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Climate in northern Eurasia 6000 years ago reconstructed from pollen data

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Abstract

Using a climatic calibration based on the scores of the plant functional types (PFTs) calculated for 1245 surface pollen spectra, the climate at 6 ka BP has been reconstructed for a set of 116 pollen spectra from the former Soviet Union and Mongolia. The results are presented as maps of climatic anomalies and maps of probability classes showing the significance of these differences from the modern climate. The reconstructed patterns are spatially coherent, but have confidence levels that vary from region to region, due to the often-large error ranges. At 6 ka, the winters were more than 2ºC warmer than today north of 50ºN, with a high significance east of the Urals. Summers were also more than 2ºC warmer than today with a high level of confidence north of the Polar Circle and in central Mongolia. In the mid-latitudes of Siberia, in northern Kazakhstan and around the Black and the Caspian seas, 6 ka summers were significantly cooler than today. The reconstructed moisture availability (ratio of actual to equilibrium evapotranspiration) was more than 10% higher than today in the Ukraine, southern Russia and northern Mongolia, and more than 10% lower than today in central Mongolia. This pattern corresponds partly with that of the water budget (annual precipitation minus evaporation) reconstructed from lake level records.

Keywords: Middle Holocene; climate; Eurasia; pollen analysis; biogeography

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1. Introduction

In order to accurately predict future changes in the climate, robust models are required. As the past has experienced major climatic changes, one of the best ways to test and improve the forecasting power of climate models is to compare model-simulated conditions for a particular past time period, with the conditions estimated from geological data. The last 20 ka cover a wide variety of climates against which atmospheric general circulation models (AGCMs) can be tested [1]. Within this time period, the mid-Holocene (6 ka) represents a key time-slice. It has been used by modellers to test whether solar forcing has a direct effect on the Earth's climate system [2]. At that time, ice sheets were reduced to their modern extent, the mid- and high-latitude summer insolation were notably higher than today and the winter insolation lower than today.

Here we present a quantitative climatic reconstruction for northern Eurasia at 6 ka based on pollen data. The aim of this paper is three fold: (1) to test the new 'PFT method' [3] on the latest pollen dataset from northern Eurasia; (2) to compare the results with earlier continental-scale climate reconstructions based on different statistical and non-statistical methods [4,5]; and (3) to discuss the reconstructed climate patterns in comparison with some AGCM simulations.

The method of climate reconstruction [3] used in the present study uses the concept of 'biomization' [6], which attributes the appropriate biome to any given pollen spectra, by grouping the pollen taxa into plant functional types (PFTs — the broad classes of plants selected by their ecology, leaf morphology and bioclimatic tolerance [7]). The method [3] uses PFT scores instead of the pollen taxa abundances used in the traditional best modern analogue method [8]. The 'PFT method' has already been successfully applied to the scarce pollen data of the Last Glacial Maximum from southern Europe [3] and northern Eurasia [9]. These studies demonstrate robust and homogeneous results of climate reconstruction, proving the hypothesis [7] that groups of taxa have a better-defined response to climate than individual taxa, whose responses to climatic change may be obscured by competitive and migrational processes.

2. Data and methods

2.1. Pollen and climate data

A set of 1245 modern surface pollen spectra covering northern Eurasia and western North America has already been used by Tarasov et al. [9] to establish the relationships between the numerical scores of the PFTs and the modern climate at the sampling sites. The present-day climate was calculated at each site by weighted distance interpolation [10] of values taken from the present-day climate database [11].

In the present study we have reconstructed four bioclimatic variables considered as important parameters for the distribution of plants, and used in the BIOME1 vegetation model [7]. These are: (1) the mean temperature of the coldest month, T_c (ºC); (2) the mean temperature of the warmest month, T_w (ºC); (3) the annual sum of growing degree days above 5ºC, *GDD5* (ºC day); and (4) the moisture availability α (%), expressed as the ratio of annual actual to annual equilibrium evapotranspiration. These bioclimatic variables were chosen over more conventional variables, e.g. annual temperature and precipitation, as they have a more direct influence on the vegetation and are better suited for data-model comparisons [5]. Both *GDD5* and T_w are relevant to defining the boundaries between the biomes in northern Eurasia [7]. For example, a *GDD5* value of 350ºC day, marks the boundary between tundra and cold deciduous forest or taiga, and $T_w = 23$ºC is chosen in the BIOME1 model to distinguish cool steppe and desert from warm steppe and desert. For these reasons, we have reconstructed both *GDD5* and T_w, despite the fact that these two parameters are well correlated today.

A newly compiled set of fossil pollen spectra, each dated to between 5500 and 6500 radiocarbon years B.P. [12] was used to reconstruct biomes across the areas of the former Soviet Union (excluding the Far East) and Mongolia. In each case, the age of the given pollen spectrum was estimated either by linear interpolation between bracketing radiocarbon dates or by correlation with the closest radiocarbon-dated pollen record. For the present study, we kept 162 pollen spectra with original counts. When several pollen records were available from one site we selected the spectrum with the best dating control.

The modern climate was also calculated at each site in the 6 ka dataset, using the same method as used for the surface sample sites. The interpolated climate may be inaccurate, however, in areas where climatic stations are rare and situated far away from the pollen site, or in regions with complicate topography [3,9]. Such inaccurate estimates may influence the calculated anomalies between 6 ka and modern climate and thus devalue the results of climate reconstruction. To avoid this problem, we compared, on a site by site basis, the biomes calculated with the BIOME1 model [7], based on modern climatic parameters, and biomes derived from the natural modern vegetation map [13]. After this test, we retained fossil spectra from 116 sites with an exact match between the modern vegetation and climate. The rejected 46 sites were located either in the mountainous regions (e.g. Caucasus, Tien-Shan, Ural, mountain ranges of Mongolia and eastern Siberia) or in the coastal areas close to the Baltic Sea, the Aral Sea, and in the Russian Arctic. The distribution of the rejected sites suggests that it is incorrect estimation of the climatic parameters used in the model, which leads to the disagreement between the model-derived biomes and the map-derived biomes.

2.2. The PFT method of climate and biome reconstruction

The 'PFT method' has been described in detail by Peyron et al. [3]. The main steps of the method can be summarised as follows.

(1) Pollen taxa are assigned to plant functional types (PFTs) which are then used to define the biomes. The list of northern Eurasian pollen taxa and associated PFTs has been published previously [9,12,14]. In each pollen spectrum, the score of each PFT is the sum of square roots of the percentage of the assigned taxa (percentages $<0.5\%$ are excluded).

(2) For each biome, the scores of all PFTs belonging to that biome are summed.

(3) Finally, the biome with the highest score or, when several biomes have the same score, the one defined by a smaller number of taxa/PFTs is assigned to the given pollen spectrum [6].

Using an artificial neural network technique [10], a relationship between each of the analysed bioclimatic parameters and the PFT scores from all 1245 modern pollen spectra was calculated [9]. This relationship, called a transfer function, was then used to reconstruct the 6 ka climate from the 6 ka PFT scores. The calculated PFT scores were also used to reconstruct the distribution of biomes at 6 ka, in order to show how the vegetation distribution relates to the differences in climate. Further, the known bioclimatic limits of modern plant growth used in the BIOME1 model [7] provide another way to interpret biome distributions in climatic terms.

3. Results

The biome distribution in northern Eurasia at 6 ka was previously reconstructed by Tarasov et al. [12], using the standard method of biome reconstruction [6]. The improvement here was the ability to define steppe biome as cool steppe and desert as cool desert (Fig. 1a), using a modification of the biomization method [14]. Cool and warm steppes (and deserts) require different climatic conditions and the ability to determine them from pollen data is a valuable contribution to the validation of models simulating past climates [14]. Fig. 1 demonstrates that the distribution of biomes at 6 ka (Fig. 1a) differed substantially from the modern distribution (Fig. 1b) derived from the vegetation map [13]. The comparison of Fig. 1a and Fig. 1b shows several main features:

(1) The taiga was absent at the European Russia and Ural sites west of 60ºE. However, it occupied sites in eastern Siberia and in the northern part of western Siberia which are dominated today by cold deciduous forest and tundra.

(2) The temperate deciduous forest belt extended both northward and southward from its modern position. The northward extension was well pronounced in Belarus. However, temperate deciduous forest was only reconstructed at one site in northwest Russia, close to Ladoga Lake, where the modern biomes are cool mixed or cool coniferous forest. The limit of cool conifer forests was also shifted northwards in Karelia and eastwards in western Siberia, where taiga grows today.

(3) From the scattered information from the modern steppe zone we reconstructed forest vegetation with a dominance of temperate deciduous taxa (e.g. *Ulmus*, *Tilia*, *Quercus*, *Alnus*) in the European sector,

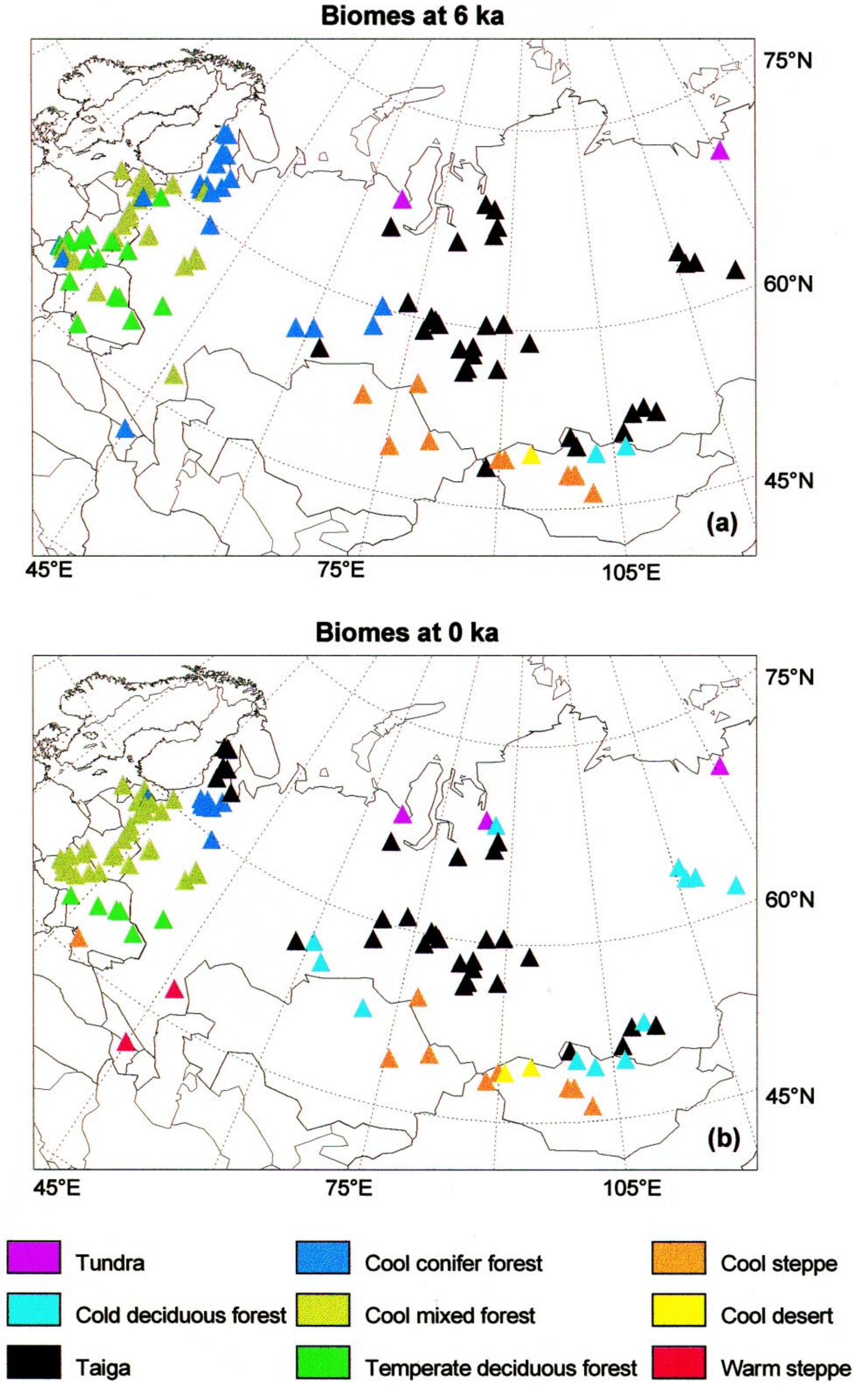

Fig. 1. (a) Pollen-derived biomes at 6 ka and (b) modern biomes derived from the vegetation map [13] at the studied sites.

and evergreen and deciduous conifers (e.g. *Picea*, *Pinus*, *Larix*) at one site in western Mongolia. Cool steppe was reconstructed at the sites from northern Kazakhstan, where modern vegetation is steppic, with patchy birch and pine forests. One of two fossil spectra from the very arid depression of western Mongolia recorded steppe, suggesting that a smaller area was occupied by cool desert at 6 ka.

The reconstructed T_c, T_w, *GDD5* and α at each site are mapped (Fig. 2) as differences between past and modern climate values. At 6 ka, T_c was 1–4ºC higher than today across northern Eurasia. However, records from western and southern Ukraine and two records from Georgia and central Mongolia demonstrate negative anomalies of T_c (Fig. 2a). T_w was higher than today in the broad band east and south of the Baltic Sea, north of the Polar Circle and in central Mongolia (Fig. 2b). However, it was lower than today in the band from southern Ukraine to eastern Siberia. A heterogeneous pattern of T_w was reconstructed in Buriatia, north of the Russian–Mongolian border. The reconstructed *GDD5* anomalies (Fig. 2c) show, not surprisingly, a very similar pattern to T_w. However, in the central part of European Russia and at three sites from Siberia and Mongolia positive anomalies of *GDD5* coincide with negative anomalies of T_w. This may suggest that 6 ka springs and autumns were warmer than today. Presently, winters are very cold in this area, and thus, the reconstructed higher values of T_c are not sufficient to explain an increase in *GDD5* at 6 ka in northern Eurasia. At 6 ka, the climate of northern Eurasia was generally wetter than today (Fig. 2d). However, records from Kazakhstan and central Mongolia, and in some areas of the eastern Baltic show drier conditions.

The northward and eastward expansion of the boreal evergreen conifers and temperate deciduous trees at 6 ka can be broadly explained by higher than present winter temperatures (Fig. 2a). Higher than present T_w and *GDD5* (Fig. 2b,c) would also explain the existence of boreal conifers at the Arctic sites where tundra grows today. The southward expansion of the forest vegetation most probably resulted from the higher than present moisture availability (Fig. 2d).

Error bars for the climatic variables reconstructed by the 'PFT method' are often large and thus only strong anomalies can be considered as statistically significant [9]. Further, the maps of bioclimatic variables (Fig. 2) demonstrate that results of reconstruction are not always homogeneous and consistent. To avoid a misinterpretation of the results, we have calculated error ranges for each climate variable as follows: (1) the climate was estimated at each of the 1245 modern pollen sampling sites, using the transfer function; (2) the difference between estimated and observed climate (residuals) was calculated; (3) the frequency distribution of these residuals was calculated; (4) 5th, 25th, 50th, 75th and 95th percentiles were estimated for each climatic parameter, as indicated in Table 1; and (5) the significance of the reconstructed climate anomalies at each fossil site was evaluated (Fig. 3). The median (50th percentile) enables us to check for biases in the reconstructed values. It is expected to be nil. Indeed, we observe that medians for T_c, T_w and α are close to zero (Table 1). The *GDD5* median (−60ºC day) is also relatively close to zero, given the large range of possible values.

Table 1
Calculated error bars for the reconstructed anomalies (6 ka minus present) of four climatic variables in terms of different confidence levels

Climatic variable	Percentiles				
	5th	25th	50th	75th	95th
T_c (ºC)	−6.0	−3.2	−0.8	1.9	5.6
T_w (ºC)	−2.5	−1	−0.1	0.9	2.6
GDD5 (ºC day)	−660	−250	−60	110	560
α (%)	−17	−4.8	3	6.3	19

Values were obtained from the frequency distribution of the deviations between estimated and observed climatic variables at the modern pollen sites.

Fig. 3a indicates that the positive T_c anomalies have been reconstructed with a high level of confidence (probability greater than 95%) in central and eastern Siberia and at several Arctic sites. Similarly our reconstruction of negative anomalies of T_c is significant in western Ukraine and around the Black Sea, but non-significant (probability less than 75%) in Mongolia. The sites where positive anomalies of T_w (Fig. 2b) and *GDD5* (Fig. 2c) have been reconstructed with a highest level of confidence (probability greater than 95%) lie in central Mongolia, in the Russian Arctic and around the Baltic Sea

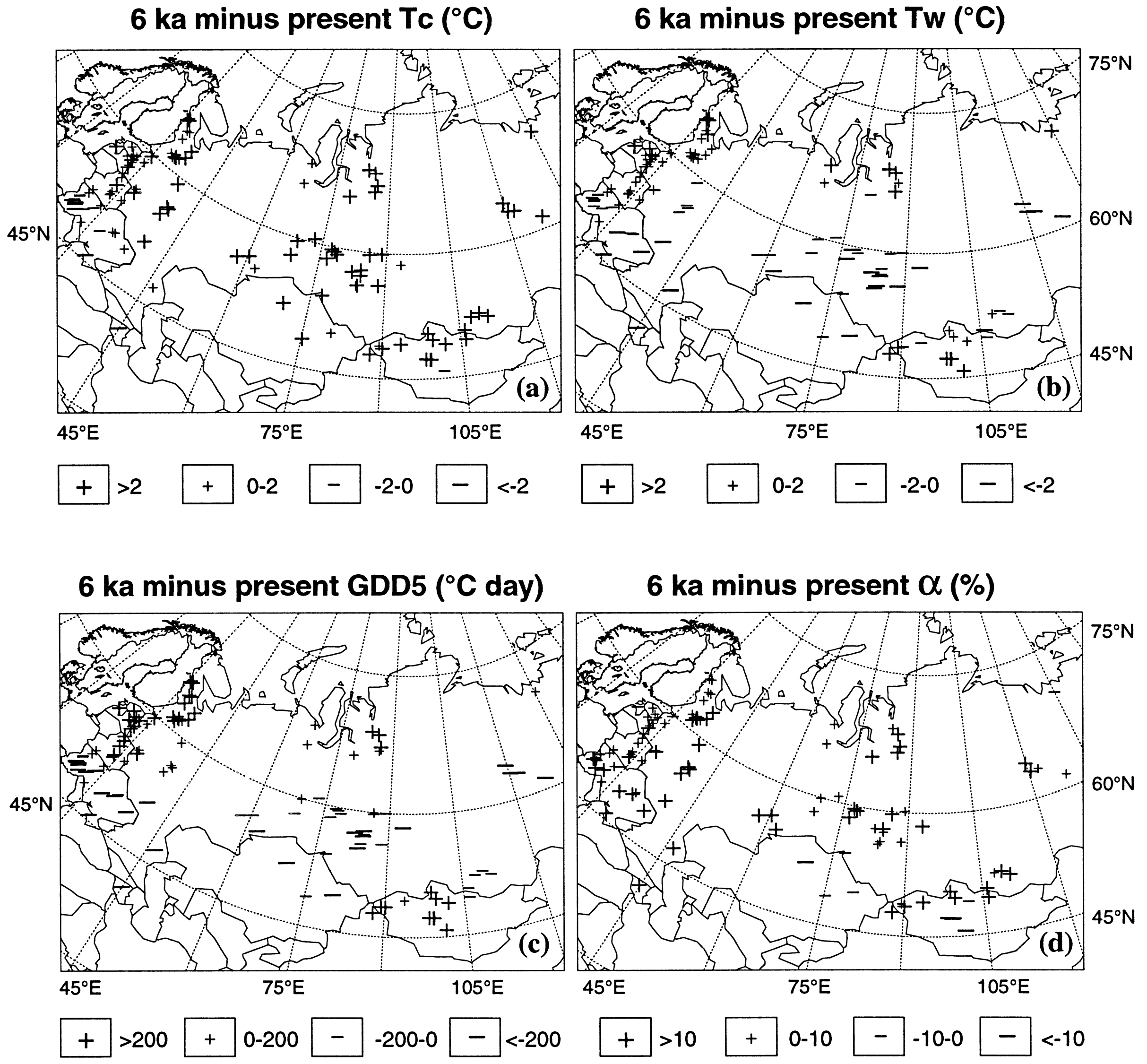

Fig. 2. Pollen-based reconstruction of bioclimatic anomalies, 6 ka minus present: (a) mean temperature of the coldest month T_c; (b) mean temperature of the warmest month T_w; (c) annual sum of daily temperatures above 5ºC *GDD5*; (d) ratio of annual actual to annual equilibrium evapotranspiration α.

(Fig. 3b,c), and the negative anomalies of T_w and *GDD5* are significant in the band from the Ukraine and the Black Sea to eastern Siberia. Comparison of Fig. 2 and Fig. 3 indicates that in all cases when the anomalies of T_w are not homogeneous (e.g. in Buriatia) or where there is a disagreement between *GDD5* and T_w anomalies, the results of reconstruction are non-significant (probability less than 75%). In Ukraine, southern Russia and northern Mongolia, reconstructed α values were higher than today with a probability greater than 95% (Fig. 3d). Less significant (probability 75 to 95%) reconstruction of positive α anomalies observed in Belarus and in Russia north of 60ºN. The reconstruction of positive anomalies around the Baltic Sea is non-significant. Similarly, the negative α anomalies reconstructed in northern Kazakhstan and at a few sites in Ukraine are non-significant.

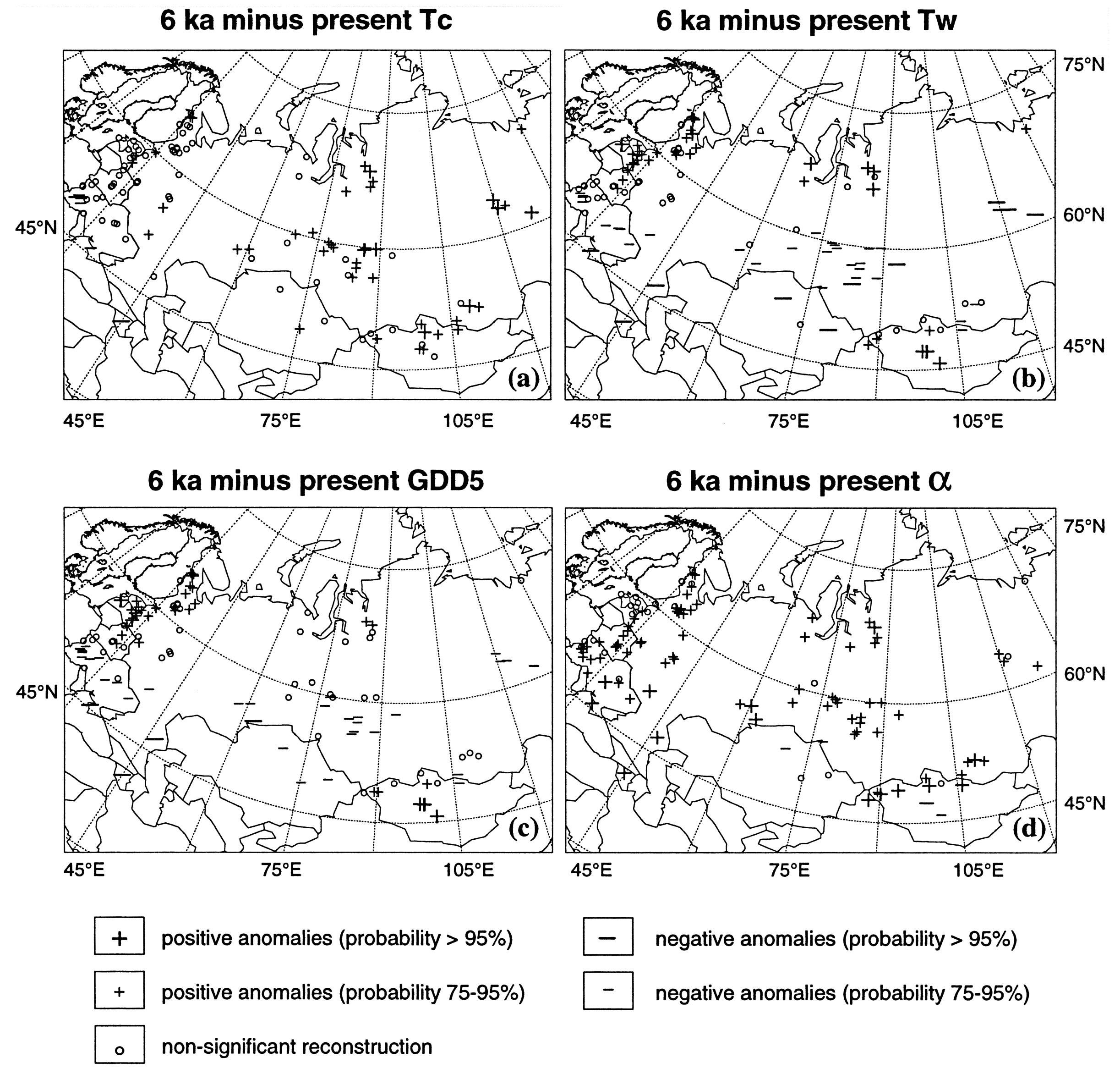

Fig. 3. Statistical significance of the reconstructed bioclimatic anomalies. For each fossil site the anomaly was considered as significant (probability greater than 95%), if it was higher than the 95th percentile (for positive anomaly) or was lower than the 5th percentile (for negative anomaly). The anomaly was considered as less significant (probability 75 to 95%), if it was higher than the 75th percentile (for positive anomaly) or lower than the 25th percentile (for negative anomaly). The anomaly was considered as non-significant if it was between the 25th and 75th percentiles.

To properly interpret the climate reconstruction results, we may either consider isolated sites with a strong significance (probability greater than 95%) or the group of sites with a less strong significance (probability 75 to 95%). In the second case, the lower level of confidence is compensated by the existence of regional coherency between sites. Therefore, even in areas where the significance level of a reconstructed parameter, such as T_c, is between 75 and 95%, one can assume that the signal is robust, if a consistent pattern is observed.

4. Discussion and conclusions

Reconstructed values of 6 ka climate show spatially coherent and generally significant patterns. The large error bars obtained with the applied 'PFT method' make the reconstructions partly non-significant (Fig. 3), suggesting that the method is less precise than the best modern analogues method. However, this is not true, as the small error ranges of the analogues method are often underestimated [5].

The results of T_c, T_w, *GDD5* and α reconstruction are consistent with the qualitative interpretation of reconstructed changes in the vegetation ([12], and this study), suggesting that the biomization method may be useful when a detailed climatic interpretation of biome distribution is required.

Frenzel et al. [4] presented global reconstructions of mean temperatures of the coldest and warmest month 5500–6000 years ago. The pronounced deviations from present-day T_c values (3 to 4ºC higher than today) shown [4] in the Russian Arctic, in Kazakhstan and in the central part of eastern Siberia, are consistent with our results. However, we have reconstructed negative anomalies of T_c in Europe further to the north than the earlier study. Cheddadi et al. [5], using the best modern analogues technique constrained by lake-status data, reconstructed winter temperatures (T_c) at 6 ka that were 2–4ºC lower than today in southern Europe and Turkey and up to 1ºC lower than today towards the northern coast of the Black Sea. This pattern is more consistent with our results (Fig. 2a) than that presented by Frenzel et al. [4].

Both the earlier studies [4,5] and the present results (Fig. 2b) showed the largest deviations in T_w temperatures (up to 4ºC higher than today) north of 65ºN. These decrease in the middle latitudes of eastern Europe and Siberia, becoming negative further to the south (e.g. Kazakhstan, Middle Asia, Caucasus). However, the negative summer temperature anomalies that we reconstructed in regions of central and eastern Siberia did not appear in the Frenzel et al. study [4]. Climate reconstructions from individual pollen records from central and southern Yakutia and the southern part of western Siberia [15] suggest that the mean July temperatures were lower than today between 6 and 6.5 ka and for some time after 6 ka, and thus are in a better agreement with our results, once again providing a warning about the dangers of generalising the classical scenario of mid-Holocene thermal maximum in different regions. There have been no previous attempts to reconstruct *GDD5* anomalies in northern Asia. However the *GDD5* anomaly reconstructed in Europe [5] shows a very similar pattern to the one obtained in the present study (Fig. 2c).

The reconstructed moisture availability (α anomaly) pattern showing wetter than present conditions in eastern Europe at 6 ka [5] correlates well with our map (Fig. 2d). There have been no previous attempts to reconstruct α in northern Asia. A comparison of α anomaly (Fig. 2d) with a map of qualitative effective moisture (annual precipitation minus evaporation) anomalies (Fig. 4) enables the reliability of the reconstructed α to be evaluated, even if, especially in arid climates, both parameters can have a different meaning [7]. Lake-status records used in Fig. 4 are inferred from the latest version of the former Soviet Union and Mongolia lake-status data base [16]. At 6 ka the lake levels (an approximate characteristic of the water balance over the catchment area [17]), were generally higher than today from Kola Peninsula to the southern Ural, including northern Mongolia and central Yakutia, consistent with the wetter conditions suggested by the α anomalies. Lakes around the Baltic Sea, in Kazakhstan and in central Mongolia show conditions similar to today or slightly drier.

Harrison et al. [18], dealing with the intercomparison of global vegetation distributions driven by the climate simulated by ten AGCMs, demonstrated that at 6 ka, (1) an increase in warm grass/shrub in the northern hemisphere is a response to a warming and an enhanced aridity and (2) a northward shift in the tundra–forest boundary is a response to warmer growing season at high northern latitudes. The biome model used by Harrison et al. [18] to simulate the vegetation distribution integrates the same bioclimatic variables as those reconstructed in the present paper. Therefore, a direct comparison of the reconstructed and simulated biomes and climate can be carried out.

The model-simulated vegetation changes associated with high-latitude summer warming are broadly consistent with both previously published regional pollen and macrofossil records [4,12,15] and with

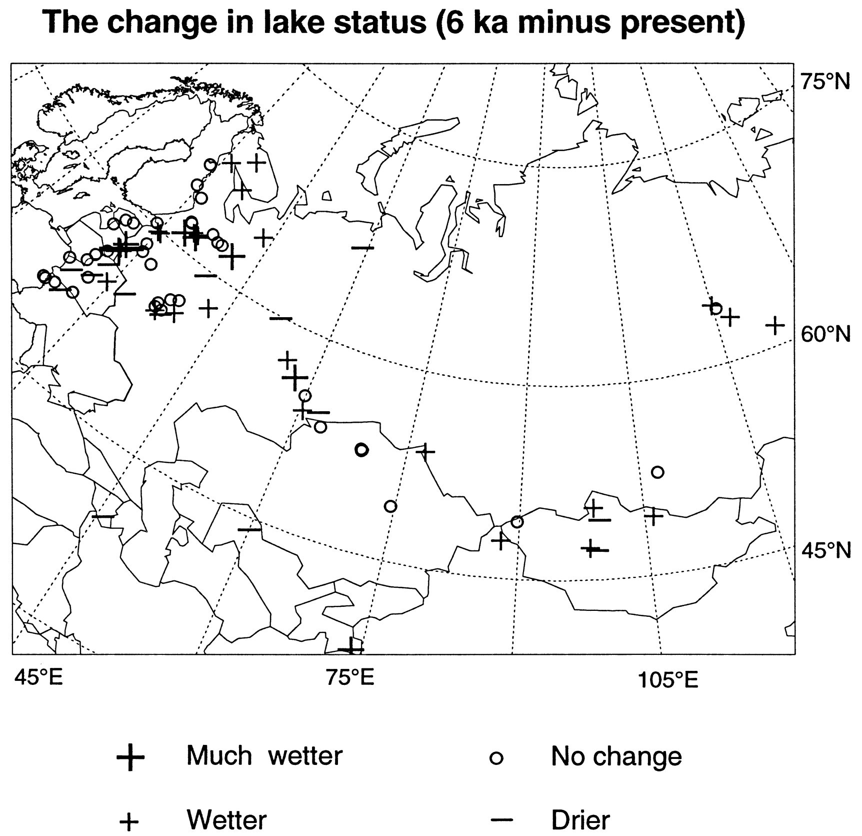

Fig. 4. Reconstruction of effective moisture anomalies inferred from lake-status data [16], 6 ka minus present.

our pollen-based biome reconstruction (Fig. 1). Data from the mid-latitudes of northern Eurasia mostly indicate rather wetter and cooler conditions at 6 ka (e.g. forests instead of steppe with higher lake levels and positive α anomalies), the opposite of the model simulations. Our reconstruction of warmer and drier than present climate in central Mongolia is in agreement with the AGCM simulations cited above.

The patterns of change in regional moisture budgets across the Old World extratropics at 6 ka simulated by five AGCMs (LMCE 4ter, UKMO HC3.2, UGAMP 2.0, ECHAM 3.2 and CCM2) have been compared with observations of changes in lake status [19]. Among those models CCM, UGAMP and UKMO simulate more positive moisture budgets over the mid-latitudes of eastern Europe and Siberia, consistent with pollen and lake-level data. However, only ECHAMP and LMCE show wetter than today conditions in northwestern Russia, the others indicating conditions somewhat drier than present. All models simulate a complicated pattern in Mongolia with conditions both drier and wetter than today. However, no one model simulates a 6 ka climate of northern Eurasia that matches exactly that reconstructed from the palaeoenvironmental data. This suggests that the effects of orbital forcing on 6 ka climate tested by the AGCM experiments are amplified by some other mechanism [20].

Our data may suggest that the higher-than-present summer insolation cannot always be considered as a direct factor controlling the vegetation distribution in the inner lands of Eurasia as recorded in central North America [1] and in the high latitudes of Eurasia (Fig. 3b).

Recent studies comparing vegetation or lake level records [18–21] with AGCM simulations demonstrate that in the models, the direct effect of increased summer insolation and of the decreased winter insolation is certainly overestimated, whilst the effects of the atmospheric circulation changes are underestimated.

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