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Reconstructions of Ground Surface Heat Flux Variations in the Urals from Geothermal and Meteorological Data

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Abstract—Ground surface heat flux variations over the last 30000, 1000, and 150 years in the Urals were first estimated on the basis of geothermal reconstructions of ground surface temperature histories and meteorological data. The heat flux histories obtained and the factors affecting climate—mean annual insolation, global solar radiation, atmospheric CO_2 concentration, and volcanic activity—were simultaneously analyzed. On the scale of glacial-interglacial cycles, variations in the flux of heat almost completely coincided with those in insolation in the Northern Hemisphere, and variations in the content of CO_2 occurred 2000–3000 years later synchronously with the response of temperature. In the last 1000 years, heat flux variations have been determined mainly by the parameters of solar radiation; however, the influence of other factors, such as atmospheric CO_2 content and volcanic activity, has also been noticeable. In the last 150 years, variations in the flux of heat have occurred in antiphase with those in the flux of solar radiation, and an increase in the atmospheric content of CO_2 has mainly contributed to the observed warming.

Keywords: geothermy, paleoclimate, heat flux, ground surface heat balance, Pleistocene, Holocene, Little Ice Age, the Urals

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INTRODUCTION

Variations in the spatiotemporal structure of incoming solar radiation are one of the important factors affecting climate variability. The assumption of external radiation factors affecting climate, which was made by J. Adhemar in the mid-19th century and developed by J. Croll, M. Milankovitch, and others, yielded a large number of conceptions, first and foremost, the so-called orbital ones, which relate the glacial-interglacial cycles of Pleistocene to variations in the Earth's orbital parameters—eccentricity, precession, and obliquity. A century later, the oxygen-isotopic paleothermometer invented by H.Urey and the intensive drilling of polar ice sheets resulted in the appearance of many reconstructions of long-term global-temperature variations, which still further stimulated the development of orbital theories, because it became possible to directly compare temperature and radiation curves. A detailed review of orbital theories is given in (Bol'shakov and Kapitsa, 2011). Ratios between radiative and climatic characteristics on shorter (from 1000-year to 24-h) time scales are of no less interest to researchers (Crowley, 2000; Bertrand et al., 2001; Goosse and Renssen, 2004; Bennett, 2008; Servonnat et al., 2010; Volobuev, 2013).

However, a direct comparison between temperature and radiation curves usually results in quite conflicting results. This can be easily explained. Such an approach is based on the simplified notions of the linear temperature response to variations in external radiative forcing. The ratio between variations in temperature and those in external radiation is called the sensitivity of climate system (Lean et al., 1995; Hansen et al., 1997, 2011; Crowley, 2000; Chung and Seinfeld, 2005; Roe and Baker, 2007; Majorowicz et al., 2012). This approach was subjected to criticism in (Peixóto and Oort, 1984; Pielke, 2003; Douglas and Knoz, 2012). It was noted that temperature is not an optimal parameter in diagnosing climate, in particular, in estimating its response to external forcing. There is always some time delay between variations in the flux of external radiation and those in temperature. This delay vanishes in considering variations in heat content or ground surface heat flux. Despite the fact that the energy characteristics of climate are important, data on these characteristics are very poor, because the direct measurements of the elements of the Earth's heat balance present difficulties (Geiger, 1965; Karl et al., 1989). The situation with heat balance estimates for the past, when significant climate changes occurred, is worse.

Borehole temperature data make it possible to estimate variations in the flux of heat and the content of heat in the Earth's crust in the past. Until recently, these data were used only for reconstructing ground-surface paleotemperatures (Lachenbruch and Marshal, 1986; Harris and Chapman, 1995, 1997; Dahl-Jensen et al., 1998; Pollack et al., 1998, 2003; Pollack and Huang, 2000; Pollack and Smerdon, 2004; Demezhko, 2001; Demezhko et al., 2005). H. Beltrami, a Canadian geophysicist, and his colleagues first called attention to the possibility for reconstructing climate changes in the ground surface flux of heat and in the heat content of the Earth's crust (Beltrami et al., 2000, 2002, 2006; Beltrami, 2001, 2002). They formulated two approaches to solving this problem: (1) on the basis of an analysis (inversion) of borehole temperatures and (2) through the transformation of earlier obtained paleotemperature reconstructions. Heat flux variations were estimated for periods from several centuries (Northern Hemisphere) to 1000 years ago (eastern Canada). The latter approach was later used for reconstructing heat flux on the basis of available meteorological data series (Huang, 2006; Volobuev, 2013). And, in (Volobuev, 2013), an attempt was made to estimate the contribution of the11-year solar radiation oscillations to climate changes in the Antarctic. In (Majorowicz et al., 2012), an inverse method was used: the 1986–2006 underground temperature variations were calculated on the basis of data on external radiative forcing and climate sensitivity. The results of a comparison between these estimates and measured borehole temperatures showed that solar radiation may be responsible for only 1/3 of the observed anomaly.

It is evident that these few investigations have not yet exhausted the informative potential of this method. A large body of the available geothermal data remains to be analyzed. Moreover, up to now, no estimates of variations in the flux of heat and the heat content of rocks on scales of a few tens of thousands of years, including the period of global climate change at the Pleistocene–Holocene boundary about 10000 years ago, have been obtained in world science. In this work, new reconstructions of the histories of variations in the ground surface heat flux $q(0, t)$ are given for the Urals. There reconstructions were obtained on the basis of earlier obtained geothermal estimates of variations in the ground surface temperature $T(0, t)$ and meteorological data on variations in the surface air temperature $T_a(0, t)$. These reconstructions are the climatic histories of the Urals on three time scales (the last 30000, 1000, and 150 years) with different time resolutions. An attempt has been made to compare the obtained reconstructions of heat fluxes with data on external radiative forcing and to estimate the obtained ratios for the three chosen time intervals.

PROBLEM STATEMENT

The reconstruction of both temperature and heat flux histories of the ground surface from borehole temperatures (inversion) is based on the solution of the one-dimensional nonstationary equation of heat conduction in a homogeneous or horizontally layered medium in the absence of heat sources and convective heat transfer factors (Carslaw and Jaeger, 1964)

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{a}\frac{\partial T}{\partial t} = 0 \quad (1)$$

with the boundary conditions

$$T(z = 0, t) = T_s(t), \quad \left.\frac{\partial T}{\partial z}\right|_{z \to \infty} = G_0, \quad (2)$$

where z is depth, t is time, a is the coefficient of the thermal diffusivity of rocks, G_0 is the stationary component of geothermal gradient, and T_s is the surface temperature.

As a boundary condition on the surface, one can specify a heat flux, which is related to temperature gradient by the Fourier law:

$$q(0, t) = -\lambda \left.\frac{\partial T(z, t)}{\partial z}\right|_{z = 0}, \quad (3)$$

where λ is thermal conductivity. The solutions of Eq. (1) with boundary conditions (2) and (3) described by simple analytical functions are given in (Carslaw and Jaeger, 1959; Lachenbruch and Marshall, 1986). In most inversion algorithms, the unknown temperature or thermal history of the ground surface is represented in the form of a combination of these simple functions.

Let us consider regularities between heat flux and temperature variations for the simplest case. Let the harmonic law of temperature variation be specified for the ground surface $z = 0$:

$$T(0, t) = T_0 + A\sin\left(\frac{2\pi}{\tau}t + \varphi\right), \quad (4)$$

where A is amplitude, τ is period, and φ is the phase of oscillations. We will describe the propagation of these oscillations to a depth by the relation

$$T(z, t) = T_0 + Ae^{-pz}\sin\left(\frac{2\pi}{\tau}t - pz + \varphi\right), \quad p = \sqrt{\frac{2\pi}{\tau}\Big/2a}, \quad (5)$$

and the variations in the ground-surface heat flux q_{an} by the equation

$$q_{an}(0, t) = -\lambda \frac{\partial}{\partial z}T(z, t)\Big|_{z = 0} = AE\sqrt{\frac{2\pi}{\tau}}\sin\left(\frac{2\pi}{\tau}t + \varphi + \frac{\pi}{4}\right) = E\sqrt{\frac{2\pi}{\tau}}T\left(0, t + \frac{\tau}{8}\right). \quad (6)$$

Here, E is the coefficient of the thermal effusivity (thermal inertia) of rocks, which characterizes the intensity of heat exchange on the ground surface. This coefficient is related to the other thermophysical parameters—thermal conductivity λ, thermal diffusivity a, and volumetric heat capacity ρC—by the relations

$$E = \sqrt{\lambda\rho C} = \lambda/\sqrt{a} = \rho C\sqrt{a}. \quad (7)$$

The heat flux variations are ahead of the temperature variations by 1/8 of the oscillation period. The physical meaning of such a shift is clear: it is precisely external heat flux variations that determine temperature variations, and not the reverse. For example, the given relations adequately describe ground surface temperature variations for both diurnal and annual cycles under the influence of varying insolation. Note that the parameter E (despite its second name—thermal inertia) determines only the ratio between the amplitudes of heat flux and temperature variations, but not the value of temperature lag.

The integral relations that relate variations in heat flux to those in surface temperature are given in (Wang and Bras, 1999):

$$q(0,t) = \frac{E}{\sqrt{\pi}}\int_0^t \frac{dT(0,s)}{\sqrt{t-s}},$$
$$T(0,t) = T_0 + \frac{1}{E\sqrt{\pi}}\int_0^t \frac{q(0,s)}{\sqrt{t-s}}ds, \quad (8)$$

where s is the variable of integration. In order to calculate a thermal history from the known temperature history, it is convenient to use the finite-difference approximation given in (Beltrami et al., 2002):

$$q(0,t_i) = \frac{2E}{\sqrt{\pi\Delta t}}\sum_{j=1}^{i}[T_j - T_{j-1}] \times [\sqrt{i-(j-1)} - \sqrt{i-j}]. \quad (9)$$

Equation (9) makes it possible to estimate instantaneous flux values at discrete times $t_i = i\Delta t$ on the basis of the temperature history approximated by the piecewise-linear continuous function.

INITIAL DATA

Earlier obtained geothermal estimates of surface-temperature variations for the Urals and meteorological data on surface air temperature variations were used in this work as initial data in reconstructing the histories of ground surface heat flux variations. Since temperature histories are different in length and, correspondingly, in time resolution, heat flux reconstructions obtained on their basis also cover different time periods: the last 30000, 1000, and 150 years.

HEAT FLUX RECONSTRUCTIONS

A Period of 30000–2000 Years Ago

The ground surface temperature history over this period was obtained in (Demezhko and Shchapov, 2001) on the basis of thermometry data for the SG-4 superdeep hole in the Urals. Calculations of the heat flux history were performed using Eq. (9). The reconstructed heat flux $q(0, t)$ and the initial temperature history $T(0, t)$ significantly differ (Fig. 1a). It follows from Eq. (6) that heat flux variations precede surface temperature variations, in our case, by approximately 2000–3000 years. The heat flux reached its maximum (0.075–0.080 W/m^2) about 10000 years ago and then started to decrease. The heat flux again started to increase after 4000 years ago.

One can assume that the dynamics of ground surface heat flux variations (at least, before 4000 years ago) was determined by variations in the yearly mean insolation $\Delta I(t)$ of the Northern Hemisphere, which were caused by variations in the Earth's orbital parameters—eccentricity, precession, and obliquity (Fig. 1b). However, the curve for heat flux variations lags behind the insolation curve. This shift may be caused, first, by the influence of climatic inertial factors that transfer external radiative forcings with a delay and, second, by errors in the chronology of the initial temperature history, which are caused by the overestimated thermal diffusivity coefficient of rocks, and this leads to a distortion of the time scale with respect to the true one by a_{ad}/a_{true} times (adopted and true values of thermal diffusivity in the numerator and denominator, respectively). In order to synchronize the curves $q(0, t)$ and $\Delta I(t)$, it is necessary to extend the flux history to its maximum coincidence with the insolation curve. However, a direct comparison of the curves is not quite correct: the time resolution of $\Delta I(t)$ is constant and that of $q(0, t)$ decreases as the distance into the past increases. The minimum resolvable interval of a geothermal reconstruction amounts to approximately $2t^*/3$, where t^* is the time (years ago) counted from the start of geothermal measurements in the hole (Demezhko and Shchapov, 2001). In (Demezhko and Solomina, 2009), a procedure of averaging in running windows of variable width was proposed in order to bring dendrochronology data to the general (with the geothermal reconstruction under comparison) form. As applied to the example under consideration, the formula for averaging the insolation curve digitized at the equal time intervals Δt has the form

$$\Delta I_i^s = \sum_{j=i-k(i)}^{i+k(i)} \Delta I_j/(2k(i)+1), \quad k(i) = \lceil i/3 \rceil, \quad (10)$$

where $\lceil x \rceil$ implies the operation of rounding to the next larger integer and $t^* = i\Delta t$.

The insolation curve smoothed in accordance with (10) for 60° N is shown in Fig. 1c. The maximum agreement between this curve and the heat flux history can be reached if the dating of the latter increases 1.35 times, which corresponds to the thermal diffusivity decreasing by the same times from 1.0×10^{-6} to 0.74×10^{-6} m^2/s (Fig. 1c). This correction shifts the curve $q(0, t)$ into the past, and its amplitude increases up to 0.09 W/m^2 due to increased thermal effusivity (when the thermal diffusivity decreases and the coefficient of thermal conductivity is conserved). The ratio between the amplitudes of variations in heat flux and insolation is $\Delta q(0, t)/\Delta I = 1.5\%$, and the squared coef-

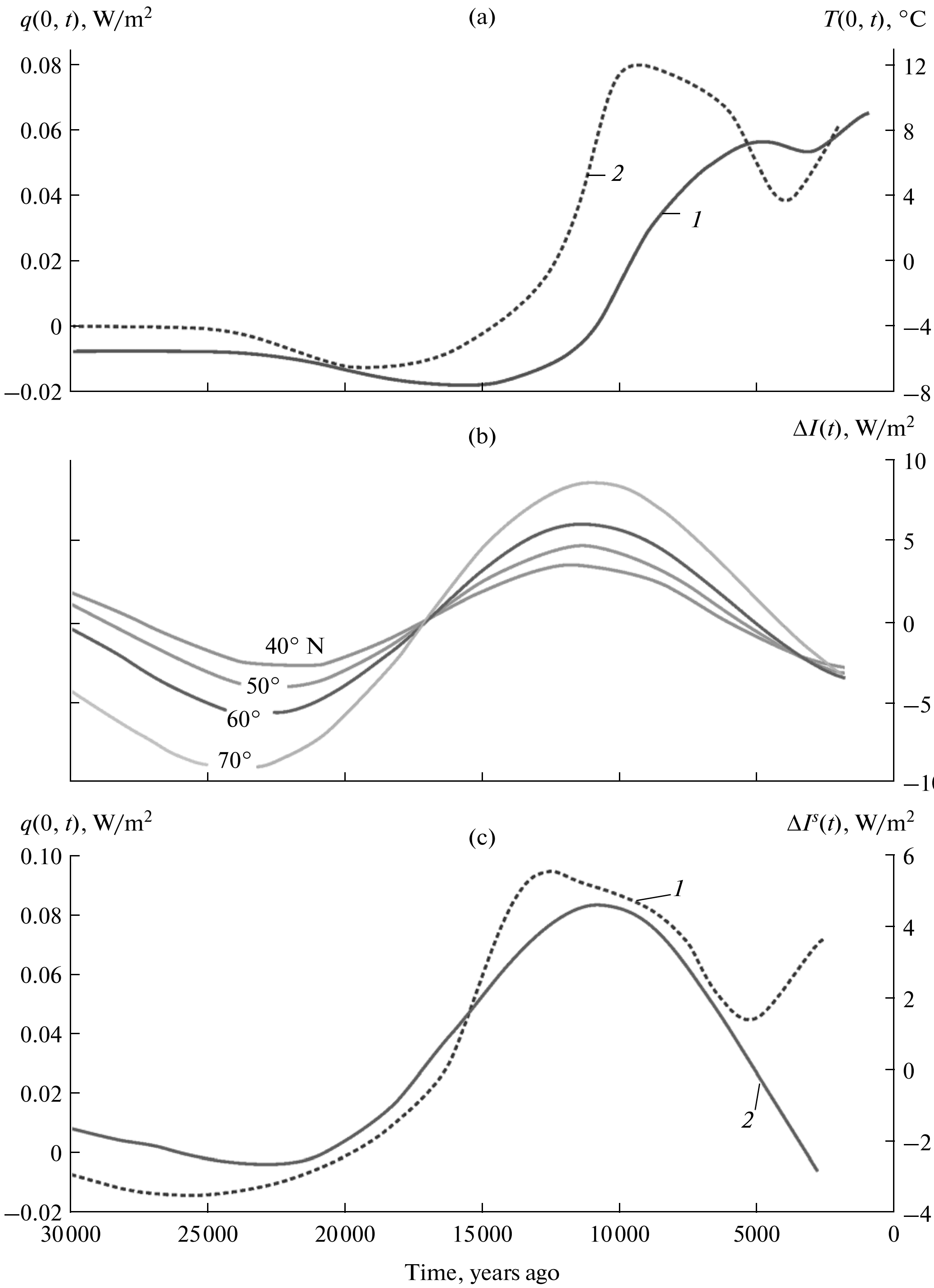

Fig. 1. Reconstruction and correction of the heat flux variation history over the last 30000 years: (a) (*1*) initial temperature history $T(0, t)$ ($a = 1.0 \times 10^{-6}$ m^2/s (Demezhko and Shchapov, 2001)) and (*2*) heat flux $q(0, t)$ reconstructed according to Eq. (9) (E = 2500 J/m^2 K s$^{1/2}$); (b) mean annual insolation variations $\Delta I(t)$ for 40°–70° N (Berger and Loutre, 1991); and (c) (*1*) corrected heat flux history $q(0, t)$ ($a = 0.74 \times 10^{-6}$ m^2/s, E = 2900 J/m^2 K s$^{1/2}$) and (*2*) insolation curve $\Delta I^s(t)$ smoothed according to Eq. (10) for 60° N.

ficient of linear correlation (determination coefficient), which characterizes the portion of the total variance in the Δq andΔI variations, within an interval of 30000–6000 years ago is R^2 = 0.98. Thus, the observed variability of ground surface heat flux is almost completely determined by orbitally induced insolation variations. Over a period of 20000–6000 years ago, the heat content of rocks increased by

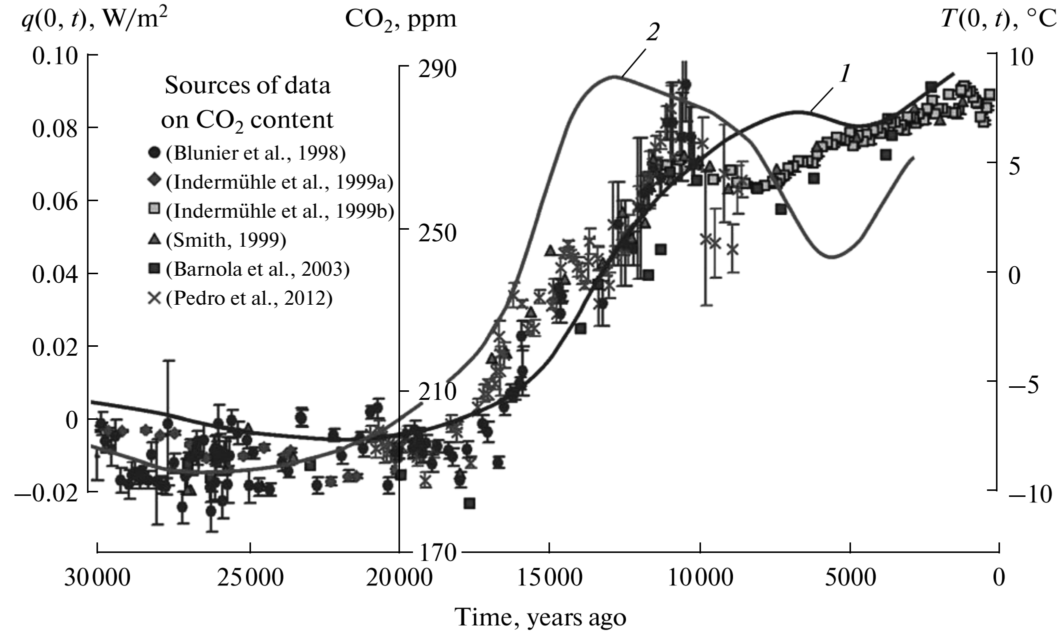

Fig. 2. Variations in (*1*) ground surface temperature $T(0, t)$, (*2*) heat flux $q(0, t)$, and (symbols) CO_2 content in the antarctic core over the last 30000 years.

2.64×10^{10} J/m^2. This value characterizes an additional amount of heat adsorbed in a rock column with a cross section of 1 m^2, which is vertically limited by the depth of propagation of the Pleistocene–Holocene warming anomaly (~2 km).

In addition to insolation, the greenhouse effect caused by an increase in the atmospheric content of CO_2 could also contribute to the Pleistocene–Holocene warming. This topic is under active discussion now (see (Shakun et al., 2012) and references therein). An increase in the greenhouse effect causes an increase in the descending flux of long-wave radiation, which must inevitably be reflected in the heat flux curve reconstructed by us. Figure 2 gives the geothermal reconstructions of temperatures and fluxes for the SG-4 hole and the data on variations in the CO_2 content in Antarctic ice cores (Blunier et al., 1998; Indermühle et al., 1999a, 1999b; Smith et al., 1999; Barnola et al., 2003; and Pedro et al., 2012). Despite a significant scatter in the estimates of the CO_2 content in the Antarctic ice, the character and chronology of the carbon dioxide variations are much closer to the temperature variations rather than to the heat flux ones. This may imply that the contribution of the atmospheric CO_2 content to the climate-induced heat flux is insignificant.

A Period of the Last 1000 Years

An earlier obtained generalized temperature history, which is based on an analysis of 49 borehole temperature profiles for the middle and southern Urals (51°–59° N, 58°–61° E), was used to estimate the history of heat flux variations over the last 1000 years (Demezhko et al., 2005; Demezhko and Golovanova, 2007). Figure 3 gives the temperature and (calculated from (9)) heat flux histories for the middle and southern Urals. The coefficient of thermal diffusivity *a* was assumed to amount to 1.0×10^{-6} m^2/s. Here, as well as in the previous example, the heat-flux variations are ahead of the temperature variations, in this case, by 75–150 years. In the 13th–16th centuries, the heat flux decreased and reached its minimum approximately in 1600, and, in the early 18th century, its rapid increase was observed. The medieval maximum in the history of heat flux variations is not as noticeable when compared to that in the history of temperature variations: the maximum values of heat flux for the 11th–12th centuries are significantly lower than its current values, while the maximum value of temperature is somewhat higher.

Heat flux variations may be caused by different radiation factors. The three main factors—solar radiation, atmospheric CO_2 concentration, and volcanic activity—are usually considered in analyzing the climate of the last millennium (Crowley, 2000; Servonnat et al., 2010).

Variations in the total solar irradiance (TSI) at the atmospheric upper boundary, which were reconstructed on the basis of data obtained from studying the isotope ^{10}Be concentration in Antarctic ice cores, were used as a characteristic of solar radiative forcing (Bard et al., 2000). The TSI depends on the solar activity and is not related to variations in the Earth's orbital parameters. Thus, the causes of variations in

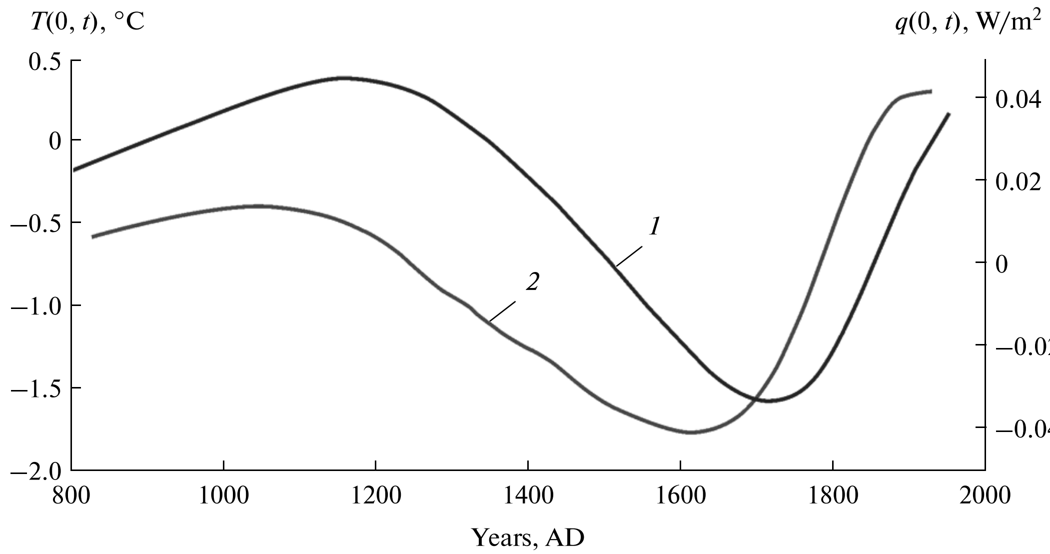

Fig. 3. (*1*) Generalized temperature history $T(0, t)$ (Demezhko et al., 2005; Demezhko and Golovanova, 2007) and (*2*) heat flux $q(0, t)$ reconstructed according to Eq. (9) ($a = 1.0 \times 10^{-6}$ m^2/s, $E = 2500$ J/m^2 K s$^{1/2}$) for the middle and southern Urals over the last millennium.

the TSI and insolation are different. In this case, within the 1000-year period under consideration, the value of orbitally induced insolation may be considered constant. More complete data on the atmospheric concentrations of carbon dioxide and sulfates which characterize the volcanic activity over the last 1000 years were obtained in studying both Antarctic and Greenland ice cores (Etheridge et al., 1998; Crowley and Unterman, 2012). In Fig. 4, the TSI is seen to have an approximately 200-year periodicity in solar activity (the so-called de Vries–Suess cycles (Braun et al., 2005)), which is pronounced against the background of long-term variations. The rapid, apparently, anthropogenic increase in the atmospheric concentration of CO_2 was observed in the early 19th century, and the maximum volcanic activity (and, correspondingly, the atmospheric concentration of SO_4^{2-}) was associated with the Samalas volcano eruption of 1257 in Indonesia (see Fig. 4).

The contribution of each of the above factors to the reconstructed heat flux variability was estimated using a multiple regression analysis. The series of all the factors were preliminarily smoothed in running windows with a variable width (10) (Fig. 5). By varying the coefficient of thermal diffusivity within a narrow range from its initial value ($a = 1.0 \times 10^{-6}$ m^2/s), its corrected value ($a = 0.93 \times 10^{-6}$ m^2/s), which provided the maximum coefficient of multiple determination ($R_\Sigma^2 = 0.94$) of heat flux with all the factors under consideration, was chosen (Table 1). The multiple determination coefficient gives an idea of the portion of the heat flux variance, which can be explained by the linear combination of the three factors—the TSI and the atmospheric contents of SO_4^{2-} and CO_2. The β coefficients (standardized multiple-regression coefficients) characterize the contribution of individual factors. The largest contribution to the flux of heat was made by variations in the flux of solar radiation: $\beta = 0.8$. This contribution (in module) exceeds the effects of the atmospheric content of CO_2 and volcanic activity 4 and 7 times, respectively. The ratio between the amplitudes of heat flux and solar radiation variations is determined by the coefficient for the TSI in the equation

Table 1. Results of a multiple regression analysis of the reconstructed heat flux, the total solar irradiance (TSI), and the atmospheric concentrations of volcanic sulfates (SO_4^{2-}) and CO_2 over the last 1000 years

Regression coefficients	TSI, W/m^2	SO_4^{2-}, kg/km^2	CO_2, ppm
Coefficient of multiple determination (R_Σ^2)	0.937		
β coefficients	0.800	–0.116	0.203

Equation of multiple regression: $q(0, t) = 0.028\mathrm{TSI} - 0.0018\,SO_4^{2-} + 0.0010CO_2 - 0.277$.

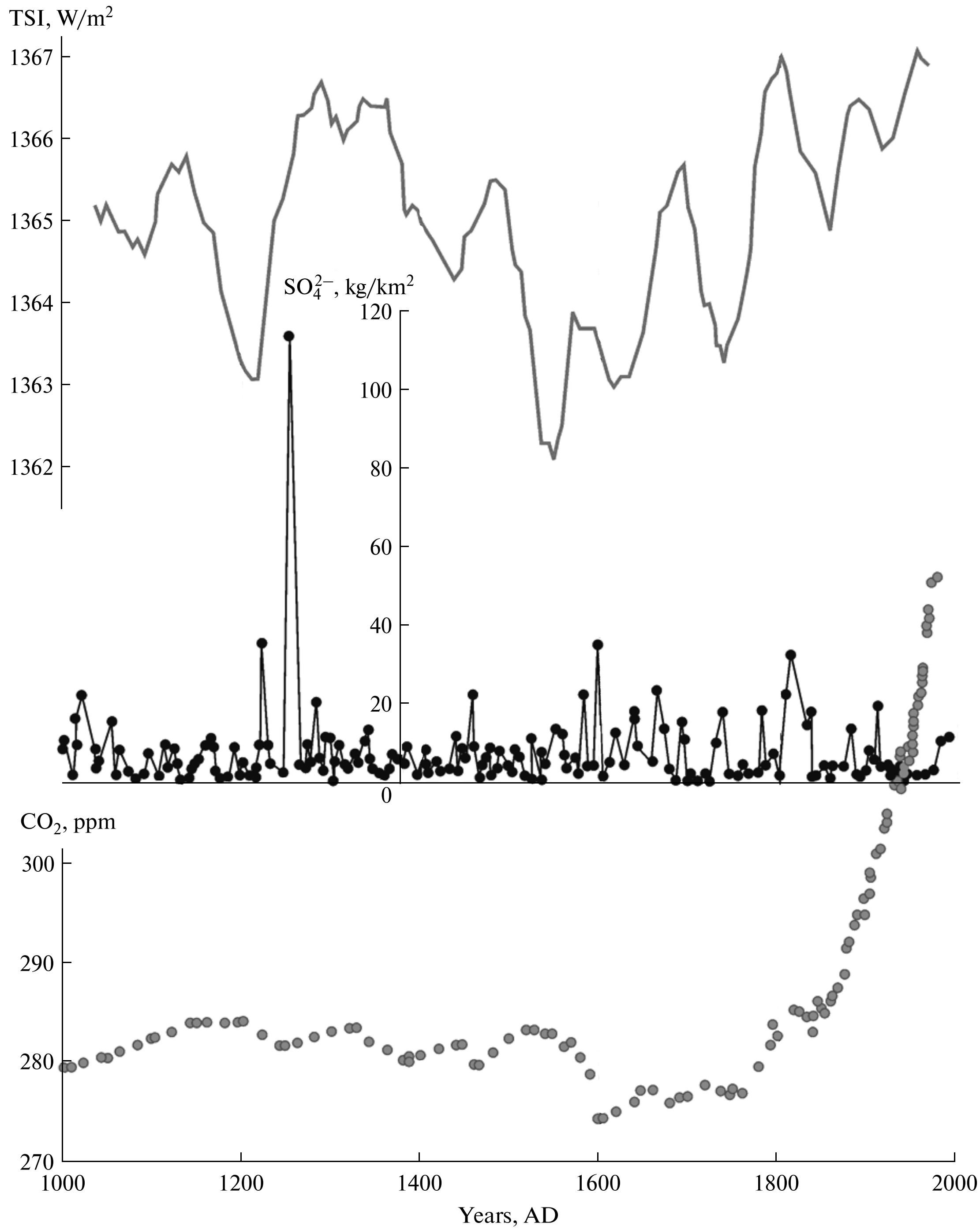

Fig. 4. Variations in the TSI at the atmospheric upper boundary (Bard et al., 2000), the content of atmospheric sulfates (SO_4^{2-}) in both Antarctic and Greenland ice cores (Crowley et al., 2012), and the content of CO_2 in the atmosphere (Etheridge et al., 1998) over the last millennium.

of multiple regression and amounts to $\Delta q(0, t)/\Delta I = 2.8\%$. It is quite expected that the negative coefficient for SO_4^{2-} implies the cooling effect of volcanic activity and the positive coefficient for CO_2 implies the warming effect (greenhouse gases).

According to the obtained curve $q(0, t)$ (see Fig. 5), within the Little Ice Age, when the heat flux remained negative (1200–1760 AD), the Earth's heat content decreased by 4.49×10^8 J/m². In the early 17th century, the heat flux started to increase and became positive only in 1760. From 1760 to 1920, the heat content of

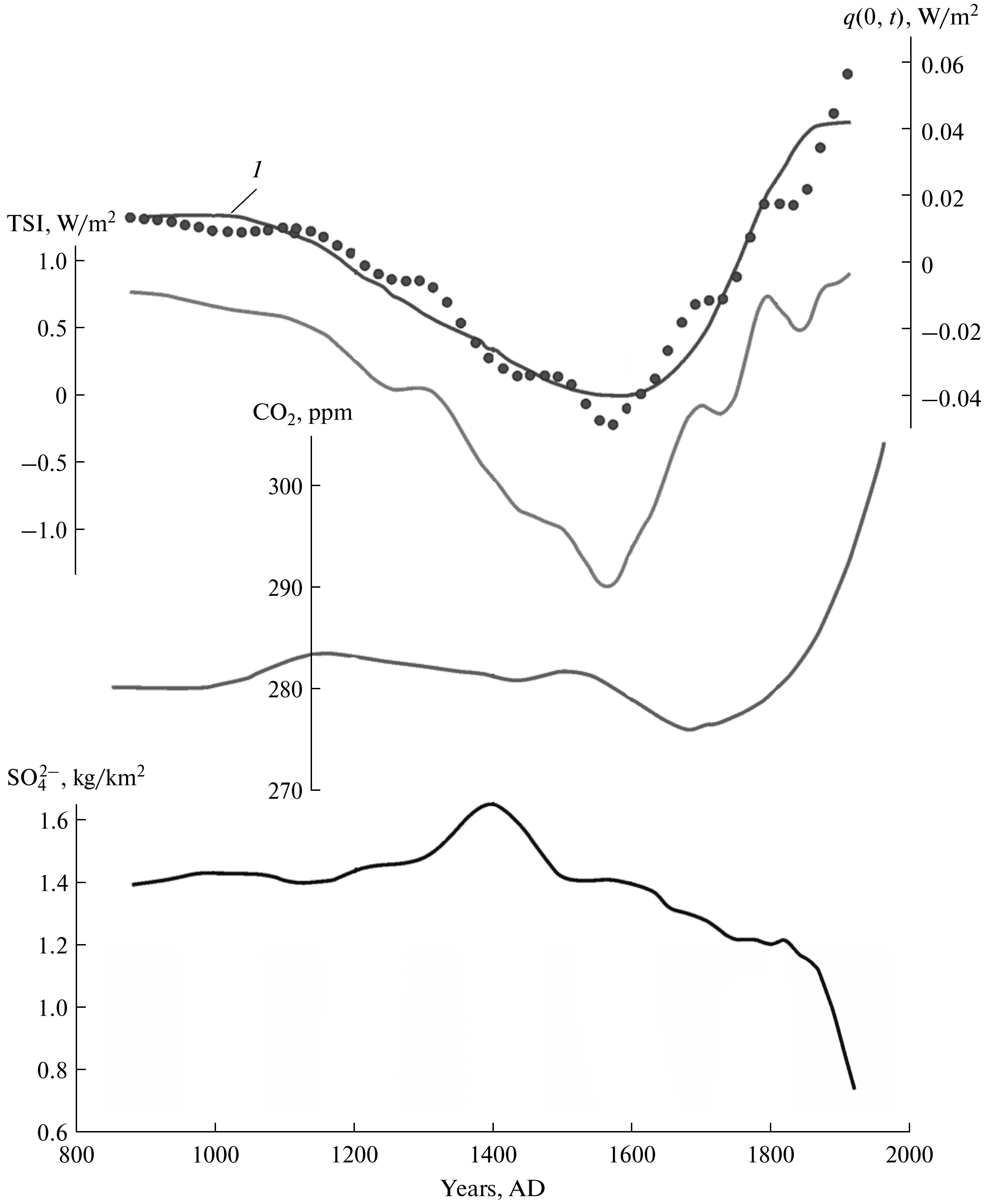

Fig. 5. Comparison of (*1*) the reconstructed heat flux $q(0, t)$ ($a = 0.93 \times 10^{-6}$ m^2/s, $E = 2700$ J/m^2 K s$^{1/2}$, and the points correspond to the flux curve approximated by the equation of multiple regression (see Table 1)) with the climate variability factors—the TSI and the atmospheric contents of CO_2 and SO_4^{2-} over the last millennium.

the lithosphere increased by 1.58×10^8 J/m^2. Thus, the current warming, which started back in the first half of the 18th century, had compensated for only 1/3 of the heat lost during the Little Ice Age by the 1920s.

The Period of the Last 150 Years

The climatic history of this period in the Urals is provided with data obtained from direct meteorological observations. The surface air temperature has been measured here since the first half of the 19th century, and, from 1930 to 1980, 150 observation stations operated here. The history of mean annual air temperature variations is given for the middle and southern Urals (51°–59° N, 58°–61° E) in (Demezhko and Golovanova, 2007). This history was obtained by generalizing 43 data series differing in length with the aid of the method described in (Hansen and Lebedeff, 1987). In

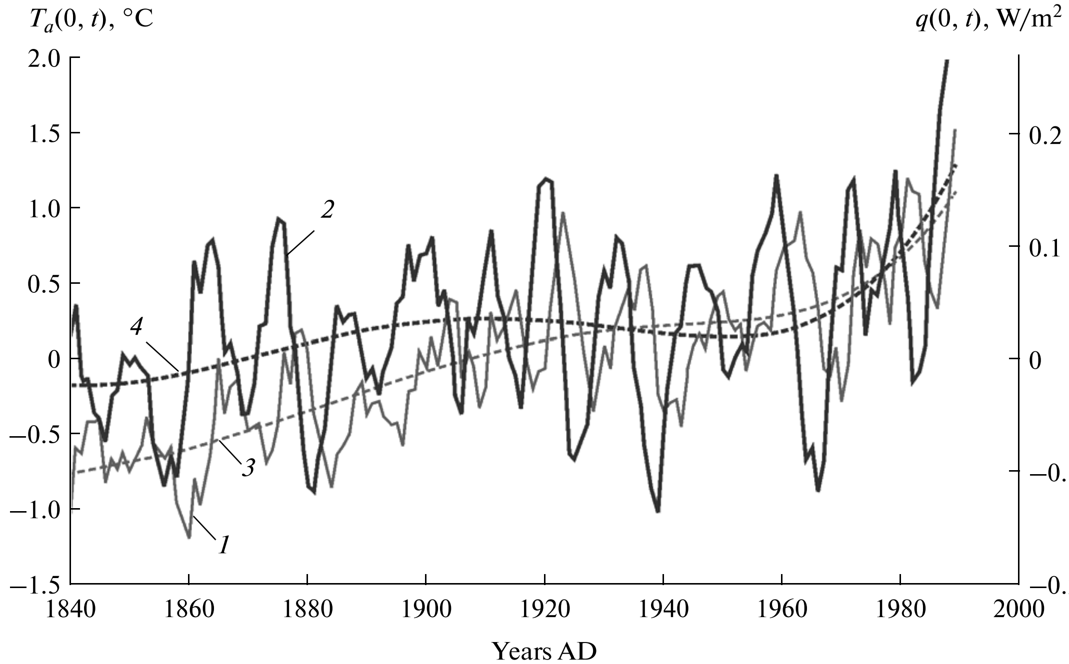

Fig. 6. Variations in (*1*) the surface-air temperature $T_a(0, t)$ (Demezhko and Golovanova, 2007) and (*2*) the heat flux $q(0, t)$ reconstructed according to Eq. (9) ($E = 2500$ J/m^2 K s$^{1/2}$) for the Urals over the last 150 years, which were smoothed in a 5-year running window, and their approximations by the fifth-order polynomial (curves *3* and *4*, respectively).

this work, this history is used for reconstructing ground surface heat flux variations. In this case, it is assumed that variations in yearly mean ground surface and air surface temperatures occurred synchronously and with approximately the same amplitude. The validity of such an assumption for centennial temperature variations was proved by direct comparisons of geothermal reconstructions with measured data (Demezhko and Golovanova, 2007) and model calculations (Gonzales-Rouco et al., 2003, 2006). The results of temperature monitoring in holes (Chapman et al., 2004) showed that the correlation between mean annual ground surface and air temperatures reached 97%.

The temperature curve and the heat flux history reconstructed on its basis are given for the Urals in Fig. 6. The main contribution to the ground surface heat flux variations is made by high-frequency oscillations that occur against the background of the total linear trend towards increasing heat flux and approximately 100-year variations. The nature of oscillations of different frequencies may also be different; therefore, it is reasonable to analyze them individually.

At first glance, the short-period heat flux variations approximately correspond to the 11-year cycle of solar activity oscillations. In fact, the most pronounced cycle in the amplitude spectrum of heat flux variations is the 12-year cycle (there is in addition a 14-year cycle) (Fig. 7). However, the annual difference between the periods of oscillations in solar radiation and ground surface heat fluxes is significant. This difference causes variations in the flux of heat to occur in different phases with respect to those in the flux of solar radiation (Fig. 8): synchronously until 1860, asynchronously from the 1870s to 1940, and again synchronously since the 1950s. It is clearly demonstrated by the behavior of the coefficient of correlation between the two data series, which was calculated in the running windows of 11-year width (see Fig. 8). The trend of the curve makes one doubt the widespread notion of the cause–effect relation between the 11-year solar activity cycle and the ground surface heat flux. Such an assumption has recently been made in (Volobuev, 2013); here, the history of ground surface heat flux variations was reconstructed using a similar method on the basis of surface air temperature data obtained at the Vostok antarctic station in 1958–2011. Synchronous 11-year variations in both solar and ground surface heat fluxes ($r = +0.5$) were noted, and it was concluded that the contribution of solar radiation is determining. This possibly erroneous opinion may be the result of a bounded series of observational data.

It is interesting that the long-term q and TSI variations described by the polynomial trends of the fifth order also occurred in antiphase. Let us make a regression analysis of the 1840–1989 q and TSI variations and add data on variations in the atmospheric contents of CO_2 and volcanic sulfates (also approximated by fifth-order trends). The ratio between the centennial variations in the factors under consideration, when compared to their millennial ones, has significantly changed (see Table 2). The effect of the atmospheric

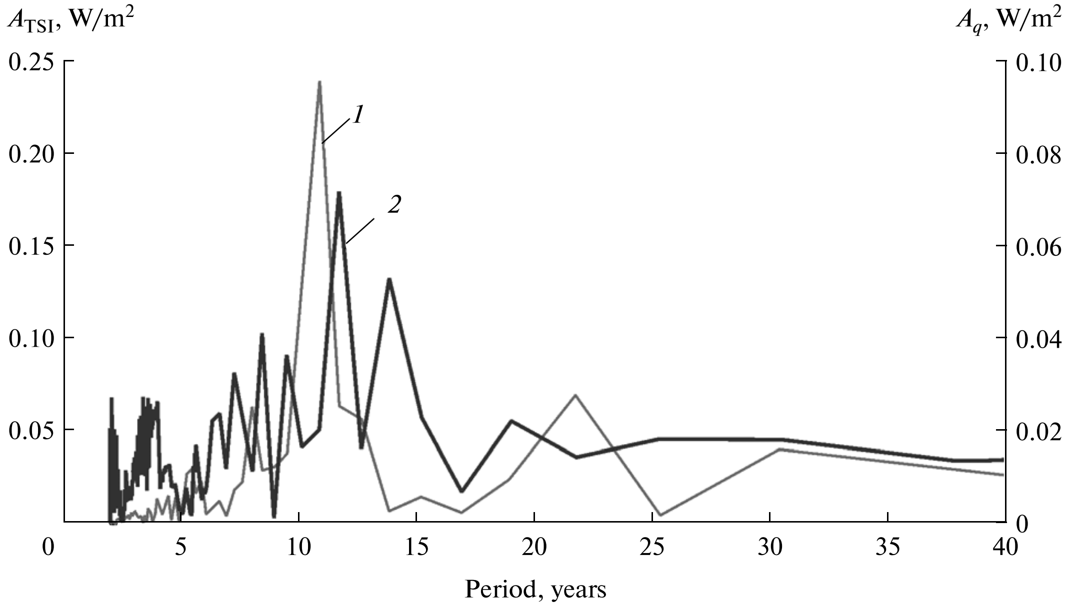

Fig. 7. Amplitude spectrum of variations in (*1*) solar radiation A_{TSI} and (*2*) heat flux A_q.

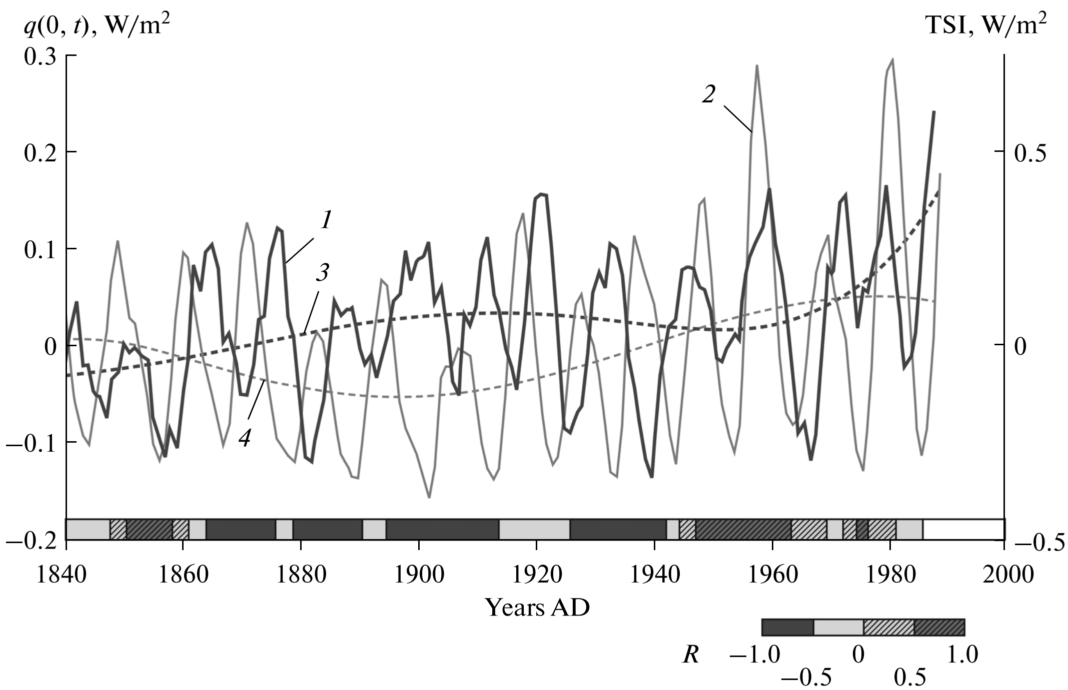

Fig. 8. Variations in (*1*) the reconstructed heat flux and (*2*) solar radiation flux (in deviations from the mean over 1836–1991) (Crowley et al., 2012) and (*3* and *4*) their approximations by the fifth-order polynomials, respectively, over the last 150 years.

content of CO_2 significantly increases and, hence, the β coefficient increases from 0.20 up to 1.27. According to the regression equation, an increase of 70 ppm in the concentration of carbon dioxide over the 1838–1989 period is bound to lead to a heat flux increase of $70 \times 0.00256 = 0.18$ W/m² (higher than the observed amplitude of flux variations!). However, the dependence of heat flux on the content of CO_2 was slightly weakened due to the negative effect of solar radiation (β = −0.46). The contribution of volcanic activity remained insignificant, although it also changed its sign. Despite the high value of the coefficient of multiple determination $R_\Sigma^2 = 0.95$, one should consider the obtained result with caution. The appearance of

Table 2. Results of a multiple regression analysis of the reconstructed heat flux, the total solar irradiance (TSI), and the atmospheric concentrations of volcanic sulfates (SO_4^{2-}) and CO_2 over the last 150 years (1838–1989)

Regression coefficients	TSI, W/m^2	SO_4^{2-}, kg/km^2	CO_2, ppm
Coefficient of multiple determination (R_Σ^2)		0.948	
β coefficients	–0.463	0.131	1.266

Equation of multiple regression: $q(0, t) = -0.181\text{TSI} + 0.0102\,SO_4^{2-} + 0.00256CO_2 - 0.762$.

difficult-to-interpret coefficients in the regression equation (negative for the TSI and positive for SO_4^{2-}) most likely suggests the absence of the mechanism of a direct linear forcing of these factors on the heat flux. It is likely that, on centennial and shorter time scales, the internal dynamics of the ocean and atmosphere plays the main role in the formation of climate. This dynamics is especially pronounced in regional climates.

Table 3 gives estimates of variations in the heat content of rocks in the upper lithosphere over the last 150 years. Table 3 also gives the geothermal estimates for the periods considered in the previous sections (the last 30000–2000 and 1000 years) and the data on variations in the heat contents of the continents, the world ocean, and the atmosphere, which were obtained from different sources (geothermal reconstructions, flux reconstructions on the basis of meteorological observations, and instrumental (satellite) measurements). The estimates of heat content variations we obtained for the Urals are 1.3–2 times higher than the mean values for the individual continents and the Earth, as a whole, which supports the conclusion that the regional variability of such factors is significant (Beltrami et al., 2006). Thus, for eastern Canada, the estimate of heat content variations over the last 100 years amounts to 23.4×10^7 J/m^2 (Beltrami et al., 2000), which is 2.6 times higher than the mean for Asia and 1.8 times higher than our estimate for the Urals. Note also that the heat lost over the Little Ice Age in the Urals (1200–1760) had been compensated for by the late 20th century (1989) only by 60%.

CONCLUSIONS

These studies have shown the efficiency of the algorithm of calculating the history of ground surface heat flux variations from data on surface temperature variations. It was shown in (Beltrami, 2002) that the direct inversion of borehole temperatures into a thermal history is very sensitive to initial data errors. Unlike this inversion, the two-phase calculation algorithm "borehole temperatures–surface temperatures–heat flux history" yields more stable results, because it allows temperature histories to be preliminarily smoothed. Moreover, it makes it possible to use meteorological data (surface air temperature) in estimating heat flux variations.

Paleoclimate data contained in heat flux variation histories significantly differ from conventional temperature characteristics. Being an energetic expression of climate processes, heat fluxes may directly be compared to energy fluxes in the atmosphere and at its upper boundary. A joint analysis of data on heat fluxes and greenhouse gas emissions makes it possible to estimate the anthropogenic contribution to ground surface heat balance variations. The ratio between the ground surface and external fluxes can be considered an alternative index of the Earth's climate sensitivity. When compared to the conventional index of climate sensitivity, which describes the response of temperature to external radiative forcing, the dimensionless ratio of these fluxes has its advantages: first and foremost, this ratio is, to a lesser degree, dependent on the time of radiative forcing.

In this work the long-term ground surface heat flux variations were first estimated for the Urals for three time scales (the last 30000, 1000, and 150 years). A preliminary analysis of the data showed that, with a time-scale decrease, the direct contribution of solar-radiation variations to the ground surface heat flux also decreases. On the scale of glacial-interglacial cycles, the heat flux variations almost completely coincide with the insolation variations in the Northern Hemisphere, and the carbon dioxide variations occur 2000–3000 years later—synchronously with the temperature response. Solar radiation also makes the main contribution to the heat flux variations of the millennial scale; however, the effects of atmospheric CO_2 content and volcanic activity are also noticeable. The centennial heat flux variations occur in antiphase with the solar radiation variations. The 12-year cycle of heat flux variations, which cannot explicitly be compared to the 11-year cycle of solar activity, has also been revealed.

The estimates of variations in the heat content of the upper lithosphere (see Table 3) make it possible to compare the energy of different episodes of climate history. Thus, during the period 20000–6000 years ago, in the Urals, the lithosphere accumulated an amount of heat that is 200 times larger than that accu-

Table 3. Variations in the heat content of rocks (in 10^7 J/m^2) for different periods

Region, objects	Period, years					Source
Middle and southern Urals	**20000–6000**	**1200–1760**	**1760–1989**	**1889–1989**	**1939–1989**	(This work), geothermal reconstructions (gr), flux reconstructions on the basis of meteorological data (mr)
	2640 (gr)	−44.9 (gr)	26.2 (gr + mr)	12.9 (mr)	8.2 (mr)	
Continents (whole world)			**1765–2000**	**1900–2000**	**1950–2000**	(Beltrami, 2002), geothermal reconstructions
			13.3	8.7	4.8	
			16.9	10.8	6.1	(Beltrami et al., 2002), geothermal reconstructions
Continents (Northern Hemisphere)			**1800–2000**		**1950–2000**	(Beltrami et al., 2006), geothermal reconstructions
			13.0		4.5	
Eastern Canada				**1900–2000**		(Beltrami et al., 2000), geothermal reconstructions
				23.4		
Asia				**1901–2000**	**1951–2000**	(Huang, 2006), flux reconstructions on the basis of meteorological data
				9.0	5.6	
Africa				5.9	3.8	
North America				8.9	4.8	
South America				7.0	4.0	
Europe				8.1	4.5	
Australia				2.7	3.8	
World Ocean					**1955–1996**	(Levitus et al., 2001), instrumental data
					50	
Atmosphere					1.3	

The sources give the mean values of climatically induced heat fluxes over a period (q, W/m^2) or heat content variations over this period for a whole continent or the Earth's ground surface as a whole (Q_s, J). For a convenient comparison, Table 3 gives the estimates of heat content variations per unit surface area (J/m^2). In recalculations, the following areas were used: 510.072×10^{12} m^2 for the Earth, 361.1×10^{12} m^2 for the World Ocean, 148.939×10^{12} m^2 for the Earth's ground surface, 100.5×10^{12} m^2 for the Northern Hemisphere (ground surface), 44.579×10^{12} m^2 for Asia, 30.065×10^{12} m^2 for Africa, 24.474×10^{12} m^2 for North America, 17.819×10^{12} m^2 for South America, 9.938×10^{12} m^2 for Europe, and 8.112×10^{12} m^2 for Australia.

mulated during the last 100 years (2640×10^7 J/m^2 and 12.9×10^7 J/m^2, respectively), and the heat lost during the Little Ice Age (1200–1760) has not yet been compensated for by the current warming, which has been lasting more than 150 years.

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