (Parrenin et al, 2007). Unlike

conventional approach we tune another paleoclimatic characteristics, the surface heat flux, which provides a physically reasonable shift. In (Waelbroeck et al., 1995) the phasing between the precession band of mid-June insolation at 65°N and δD was found about 3 kyr (with the uncertainty ± 3 kyr). A reliable estimation of the phase in the obliquity band was not obtained and therefore it was not accounted for. Considering the period of precession 23 kyr and using equation (12) we obtain the close estimate $23/8 \approx 2.9$ kyr. For the obliquity band the phase shift is equal to $41\text{kyr}/8 = 5.1$ kyr.

Second. For correct comparison with geothermal reconstruction the insolation curve must have the same resolution. The procedure of averaging in uneven running windows was applied to modify the insolation curve to a form comparable with the geothermal one. Such a procedure limits the tuning interval within the last cycle of precession.

Third. The reliability of the new time scale after synchronization with the orbital insolation also depends on how much the thermal diffusivity changed from the initial value. In our study the best coincidence of insolation and heat flux ($R = 0.99$) in the most part of the reconstructed interval is achieved by varying the thermal diffusivity from $1 \times 10^{-6} \text{ m}^2/\text{s}$ to $0.71 \times 10^{-6} \text{ m}^2/\text{s}$, i.e., within the range of its natural variability for the crystalline rocks of the Urals: $(1 \pm 0.3) \times 10^{-6} \text{ m}^2/\text{s}$ (Demezhko, 2001). [Therefore a hypothesis on the orbital factor as the main cause of the surface heat flux variability is quite justified.](#)

Fourth. Using the reconstructed surface heat flux instead of the surface temperature does not exclude the existence of residual time shift because the relation between insolation changes and the heat flux may be indirect. Such a shift can be caused by the climate delayed feedbacks. For example, orbital variations of insolation could change the extent of continental and sea ice cover in the Northern Hemisphere, albedo and North Atlantic warm currents. The secondary heat source distributed in the atmosphere arose, which could significantly affect spatial distribution of the SHF change. However, this is beyond the scope of our study.

Assuming the surface heat flux varies proportionally to the external forcing one can consider the ratio $\Delta q/\Delta I$ as an alternative measure of the Earth's climatic sensitivity. The ratio of two heat fluxes is a non-dimensional parameter, and additionally depends less on radiative forcing duration by contrast to traditional index of climatic sensitivity representing temperature reaction on the external radiative forcing ($\Delta T/\Delta I$).

The reconstructed surface heat flux reflects impact of all possible sources of radiative forcing. In addition to solar insolation, greenhouse gases (such as CO_2) can be a source of additional forcing. On the other hand the increase of carbon dioxide may be a consequence of temperature increasing. Comparing the chronology of surface flux, temperature and carbon dioxide concentration changes, we can draw some conclusions about the causes of climate changes.

The described algorithm of GST-SHF transformation is quite easy to realization and allows estimating of SHF history with high precision. Using this algorithm, we have first estimated long-term surface heat flux changes in the Urals for the past 35 kyr. ~~The reconstructed SHF variations are almost completely coincides with changes in insolation of Northern Hemisphere on the scale of the last glacial-interglacial cycle.~~ The amplitude of heat flux variations was about 1.3 percent of the insolation changes range at the latitude of 60° N. The increase of carbon dioxide concentrations occurred 2-3 thousands of years later than the heat flux increase and synchronously with temperature response.

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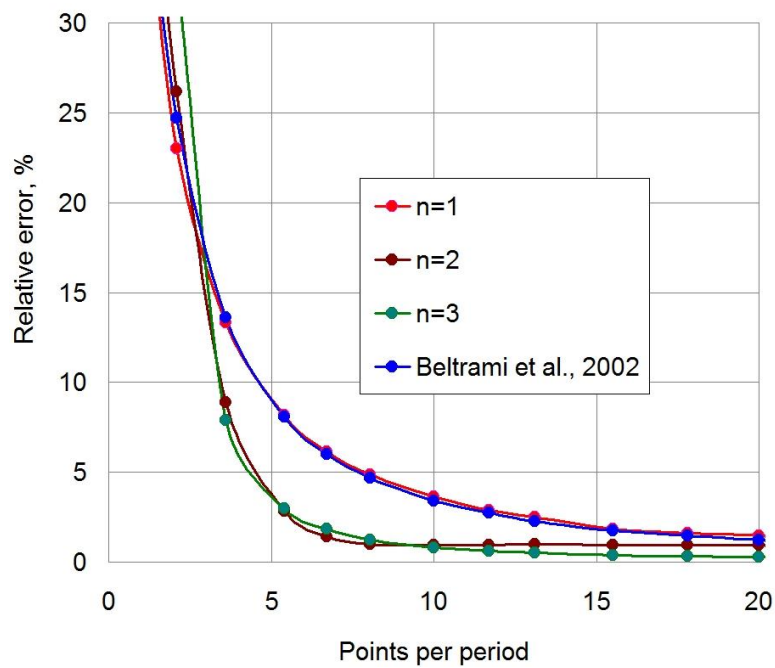


Figure 1. Testing the algorithms of GST-SHF transformation by applying it to a harmonic function of GST change. Relative error of SHF estimation (the ratio of the standard error of the SHF estimation to the real amplitude of SHF variations) versus the GST discretization frequency (points per period)

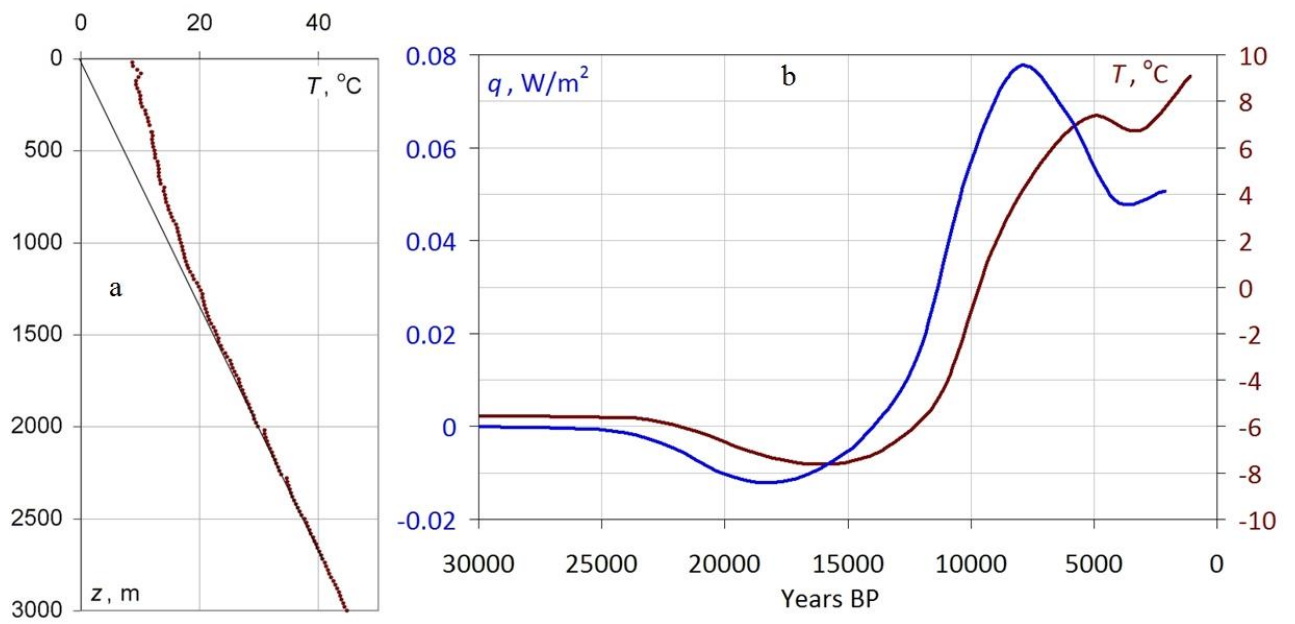


Figure 2. Initial data and surface heat flux a) Temperature-depth profile from the borehole SG-4 (Demezhko and Shchapov, 2001, brown line), b) GST history $T(t)$ ($a = 1.0 \cdot 10^{-6} \text{ m}^2/\text{s}$, Demezhko and Shchapov, 2001, brown line) and calculated according to Eqs. (1-5) SHF history $q(t)$ ($E = 2500 \text{ J} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \cdot \text{s}^{-1/2}$, blue line).

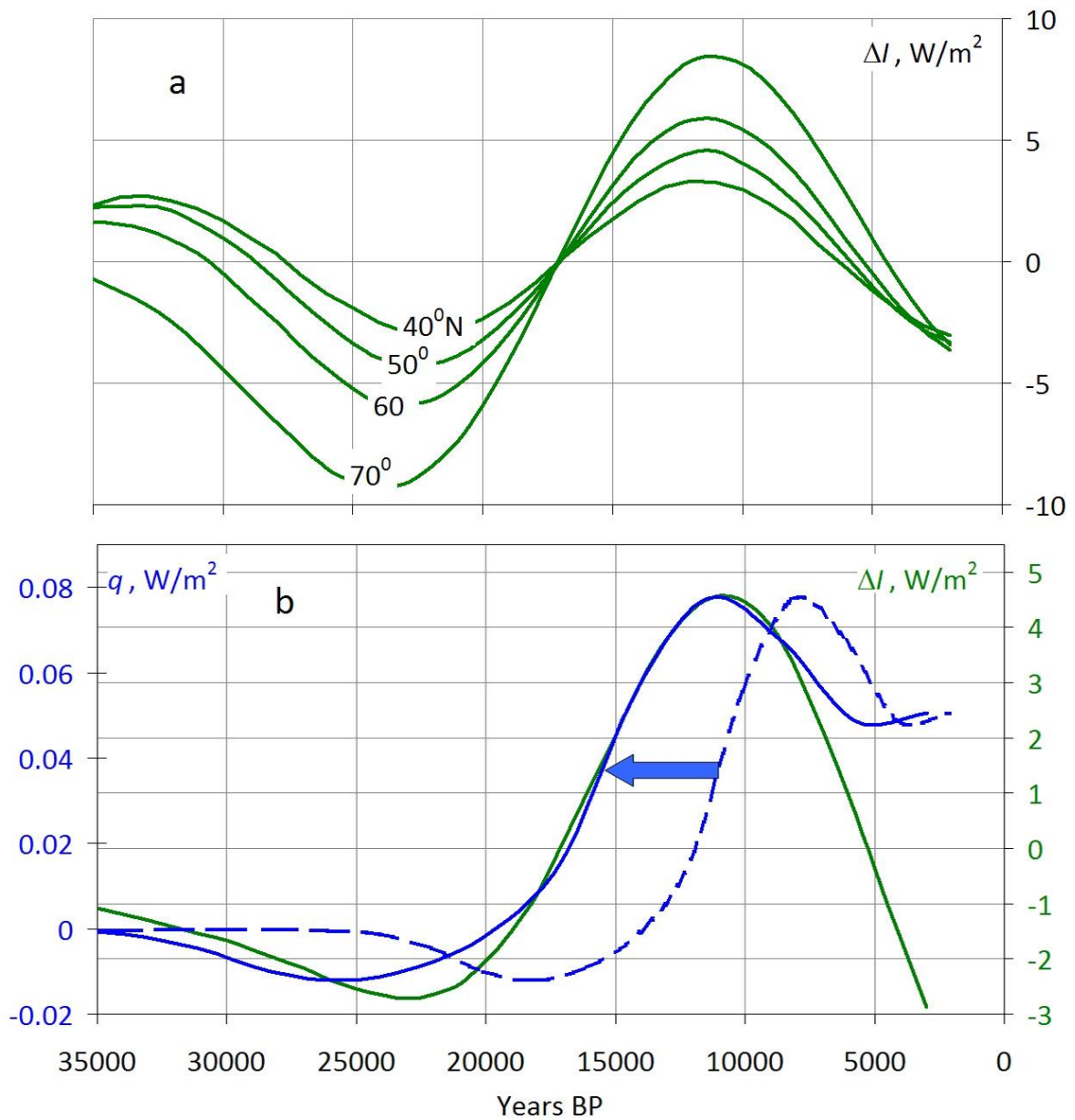


Figure 3. The comparison of SHF history with solar insolation changes in the Northern Hemisphere caused by changes in Earth's orbital parameters and time scale correcting. a) Annual insolation changes $\Delta I(t)$ at the latitudes of 40-70° N (Berger, Loutre, 1991); b) annual solar insolation at the latitude of 60° N smoothed in uneven running windows (green line), SHF history in the initial timescale ($a = 1.0 \cdot 10^{-6} \text{ m}^2/\text{s}$, blue dashed line) and SHF history in the corrected timescale ($a = 0.71 \cdot 10^{-6} \text{ m}^2/\text{s}$, blue solid line).

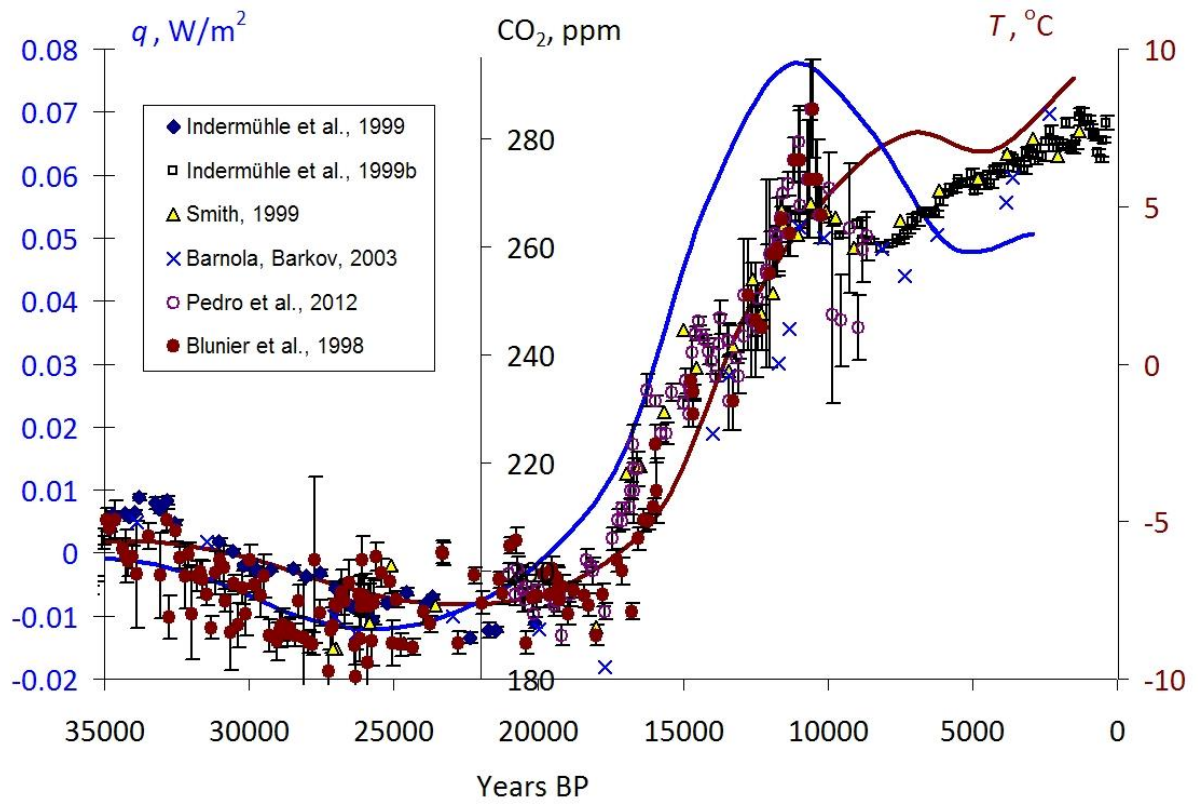


Figure 4. The comparison of GST history $T(t)$ (brown line), SHF history $q(t)$ (blue line) and CO₂ concentration in the Antarctic ice cores (multicolored markers).