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GEOPHYSICS

The History of the Mean Temperature of the Northern Hemisphere over the Last 11000 Years

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The magnitude and the sign of future climate changes are determined by a complex superposition of anthropogenic and natural factors. There are a number of reasons to believe that over the last centuries the climate has been cooling and will continue to do so in the future [1–4]. This can, to a some extend, reduce the relative temperature rise caused by anthropogenic activity. Hence, the quantitative study of regularities of the natural evolution of climate has a great significance. Attempts to estimate the parameters of natural climate variations were repeatedly made in the past [5, 6]. However, the lack of detailed information on the mean annual global and hemispheric temperatures for a sufficiently long timespan was, up to the present, a serious obstacle that prevented one from making generalizations. In this work we attempt to reconstruct the temperature series for the Northern Hemisphere during the Late Glaciation-Holocene from paleoclimatic data. Results of modern instrumental observations were also used.

For the paleoclimatic reconstruction of Late Glaciation and Holocene, we used the informational-statistical method [7] based on the statistic relation between the contemporary spore and pollen spectra and climatic conditions (mean temperatures for July and January, mean annual temperatures, and total annual precipitation). The accuracy of determinations of mean values is as follows: July and mean annual temperatures, ±0.6°C; January temperature, ±1°C; and total annual precipitation ±25 mm.

More than 60 paleoclimatic curves with different degrees of detail were drawn out by this method for plane regions of northern Eurasia. Figure 1 illustrates the reconstructed mean July temperatures for some regions located in temperate and subpolar latitudes and spaced many thousands of km apart. The rather good correlation between all these curves is an additional argument in favor of the recent concept [2, 8, etc.] that all large-scale (about one degree) climate variations in Late Glaciation–Holocene are manifested in all parts of the globe with a remarkable synchronism but different amplitude. Based on this conclusion and on the abundant temperature variation data on vast land regions, we attempted to reconstruct global climate variations over the last 11000 years.

The principal obstacles in obtaining the time series of mean global temperature from palynological data are the following: initial series for specific palinological sections differ in duration as well as in time step; the sampling (section) sites are chaotically spaced.

To overcome the first obstacle, we reduced all series to a standard time scale (at 25-year intervals) and a single period (11 ka B.P.—1950). When performing this procedure, we took into account results of the comparison of temperature series obtained at different sections, which demonstrate substantial compatibility despite the large distances between them. The fact that the studied series contain information on rather long-term and large-scale temperature variations only is, in our opinion, the reason why these series demonstrate consistent temperature changes. But the scale of these variations is different for different sections. As a rule, their amplitude increases with an increase in the geographical latitude of the section; this is in good agreement with conclusions obtained from the instrumental climate observations in [9]. Hence, we assume that each of the reconstructed temperature series $T_i^!$ can be represented as a sum:

$$T_i^! = T_i(t) + \varepsilon_i(t), \qquad (1)$$

where $T_i(t)$ is the mean annual air temperature over the section i at instant of time t and $\varepsilon_i(t)$ are the accuracy of measurements. Note that for any two sections i, j, functions $T_i(t)$ and $T_j(t)$ are connected by a linear relation. In order to determine the shape of the signal $T(t)$ as exactly as possible, we selected the nine most detailed series, the duration of which exceeds the chosen time

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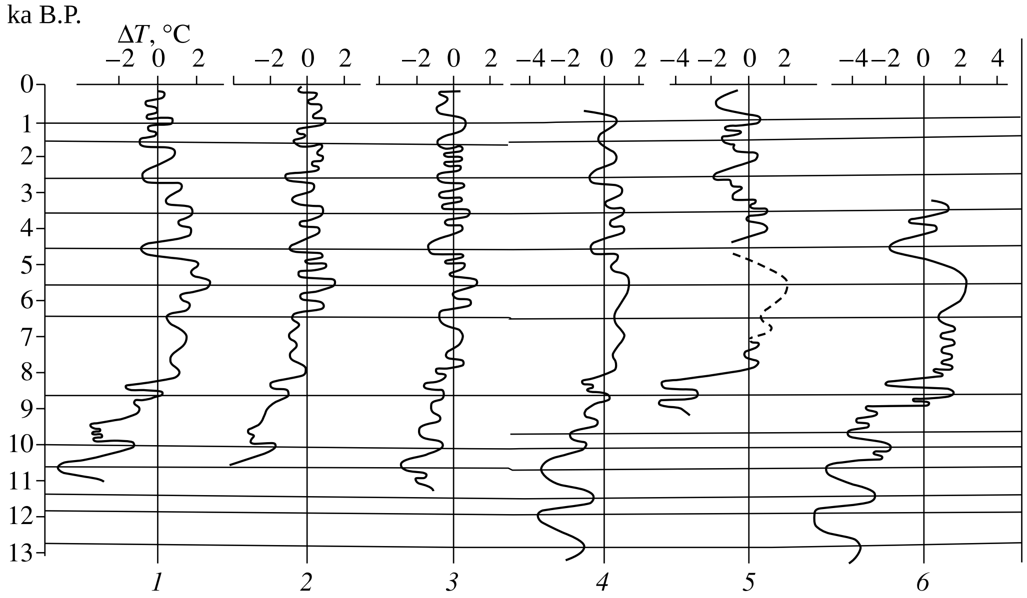

Fig. 1. Paleoclimatic curves (the deviations of the mean June temperatures from the present–day ones (in °C) for different regions of northern Eurasia: (*1*) Karelia, (*2*) central Western Siberia, (*3*) central Yakutia, (*4*) central Byelorussia, (*5*) Bashkiria, (*6*) Primorsk region.

interval, and constructed the averaged temperature series

$$\bar{T}(t) = \frac{1}{9}\left[\sum_{i=1}^{9} T_i(t) + \sum_{i=1}^{9} \varepsilon_i(t)\right]. \qquad (2)$$

If we assume, additionally, that $\mathrm{Cov}(\varepsilon_i, \varepsilon_j) = 0$, then the signal to noise ratio for this series must be substantially greater than that for the initial ones. In a first approximation, we can neglect the second term in (2) and consider that the averaged series does not involve a noise.

We estimated coefficients of the linear regression of each initial series on averaged series (2). The closing of gaps and the extrapolation of initial series was carried out by substitutions of corresponding points of averaged series (2) transformed with consideration taken for the regression coefficients.

In order to overcome the second obstacle, the results of temperature measurements at chaotic sampling (section) sites were interpolated into zones of a regular 5° latitude by 10° longitude grid. We chose the interpolation technique of Jones *et al.* [10] for compiling the global grid archives of air temperatures. In accordance with this technique, the temperature in a grid zone is determined by the sum of temperatures measured at nearest points with weights that are inversely proportional to their distance from the zone. The grid data obtained in this way were integrated for the territory of the former USSR. In our opinion, the series obtained constitute important information on the change in the global climate and can be used, in particular, for reconstructing the time series of the global mean temperature of surface air. Actually, although the change in the global climate is followed by a very nonuniform spatial distribution of climatic parameters, the mean temperatures for rather large regions can be calculated with reasonable accuracy by means of a linear transformation of the mean global temperature. In other words, the following statistic model is applicable:

$$T_{\mathrm{r}}(t) = \alpha + \beta T_{\mathrm{ge}}(t) + \varepsilon(t), \qquad (3)$$

where $T_{\mathrm{r}}(t)$, $T_{\mathrm{gl}}(t)$, and $\varepsilon(t)$ are the mean regional temperature in the year *t*, mean global temperature in the year *t*, and random noise, respectively. It is evident that the greater the size of a region, the more precise will be the model (3). Therefore, the coefficients of correlation between the mean global temperatures and temperatures for both the Northern and Southern Hemispheres calculated from the data of Jones *et al.* [11] are equal to 0.95. But model (3) may be of use for considerably smaller regions, as was demonstrated in [9] for the 10° latitude by 360° longitude zone of the Northern Hemisphere (data on instrumental observation of climate).

In our work, the β coefficient was obtained by averaging (with weights proportional to area) corresponding coefficients for a 10° latitude by 40° longitude region (in our works, for regions 10° lat. by 40° long. in size) of the former USSR. In this case, the value of β is equal to 1.47. Therefore, we used the following formula for calculating the global average temperature:

$$T_{\mathrm{gl}} = \frac{1}{\beta}T_{\mathrm{r}} - \frac{\alpha}{\beta}, \qquad (4)$$

where $\beta = 1.47$, and the constant α was chosen in such a way that the mean value of the series obtained over the 1851–1950 period coincided with the mean hemi-

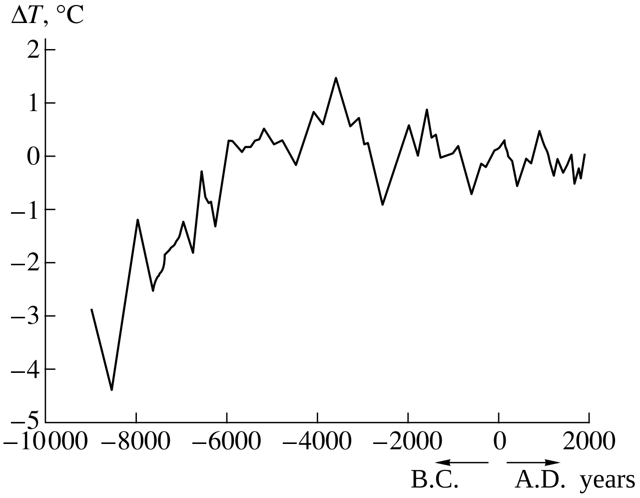

Fig. 2. Change of mean temperature in the Northern Hemisphere (expressed as anomalies relative to 1951–1980) over the last 11000 years.

spheric temperature anomaly over the same period (–0.25°C) derived from instrumental observation [11] (previously, Jones's series was recalculated relative to data for 1951–1980). Thus, the obtained T_{gl} series (Fig. 2) is a reconstruction of anomalies (relative to 1951–1980) in the mean annual temperature of the surface air in the Northern Hemisphere.

This reconstructed series depicts a complex pattern of alternating cooling and warming periods during Late Glaciation–Holocene. We cannot agree with the statement [12] about a remarkable climatic stability over the last 10 ka, which is based on recent results from the investigation of the Greenland ice core at the Summit station. The onset of temperature extremums are in good agreement with the existing notions based on isolated local reconstructions. One should not consider this fact surprising because of the suggestion mentioned above about the global character of large-scale climate variations. As for temperature variation amplitudes, the pattern presented in Fig. 2 is, in contrast, inconsistent with conventional notions [13]. Perhaps only the big Atlantic optimum (6–5 ka B.P.) retains its significance as the warmest and, simultaneously, the most continuous Holocene period. Mean temperatures and the peak values exceeded present-day values by 0.82°C and 1.4°C. Our estimate of the mean temperature is in good agreement with calculations (0.6–0.7°C) in [14] conducted on the basis of paleoclimtic reconstruction for a nontropical zone of the Northern Hemisphere.

Our estimate is perhaps more valid because it is based on a distinct pattern of latitudinal temperature distribution anomalies registered by reliable instrumental observations over almost 150 years. The subboreal (4.2–3.3 ka B.P.) maximum was the second highest temperature value; temperatures during the Early Holocene warming differed from present-day ones by only few decigrades. This, however, seems natural if we take into account the preservation of much of the continental ice and cold North Atlantic in this period. The temperature curve obtained is valuable initial material for constructing a long-range prediction of the behavior of natural climate. In doing so, our first objective was to determine the temperature effects of long period (about 10^4–10^5 years) cycles of the natural climate, which, apparently, are related to alterations of the parameters of Earth's heliocentric orbit.

In order to determine the temporal trend of the climate change, we used the standard procedure for time series analysis [15]. The study of the history of several interglaciations let us to choose a quadratic function for estimating the temperature change trend. The coefficient of correlation between the relation

$$Y(t) = At^2 + Bt + C, \tag{5}$$

and experimental data reaches 0.93; $Y(t)$ is the trend estimate of a temperature change; t is time; A, B, and C are coefficients.

Our results show that the rate of mean global temperature drop caused by orbital factors will be of the order of $(3–6) \cdot 10^{-4}$°C per year during, at least, the next few thousand of years. This value is an order of magnitude less than the rate of the temperature rise registered by instrumental observations during the last century and assumed for the 21th century. Nevertheless, the trend, which is well pronounced and stable in amplitude and sign, suggests that the significant temperature effect resulting from orbital variations should be taken into consideration for correct forecast and the long-range (over several centuries) climatic reconstruction. The aforesaid statement refers equally to the calculation of anthropogenic warming, the significance of which will be progressively diminished due to the action of powerful orbital factors.

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