

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

4
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9
10 **Abstract**

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

21
22 **1 Introduction**

23 The role of orbital factors in Pleistocene climatic variations has been studied more than 100
24 years since Joseph Adhemar, James Croll and Milutin Milankovitch. A popular approach is
25 comparing paleotemperatures reconstructed from proxy data (oxygen isotopes, palynological
26 or others) with theoretically calculated insolation. Some investigators (Peixóto and Oort,
27 1984; Pielke, 2003; Douglass and Knox, 2012) criticized this approach. They noted that
28 temperature field is not an optimal parameter for climate attribution, particularly for

1 evaluation of climatic reaction on the external radiative forcing. There is a lag between
 2 external radiative flux and temperature changes, which is disappeared if we consider the heat
 3 content or the surface heat flux changes. The advantage of heat flux estimation over
 4 temperature one was not realized in full up to date. Wang and Bras (1999) proposed the
 5 integral relation to estimate surface heat flux (SHF) changes from ground surface temperature
 6 (GST) variations. A finite-difference approximation of the relation between the GST
 7 (represented by a piecewise linear function of temperature), and the SHF was proposed by
 8 Beltrami et al. (2002). SHF history reconstructions based on borehole temperature data were
 9 made in timescales from several centuries to millennium (Beltrami et al., 2002, 2006; Huang,
 10 2006). Another approach was used in (Majorowicz et al., 2012). Subsurface temperatures
 11 were calculated from solar irradiance change using information about climate sensitivity.

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

16

17 **2 The method**

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

$$20 \quad q(0,t) = -\lambda \left. \frac{\partial T(z,t)}{\partial z} \right|_{z=0} \quad (1)$$

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

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

$$24 \quad T(0,t) = D(t)^{\frac{n}{2}} \quad (2)$$

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

$$27 \quad T(z,t) = 2^n \Gamma\left(\frac{1}{2}n + 1\right) i^n \operatorname{erfc} \frac{z}{\sqrt{4at}} T(0,t) \quad (3)$$

1 where $a = \frac{\lambda}{\rho C}$ is thermal diffusivity, ρ is density, C is specific heat capacity, $i^n \operatorname{erfc}(\alpha)$ is the
 2 n -th repeated integral of the error function of α and $\Gamma(\beta)$ is gamma-function of argument β .
 3 Differentiation of (3) yields SHF

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

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

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

$$8 \quad T_i = T_0 + \sum_{j=1}^i D_j (i-j+1)^{\frac{n}{2}} \quad (5)$$

9 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
 10 is uniform time interval. For each addend of this sum

$$11 \quad T_i = D_i i^{n/2}, \quad q_i = k_n \frac{E}{\sqrt{\Delta t}} D_i i^{\frac{n-1}{2}}, \quad k_n = \frac{\Gamma\left(\frac{1}{2}n+1\right)}{\Gamma\left(\frac{1}{2}n+\frac{1}{2}\right)}. \quad (6)$$

12 Using a recurrence equation

$$13 \quad D_1 = T_1 - T_0$$

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

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

$$15 \quad q_i = k_n \frac{E}{\sqrt{\Delta t}} \sum_{j=1}^i D_j (i-j+1)^{\frac{n-1}{2}} \quad (8)$$

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

$$19 \quad \overline{q}_{i-0.5} = q_{i-1} + \frac{2}{n+1} (q_i - q_{i-1}). \quad (9)$$

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

$$3 \quad T(0,t) = A \sin(\omega t + \varphi), \quad (10)$$

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

$$6 \quad T(z,t) = A e^{-kz} \sin(\omega t - kz + \varphi), \quad k = \sqrt{\omega/2a}. \quad (11)$$

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

$$8 \quad q(0,t) = -\lambda \left. \frac{\partial T(z,t)}{\partial z} \right|_{z=0} = AE \sqrt{\omega} \sin(\omega t + \varphi + \frac{\pi}{4}) = E \sqrt{\omega} T(0, t + \frac{\pi}{4\omega}). \quad (12)$$

9 The relationship between the amplitudes of GST and SHF changes is determined by thermal
10 effusivity E and frequency ω . The heat flux changes are ahead of temperature changes by
11 $\pi/4$, i.e., one-eighth of the oscillation period.

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

20

21 **3 GST data and SHF estimation**

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

1 The reconstruction of the surface heat flux history was conducted using the algorithm
2 described above with $n = 3$ (see Fig. 2). GST and SHF curves are different in shape. The
3 temperature increase started about 15 kyr BP and after a short break it continued to 1 kyr BP,
4 while the heat flux increase began about 3 kyr earlier. The heat flux reached its maximum of
5 0.08 W/m^2 about 8 kyr BP and then it began to decline.

6

7 **4 The comparison of the SHF with solar insolation**

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

1 by 1.4 times. It corresponds to the thermal diffusivity decrease from initial value of $a =$
2 $1.0 \cdot 10^{-6} \text{ m}^2/\text{s}$ to $0.71 \cdot 10^{-6} \text{ m}^2/\text{s}$. The interval of uncertainty for the optimal diffusivity value
3 under $R \geq 0.95$ is $(0.71 \pm 0.06) \cdot 10^{-6} \text{ m}^2/\text{s}$.

4 Linear regression analysis of q and ΔI from 35 to 6 kyr BP showed that change of insolation
5 on $1 \text{ W}/\text{m}^2$ produces an additional surface heat flux equals to $0.013 \text{ W}/\text{m}^2$. At that only a
6 small portion of insolation changes (about 1.3%) was spent to the increase of the lithosphere
7 heat content. The ratio $\Delta q/\Delta I$ may be considered as a dimensionless measure of climate
8 sensitivity of the region under study to long-term orbital forcing variations.

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

18

19 **5 The comparison of the SHF with CO₂ changes**

20 Another source of the additional radiative forcing during the Pleistocene-Holocene transition
21 could be greenhouse effect caused by the increase of carbon dioxide concentration in the
22 atmosphere (see Shakun et al., 2012 and references therein). An additional downward heat
23 flux necessarily would contribute to SHF changes. Figure 4 shows geothermal
24 reconstructions of surface temperatures and heat fluxes from the borehole SG-4 (on the time
25 scale corrected after SHF-insolation synchronization) and carbon dioxide concentration
26 changes in Antarctic ice cores (Blunier et al., 1998; Indermühle et al., 1999; 1999b; Smith,
27 1999; Barnola et al., 2003; Pedro et al., 2012). Despite the substantial dispersion of CO₂
28 estimations, a character and a chronology of CO₂ concentration changes are much closer to
29 temperature changes rather than to heat flux variations. It may mean no significant
30 contribution of CO₂ forcing to climatically caused heat flux and thus to the temperature
31 increase during Pleistocene-Holocene warming.

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

5

6 **6 Discussion and conclusions**

7 The reconstruction of the surface heat flux history using data on the past surface temperature
8 changes represents a new instrument for climate analysis. The reconstructed SHF variations
9 and radiative forcing changes may be compared directly because they are expressed in the
10 same units of energy flux (W/m²).

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

15 First. Since the concentration of $\delta^{18}O$, δD in the ice cores or marine sediments associated with
16 paleotemperature fluctuations, the time shift between the orbital insolation and temperature
17 reaction can be estimated only from independent absolute markers. Because of the rarity of
18 such markers it is generally considered that the shift is a constant (Parrenin et al, 2007).
19 Unlike conventional approach we tune another paleoclimatic characteristics, the surface heat
20 flux, which provides a physically reasonable shift. In (Waelbroeck et al., 1995) the phasing
21 between the precession band of mid-June insolation at 65°N and δD was found about 3 kyr
22 (with the uncertainty ± 3 kyr). A reliable estimation of the phase in the obliquity band was not
23 obtained and therefore it was not accounted for. Considering the period of precession 23 kyr
24 and using equation (12) we obtain the close estimate $23/8 \approx 2.9$ kyr. For the obliquity band the
25 phase shift is equal to $41\text{kyr}/8 = 5.1$ kyr.

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

30 Third. The reliability of the new time scale after synchronization with the orbital insolation
31 also depends on how much the thermal diffusivity changed from the initial value. In our study

1 the best coincidence of insolation and heat flux ($R = 0.99$) in the most part of the
2 reconstructed interval is achieved by varying the thermal diffusivity from $1 \times 10^{-6} \text{ m}^2/\text{s}$ to
3 $0.71 \times 10^{-6} \text{ m}^2/\text{s}$, i.e., within the range of its natural variability for the crystalline rocks of the
4 Urals: $(1 \pm 0.3) \times 10^{-6} \text{ m}^2/\text{s}$ (Demezhko, 2001). Therefore a hypothesis on the orbital factor as
5 the main cause of the surface heat flux variability is quite justified.

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

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

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

24 The described algorithm of GST-SHF transformation is quite easy to realization and allows
25 estimating of SHF history with high precision. Using this algorithm, we have first estimated
26 long-term surface heat flux changes in the Urals for the past 35 kyr. The amplitude of heat
27 flux variations was about 1.3 percent of the insolation changes range at the latitude of 60° N .
28 The increase of carbon dioxide concentrations occurred 2-3 thousands of years later than the
29 heat flux increase and synchronously with temperature response.

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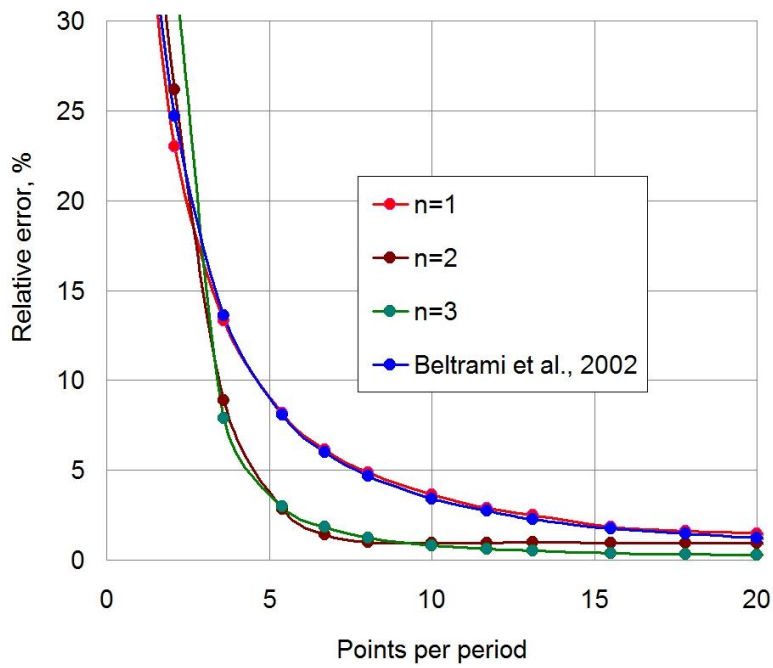
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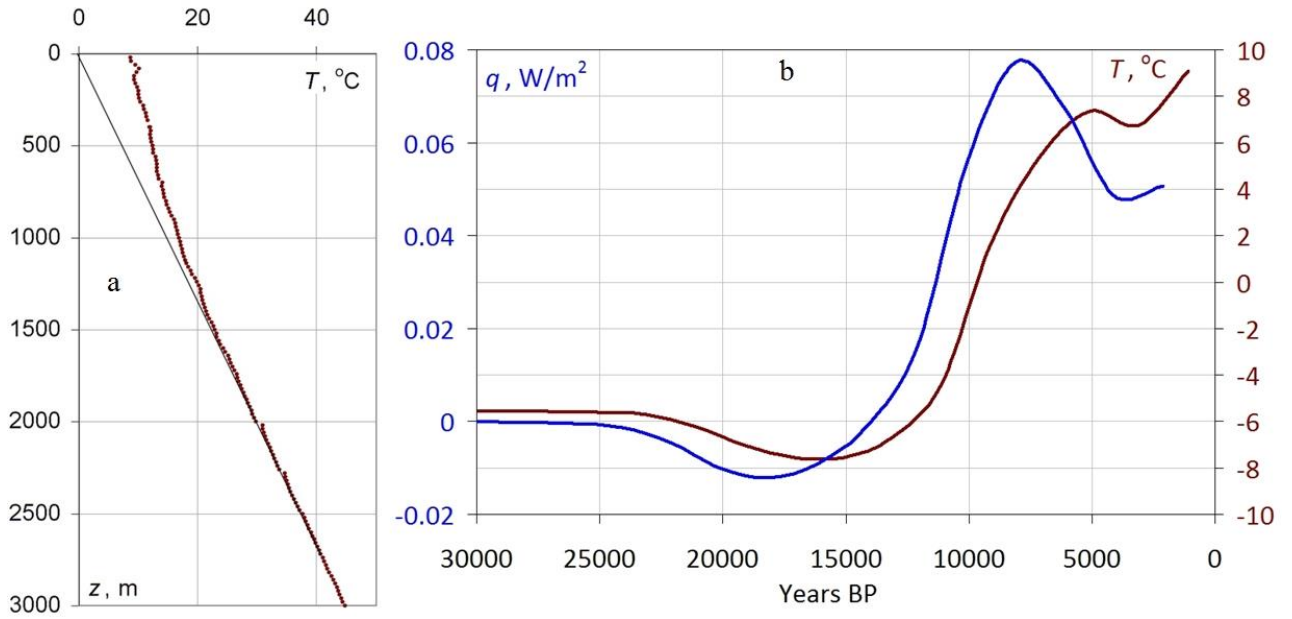
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Figure 1. Testing the algorithms of GST-SHF transformation by applying it to a harmonic function of GST change. Relative error of SHF estimation (the ratio of the standard error of the SHF estimation to the real amplitude of SHF variations) versus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



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3 Figure 2. Initial data and surface heat flux a) Temperature-depth profile from the borehole

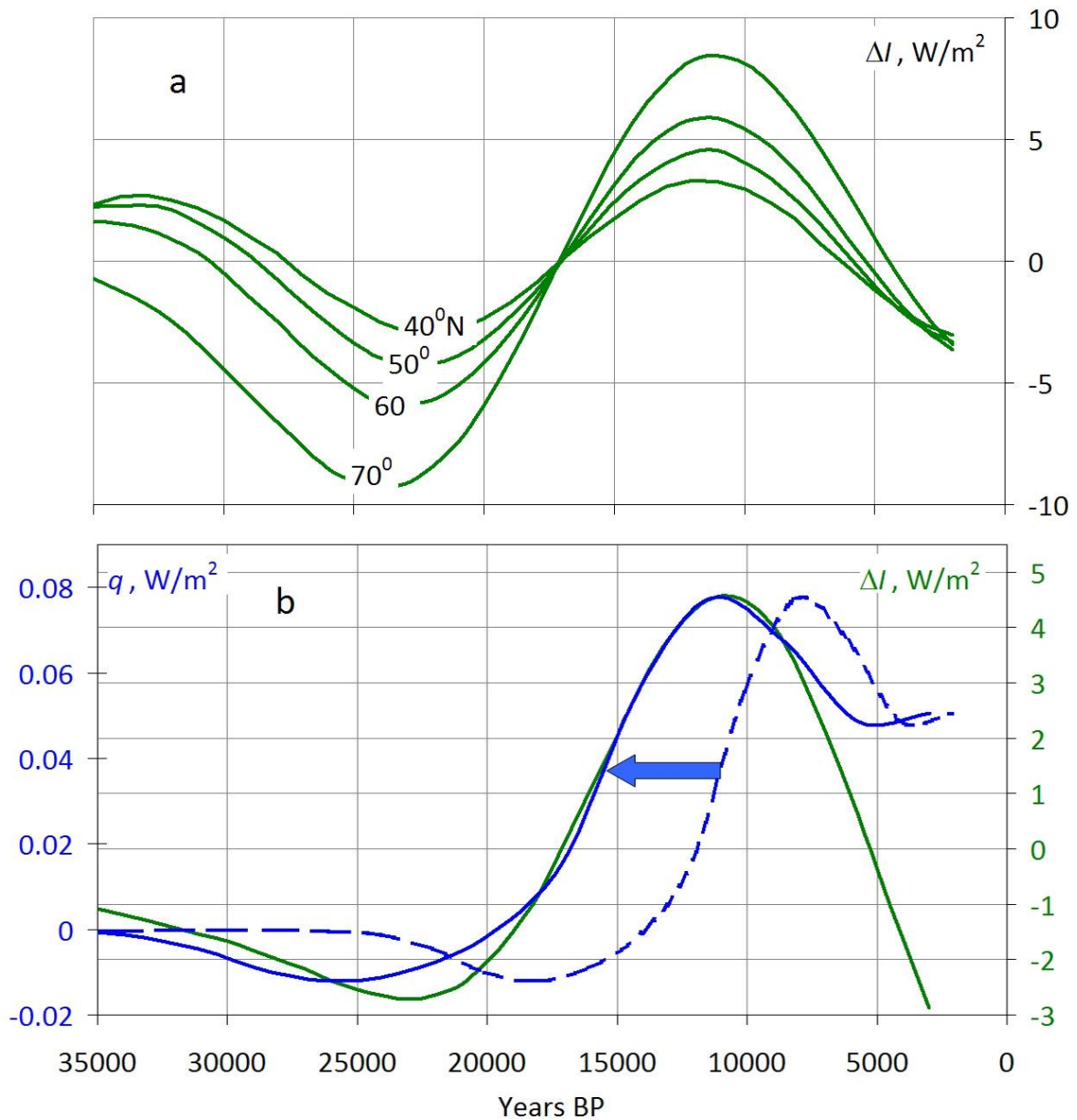
4 SG-4 (Demezhko and Shchapov, 2001, brown line), b) GST history $T(t)$ ($a = 1.0 \cdot 10^{-6} \text{ m}^2/\text{s}$,

5 Demezhko and Shchapov, 2001, brown line) and calculated according to Eqs. (1-5) SHF

6 history $q(t)$ ($E = 2500 \text{ J} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \cdot \text{s}^{-1/2}$, blue line).

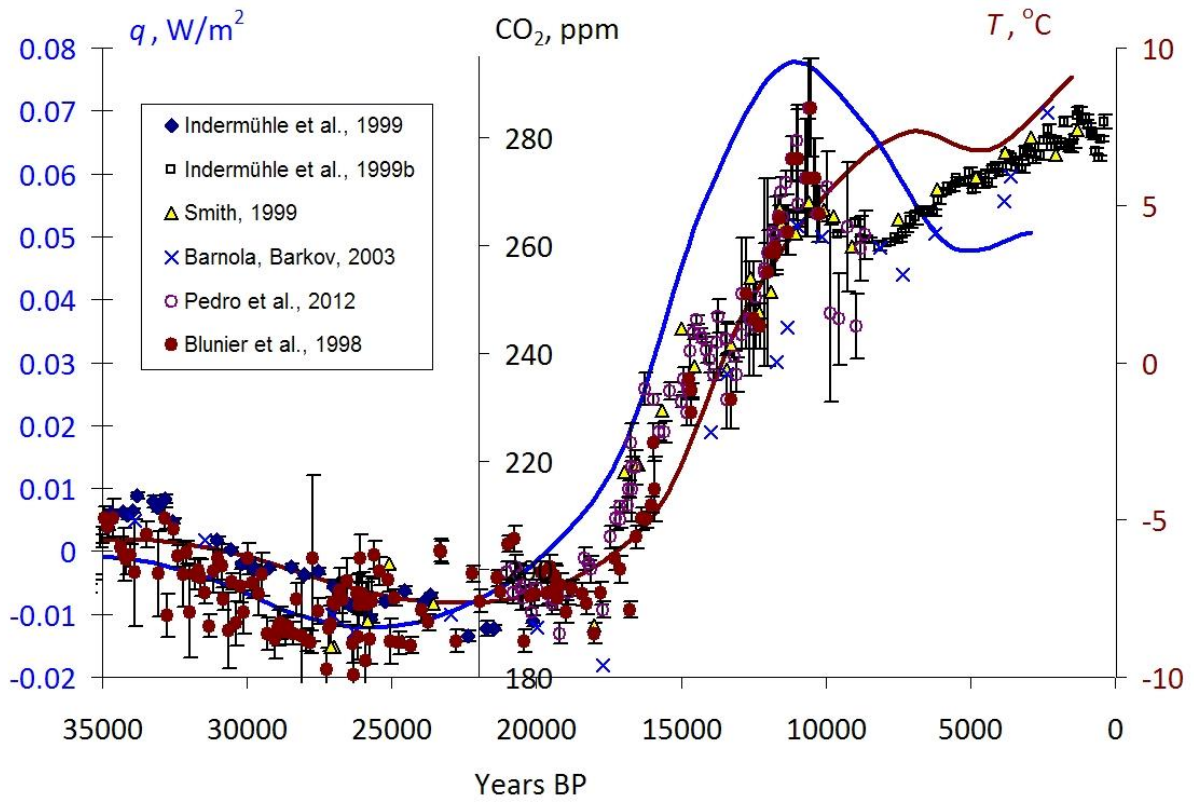
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Figure 3. The comparison of SHF history with solar insolation changes in the Northern Hemisphere caused by changes in Earth's orbital parameters and time scale correcting. a) Annual insolation changes $\Delta I(t)$ at the latitudes of 40-70° N (Berger, 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).



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3 Figure 4. The comparison of GST history $T(t)$ (brown line), SHF history $q(t)$ (blue line) and

4 CO₂ concentration in the Antarctic ice cores (multicolored markers).