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GEOPHYSICS

Geothermic Estimates of the Amplitudes of Holocene Warming in Europe

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Periodic alternation of ice ages and warm interglacial periods is a characteristic feature of the Earth's climatic system in the Quaternary Period. This is testified by the data from oxygen isotopic analysis on deep-sea sediment and ice cores [1]. At the same time, the mechanism of glaciation fluctuations remains unclear in many respects. Indications of the spatial distribution of climate characteristics during the periods of its global changes are needed to understand more clearly the causes of these fluctuations. The last climate change occurred approximately 10 000 yr ago in the beginning of the modern interglacial period (Holocene). In our paper, we analyze the spatial distribution of geothermic estimates of the amplitudes of Holocene warming in Europe.

The geothermic of the reconstruction of ground surface paleotemperatures is based on the analysis of the modern vertical distribution of rock temperature in boreholes. Climate-induced fluctuations of ground surface temperatures ascend across the rock sequence and provoke perturbations in the steady-state temperature field formed by the background heat flow and thermal properties of the medium. The analysis of the modern transient anomalies allows us to estimate the temperature history of the surface in the borehole region [2–4]. In order to estimate the Holocene warming amplitude, one needs the data on temperature measurements in 1.5- to 3-km-deep boreholes drilled in low-permeable rocks with homogeneous thermophysical properties. It is clear that such rocks are scarce.

Recently, the geothermy has been used for reconstructing surface paleotemperatures of glaciers [5]. Although temperature measurements in a homogeneous ice column are more accurate, it is necessary to take into account the vertical current in the medium, which somewhat decreases the reliability of the reconstructions.

We have used 11 geothermic estimates of the Holocene warming amplitude (Table 1). Estimates from boreholes Sg-4 and K-3000 were obtained by Demezhko. The estimate from borehole K–3000 is published here for the first time (the temperature measurements were provided by Prof. R.I. Kutas, Ukraine). The other estimates were taken from literature. In this work, the Holocene warming amplitude ΔT is the difference of the mean temperature of the Earth's surface between 15–30 and 8–0 ka BP.

The spatial distribution of the estimates of ΔT (Fig. 1) demonstrates clear asymmetry with respect to the geographical North Pole: the maximal values of amplitude are confined to the North Atlantic regions. This regularity contradicts the popular concept of the latitudinal dependence of the amplitude of global climatic changes. On the other hand, this region is the center of the modern positive anomaly of air surface temperature (the most significant on the planet) related to the system of warm currents in the North Atlantic (the Gulf Stream, North Atlantic, and Norwegian currents).

In order to obtain a quantitative characteristic of the relation between the ice age climate and Holocene climate, the modern values of annual mean air surface temperature at the points of boreholes were presented as a function of their geographical latitude (circles in Fig. 2). Assuming that, in the absence of an anomaly, the latitudinal temperature distribution in the range 45–75° N would be close to linear distribution, the influence of the anomaly can be estimated by the contribution of the unexplained variance $1 - R^2 = 12\%$, where R is the coefficient of linear correlation. The mean values of temperature 15–30 ka BP at the same points can be obtained by subtracting the estimates ΔT from the modern temperatures (triangles in Fig. 2). It is assumed that the amplitudes of the air surface temperature and ground surface temperature are similar. The latitudinal dependence in ice age, as compared to the modern one, demonstrates a 1.7-fold higher latitudinal gradient (–0.7

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Distribution of geothermic estimates of Holocene warming

No.	Borehole	Geographical position	Coordinates		ΔT, K	Data source
			N	E		
1	Fil-240	Transylvania	46°23′	24°38′	10	[6]
2	Lj-1	Slovenia	46°30′	16°11′	10	[7]
3	K-3000	Ukraine	48°34′	32°17′	12	
4	KTB	SE Germany	49°47′	12°08′	9	[8]
5	De-1	Czech Republic	49°49′	17°23′	11	[9]
6	Udryn	Poland	54°14′	22°56′	17	[10]
7	Il-1	Southern Ural	55°00′	60°10′	8	[11]
8	SG-4	Middle Ural	58°24′	59°46′	12	[4, 12]
9	Krl	Karelia	63°15′	36°10′	18	[13]
10	Kol	Kola Peninsula	67°45′	35°25′	20	[14]
11	GRIP	Greenland	72°36′	37°39′W	23	[5]

and –1.2 K per degree of northern latitude, respectively) and 3 times smaller deviation from the linear dependence ($1 - R^2 = 4\%$). An approximation to the linear dependence indicates a sublatitudinal strike of annual mean isotherms during the recent glacial epoch. Hence, the North Atlantic temperature anomaly did not exist at that time, or this anomaly was significantly suppressed. We can suppose that the Holocene warming is first of all related to the formation (or resumption) of the modern system of currents in the North Atlantic. This is the main conclusion of this study.

The obtained reconstruction allows us to make a number of paleoclimatic conclusions.

1. The modern southern permafrost boundary correlates with the annual mean isotherm –2°C. During the recent ice age, it reached 50° N, which is confirmed by several paleobotanic data.

2. The latitudinal profile south of 49° N in the ice age approaches the modern profile of annual mean temperatures (Fig. 2, dashed line) that passes through the continental regions of eastern Siberia, Mongolia, and China, which are far from the oceanic influence. Thus, the modern climate in these regions can be considered an analogue of the glacial climate of southern Europe. North of this boundary, the profiles diverge. A 3–8 K temperature difference between them is possibly caused by the albedo component, i.e., a decrease in the insolation caused by the growth of ice and snow covers.

3. Glacial temperatures in boreholes Kol and Krl, which are located in the domain of the Scandinavian ice

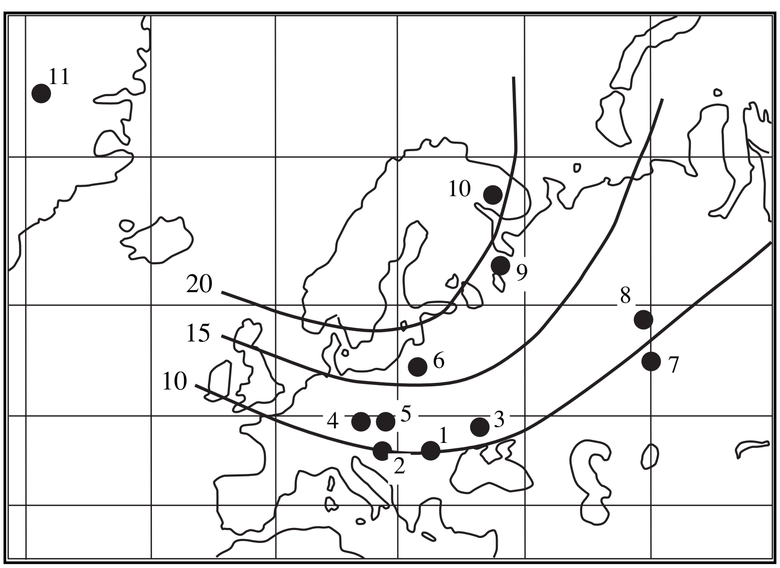

Fig. 1. Contour lines of the anomalies of geothermic estimates of the Holocene warming amplitude in Europe. Dots show the locations of boreholes analyzed (numerals correspond to borehole numbers in table.

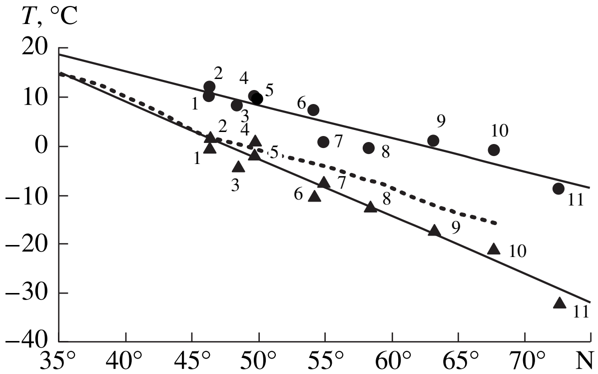

Fig. 2. Modern annual mean air temperatures (●) and mean temperatures during the recent glaciation (15–30 ka BP) (▲) vs. geographical latitude (numerals correspond to borehole numbers in Table 1). Solid lines correspond to linear approximation of latitudinal dependence; dashed line shows the distribution of modern temperatures along the profile across the continental regions of Siberia, Mongolia, and China.

sheet, only slightly deviate from the general linear trend, which indicates a weak warming effect of the glacier on the 15-ka period estimated here.

The data presented in our paper, first of all, indicate a high paleoclimatic informativity of the geothermy. The obtained pieces of evidence can serve as an independent confirmation (or refutation) of the existing concepts about climatic changes at the Pleistocene/Holocene boundary.

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