Paleoclimatic reconstructions for the south of Valdai Hills (European Russia) as paleo-analogs of possible regional vegetation changes under global warming

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Abstract
The possible response of forest ecosystems of south taiga at the south of Valdai Hills on projected future global warming was assessed using analysis of pollen, plant macrofossil and radiocarbon data from four profiles of buried organic sediments of the last interglacial and several cores from modern raised bogs and two small forest mires in the Central Forest State Natural Biosphere Reserve (CFSNBR; Twer region, Russia). The future pattern of climatic conditions for the period up to 2100 was derived using the data of A2, B1 and A1B emission scenarios calculated by the global climatic model ECHAM5-MPIOM (Roeckner E et al 2003 The Atmospheric General Circulation Model ECHAM 5. PART I: Model Description, Report 349 (Hamburg: Max-Planck Institute for Meteorology) p 127). The paleoclimatic reconstructions showed that the optimum of the Holocene (the Late Atlantic period, 4500−4800 ¹⁴C yr BP) and the optimal phases of the last interglacial (Mikulino, Eemian, 130 000−115 000 yr BP) can be considered as possible analogs for projected climatic conditions of the middle and the end of the 21st century, respectively. The climate of the CFSNBR during the Holocene climatic optimum was characterized by higher winter (about 3 °C higher than at present) and summer temperatures (about 1 °C higher than present values). Precipitation was close to present values (about 600–800 mm yr⁻¹). Vegetation was represented by mixed coniferous and broad-leaved forest. In the warmest phases of the last interglacial the winter temperature was 5–8 °C higher than present values. The summer temperatures were also about 2–4 °C higher. Broad-leaved and hornbeam trees were the dominant tree species in vegetation cover.

Keywords: climate and vegetation changes, paleoclimatic reconstructions, Holocene, the last interglacial, boreal forest ecosystem

1. Introduction
Climatic conditions strongly affect all natural, economic and social processes in Europe and vary enormously across space and time (Grove 1988). An assessment of the reaction of south taiga forest ecosystems on global climatic changes, appearing mainly as temperature increase and changes in precipitation regime, remains one of the actual fundamental problems,
demanding multi-proxy investigations. The expertise of the modern state of landscapes and prognosis of their future changes are obviously impossible without a deep understanding of past climate and vegetation cover dynamics, as well as ecosystem function. Detailed paleoclimatic reconstructions can help to find the paleo-analogs for prediction of the possible future landscape dynamics under the present rapid climatic changes.

The paleo-analog approach was developed more than 20 years ago, and it was mainly applied for assessing the expected changes of the landscape components on a global scale, such as the entire Northern Hemisphere, Northern Eurasia or at the level of the zonal structure of the East European Plain and Siberia (Velichko 2002, Velichko et al 2004). The results of the climatic reconstructions for several time slices in the past showed that the mean global temperatures during the Holocene thermal optimum (about 6–5.5 kyr BP) and during the optimum of the last interglacial (Mikulino–Eemian–Sangamon, stage 5e of the deep-sea oxygen curve, about 125 kyr BP) were 0.7–1.0 °C and 1.7–2.0 °C higher than modern values, respectively. In particular these time slices are commonly used for prognosis of the landscape states in the 21st century (Velichko et al 2004, 2008).

The present work is the first attempt to use the paleogeographic data for predicting possible vegetation changes at the regional level. The prognoses are based on temporal reconstructions of the main climatic characteristics (temperature of the coldest and warmest months and precipitation) during the Holocene and the last interglacial inferred from proxy data collected in the Central Forest State Natural Biosphere Reserve (the south part of Valdai Hills) in Russia.

2. Study area

The Central Forest State Natural Biosphere Reserve (CFSNBR) is situated 360 km west of Moscow (the Tver region) in the southern part of Valdai Hills (56°35’N, 32°55’E). The total area of the CFSNBR is 705 km². This territory is located in the marginal part of the Weichselian ice sheet. It is a slightly hilly area, with elevations of 220–250 m above sea level (asl). The highest moraine ridge in the south of the CFSNBR (up to 280 m asl) is also the main watershed in the East European Plain between the Caspian and the Baltic basins.

The climate of the area is moderate continental with relatively mild winters and warm summers. According to meteorological observations conducted in the CFSNBR (measurements since 1963) the mean July temperature is 17.0 °C, the temperature in January is −10.0 °C and the mean annual temperature is 3.8 °C. Annual precipitation does not exceed 700 mm yr⁻¹.

Vegetation of the CFSNBR is represented by primary southern taiga forest that is not disturbed by any serious anthropogenic activity. Spruce forests dominate the vegetation cover (47%). Birch and aspen forests, formed due to windfalls and forest fires, cover about 40%. River valleys are occupied by black alder communities (1–2%). Mires and swamp pine forests cover 6% and 10%, respectively. The CFSNBR is located close to the boundary between the southern taiga and mixed coniferous–broad-leaved forest zones. This position causes the forests in the area to be very sensitive to climatic and environmental changes.

3. Methods

The reconstructions of paleoclimatic conditions for the area of the CFSNBR are based on pollen, plant macrofossil and radiocarbon data from four profiles of buried organic sediments of the last interglacial and several cores from modern raised bogs, such as medium-size massive ‘Staroselsky moch’ and two small forest mires. The results of these paleobotanical studies have been presented in detail in our previous publications (Novenko et al 2008, 2009).

Climatic characteristics (mean temperatures of the warmest and coldest months) for the time slices during the last interglacial were determined using the floristic method of paleoclimatic reconstruction—the method of climagrams. This method was developed in the Laboratory of Evolutionary Geography IG RAS (Grichek 1985). Climagrams are special graphs showing the present temperature limits of different plants. To create these graphs, meteorological data from a large number of sites within the area where the species considered are presently growing have been collected. Combination of graphs for all taxa presented in the fossil assemblage gives the temperature conditions when these species could grow simultaneously.

As the fossil flora from Holocene sediments is not sufficiently available to apply the method of climograms, the climatic parameters during the Holocene (temperature of warmest and coldest months, mean annual temperature and annual precipitation) were calculated using the transfer function developed by Klimanov (1984). This approach is based on multi-dimensional regression models which describe every pollen assemblage as a function of climatic variables. The close relation between the percent proportions of pollen assemblages and climatic characteristics (temperature and humidity) allowed us to develop this model. The mean statistical errors for the reconstructions are ±1 °C for both the mean annual temperature and temperatures of July and January, and ±100 mm for annual precipitation.

4. The last interglacial

As the last interglacial is beyond the range of radiocarbon dating, precise dating of the records is still problematic. According to paleogeographical data, the Mikulino (Eemian, Sangamon) interglacial corresponds to Marine Isotope Stage 5e (Imbrie et al 1984), the beginning of which is assigned to 126,000 yr BP. Usually the age-dependent model of the interglacial profiles is based on correlation with other proxies: stable isotope data from deep ice cores (NorthGRIP Members 2004), annual layer counting of lake sediments (Müller 1974, Brauer et al 2007) or stalagmite data (Holzkämper et al 2004). A generally accepted approach for correlation of individual sections and describing vegetation history during the last interglacial is to use various biostratigraphic schemes, based
Figure 1. Pollen and plant macrofossil diagram of the profile of Mikulino (Eemian) deposits in the CFSNBR (simplified following Novenko et al. 2008) and temperature reconstructions. Lithology: 1—peat, 2—lake sediments, 3—till.

mainly on pollen analysis. The scheme developed by Grichuk (1982) for the East European Plain has been adopted in our study. According to this system the Mikulino interglacial comprises eight main phases revealed by the sequence of zones on the pollen diagrams (so-called ‘zones M1–M8’).

The pollen and macrofossil data of the sections investigated in the CFSNBR recorded a typical succession of forest communities during the Mikulino interglacial (figure 1). The transition to interglacial conditions encouraged the spread of a spruce forest, and then light pine and birch–pine with well-developed shrub understory communities occupied the area (zone M2). The zonal type of vegetation during the next phases of vegetation development (zones M3, M4 and M5) was oak forest (Quercus robur) with elm (Ulmus laevis, U. scabra), ash (Fraxinus exelsior) and maple (Acer platanoides). At the end of this stage hornbeam (Carpinus betulus) and lime (Tilia cordata, Tilia platyphyllos) appeared in the forests. The characteristic feature of these stages is the abundance of hazel (Corylus avellana). Important components of vegetation were communities of Alnus incana on the wet soil and swamped forests of A. glutinosa. The interglacial climatic optimum (zone M6) was marked by broad-leaved communities formed mainly by hornbeam, with an admixture of lime, oak and elm. Macrofossils of some warm demanding aquatic plants, now extinct in this region (Brasenia holsatica, Salvinia natans, Trapa natans, Caulinia cf flexilis) were found here. During the post-optimal phase of the warm period, the gradual cooling and increasing humidity of the climate brought about a development of spruce forests (zone M7). The roles of broad-leaved trees fell gradually. Along with dark-coniferous communities, open birch and pine–birch woodlands appeared. At the termination of the interglacial (zone M8) the boreal forest was replaced by open larch–pine–birch woodlands and wet meadows.

The mean temperatures of July ($T_{VII}$) and January ($T_I$) were calculated for zones M3–M8 with the most representative list of fossil flora (figure 1). The reconstruction has shown that, even at the beginning of the interglacial (zone M3), $T_{VII}$ could exceed its present value by at least 1°C. During the warmest phases it was 2–4°C higher than the modern era and it decreased slightly in the post-optimal phases (M7) to its present value (17°C). In the final phase of the interglacial, the mean July temperature was equal to 15–16°C.

In the warmest phases of the last interglacial the mean January temperature rose and remained in the interval from −4 to −1°C, which was 6–9°C higher than modern conditions. During the spruce phase (M7) the calculated temperature of the coldest month ranged between −2 and −6°C, and it was at least 4°C higher than at present. The reconstructed January temperatures for the beginning and the end of the interglacial are characterized by a relatively wide uncertainty interval. One can suppose, however, that the temperatures during these phases were either equal or somewhat lower than at present. Nevertheless the curves of mean temperatures of the coldest and warmest months show that the heat supply rose gradually from the beginning of the interglacial to its middle part, when
they reached the maximal values. After that the temperature went down which indicates the onset of the cold epoch.

The assessment of precipitation during the Mikulino interglacial on the basis of obtained data is problematic. According to spatial reconstruction of the climatic characteristic for the area of the East European Plain, the south part of the Valdai Hills area is situated in a zone that is characterized by an insignificant increase of annual precipitation in the thermal optimum of the interglacial compared with modern conditions (Velichko et al. 2008).

5. The Holocene

Pollen and macrofossil study of peat cores in the CFSNBR, as well as obtained radiocarbon data, allow determination of the vegetation history and climatic characteristic in the south part of the Valdai Hills in the Late Glacial and Holocene (Novenko et al. 2009). The sequences of climatic periods (phases) of the Holocene were performed according to the Blytt–Sernander classification, modified for the East European Plain by Khotinski (1977).

In the interstadial Alleröd (10 800–10 200 14C yr BP), the territory of the CFSNBR was occupied by periglacial steppe with patches of pine, birch and spruce woodlands in better protected locations. During the last cold phase of the Late Glacial—stadial Younger Dryas (10 200–9500 14C yr BP), the forested area was greatly reduced, and the role of steppe-like (Artemisia-dominated) communities increased due to the onset of a colder and drier climate. The main phases of the Late Glacial are clearly pronounced in the long-term temperature pattern. The maximal mean July and January temperatures in the Holocene are clearly pronounced in the long-term temperature of a colder and drier climate. The main phases of the Late Glacial—stadial Younger Dryas (10 200–9500 14C yr BP) appeared as the warmest phase of the Holocene, where the temperature of the coldest month rose to −6.5 °C (3 °C above modern conditions). The mean annual and summer temperatures exceeded their present values by 1 °C. Precipitation amounts were 600–800 mm yr⁻¹ (close to the modern climate).

The cooling that followed after the Holocene optimum resulted in moistening of the area and increasing the presence of Pinea in the forest composition. Oligotrophic Sphagnum bogs began to spread over the area in that time. The Subboreal (4500–2500 14C yr BP) and Subatlantic (after 2500 14C yr BP) periods are marked by complex vegetation dynamics characterizing by alternation of phases of spruce forests, typical for a taiga zone (the Early and the Late Subboreal, the Middle Subatlantic), and phases of mixed coniferous broad-leaved forest with a high proportion of lime and elm (the Middle Subboreal, the Early and Late Subatlantic). The plant cover during the Late Subatlantic was mainly characterized by spreading of secondary birch forests, probably induced by human impact.

Several warming and cooling periods in the second part of the Holocene have been identified too. Warm phases corresponded to the Middle Subboreal (at approx. 3500 14C years BP), the Early Subatlantic (at 2500 14C years BP) and the medieval warm period (MWP, 9th–12th centuries). The climate of warm periods is characterized mainly by an increase in winter temperatures by 1–4 °C above modern values. The deviation of mean annual and summer temperatures from their present values did not exceed 1 °C.

The most significant cold phase (the Little Ice Age, 15th–17th centuries) was determined by a decrease in winter temperature up to −15 °C. The proportion of warm demanding broad-leaved trees falls abruptly, oak disappeared completely, and spruce forests and wetland ecosystems become widespread (Novenko et al. 2009).

6. Proposed changes of climatic conditions on the study area under different climatic scenarios

Different climatic scenarios propose a significant increase of global temperature during the next 100 years mainly due to the increase in concentration of greenhouse gases in the atmosphere (IPCC 2007). Modeling results provided by the global climatic model ECHAM5 (Roeckner et al. 2003) for the area of the Valday Hills propose increasing the winter and summer temperatures at the end of the 21st century by 7–8 °C and 2–3 °C, respectively, both for the A2 scenario (Roeckner et al. 2006b) assuming regionally oriented economic development and slower and more fragmented technological changes and for a good mid-line scenario of CO₂ emission and economic growth (A1B) (figure 3) (Roeckner et al. 2006a). Modeling experiments carried out using scenario B1 (assuming the introduction of clean and resource-efficient technologies in world economy) propose an increase of the January and July temperatures for the middle of the 21st century in the
area of CFSNBR by 3–4 °C and 1 °C, respectively. In the second part of the century modeling projections using the B1 scenario (Roeckner et al. 2006c) propose no visible changes in the air temperature. This temperature pattern corresponds well to Holocene optimum conditions (Atlantic period). Higher increases of annual air temperatures for the end of the century projected by A2 and A1B correspond well to temperature conditions observed at the optimum of the Mikulino interglacial period.

7. Regional prognosis and conclusions

Holocene climatic reconstructions have shown a very high sensitivity of vegetation cover to changes of climate conditions. The relatively short-term (with duration less than 1000 yr) and sharp (with amplitude about 10 °C) temperature fluctuation in the Late Glacial and the Early Holocene (12 000–8000 yr BP) led to significant vegetation changes. It took several millennia to replace boreal forests that occupied the area of the CFSNBR during the Allerød interstadial by open treeless landscape in the Younger Dryas cold phase. It is noteworthy that a rapid expansion of forests occurred over the territory at the beginning of the Boreal period of the Holocene.

Bearing in mind the environmental conditions of the Holocene optimum (the late Atlantic period) as a model of vegetation changes for the middle of the 21st century, one can expect changes in the internal structure of plant communities, such as an increase in abundance of broad-leaved trees (lime,
Figure 3. Proposed air temperature changes for the area of Valday Hills under different climatic scenarios. The smoothed trends (20-year time averages) were calculated using mean values from three model runs for a grid point (56.89° N, 33.75° E) located close to the CFSNBR area.

1—Conditions are comparable with the Holocene thermal optimum. 2—Conditions are comparable with the optimum of the last interglacial.

elm and, probably, oak) in forest stands and in the understory. Spruce forests are reduced and their areas will be obviously replaced by secondary stands of birch and aspen.

Data obtained on climatic fluctuations in the second half of the Holocene suggested a rather well-determined response of vegetation to both climate warming and cooling. Thus, increase of the January and July temperatures by 1–2°C and 1°C, respectively, in some periods of the Late Holocene resulted in reduction of areas occupied by south taiga communities and expansion of coniferous broad-leaved forests. The main phases of the last millennium are well pronounced in the paleogeographical data of the CFSNBR. The decrease of winter temperature by 7°C during the Little Ice Age in comparison with the Medieval Climatic Optimum led to a decay of the broad-leaved communities in the CFSNBR and gave an impulse to active processes of wetland development (Novenko et al 2009).

The provided climatic and environmental reconstructions have shown that the most rapid vegetation changes in the Holocene occurred during at least several centuries or millennia, while the observed temperature growth spanned only a few decades. One can expect a lag between climate and vegetation dynamics and catastrophic ecosystem changes are unlikely to occur in the 21st century.

According to climatic reconstructions for the last interglacial, admitted as a paleo-analog of expected warming at the end of the 21st century, the mean January temperature during the warmest interval of the interglacial (the so-called hornbeam phase) exceeded the modern value by about 5–8°C. Increase of mean winter temperatures by up to −1 to −4°C may result in the disappearing of spruce from the biome and its replacement by broad-leaved trees, birch and aspen. The timescale of the response is relatively large, which can be well illustrated by analysis of migration rates of forest communities under climatic changes. Calculation based on radiocarbon dated plant macrofossils in Western Europe provided by Huntley and Birks (1983) showed that the dispersal rate for hornbeam in the first half of the Holocene does not exceed 300–700 m yr\(^{-1}\). Therefore broad-leaved forests with hornbeam as a dominant component are unlikely
to appear in the investigated area. It is possible to use the Mikulino interglacial optimum as a model for expected landscape changes at the level of the type of plant cover.

The results obtained have shown that the approach of paleo-analogs, based on proxy paleogeographic data, can be successfully used for predicting expected changes in landscape components. It can also be applied for verification and improvement of different mathematical models. Though the reconstructions of vegetation do not fully correspond to the short-term changes expected in the coming decades, they may be used to assess the trends of landscape evolution.

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