Available online at www.sciencedirect.com

ScienceDirect

Russian Geology and Geophysics 55 (2014) 463–471

RUSSIAN GEOLOGY AND GEOPHYSICS

www.elsevier.com/locate/rgg

The response of the environment of the Angara–Lena Plateau to global climate change in the Holocene

E.V. Bezrukova [a,b,*], A.V. Belov [c], P.P. Letunova [a,b], N.V. Kulagina [d]

[a] *A.P. Vinogradov Institute of Geochemistry, Siberian Branch of the Russian Academy of Sciences, ul. Favorskogo 1a, Irkutsk, 664033, Russia*
[b] *Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, pr. Akademika Lavrent'eva 17, Novosibirsk, 630090, Russia*
[c] *V.B. Sochava Institute of Geography, Siberian Branch of the Russian Academy of Sciences, ul. Ulan-Batorskaya 1, Irkutsk, 664033, Russia*
[d] *Institute of the Earth's Crust, Siberian Branch of the Russian Academy of Sciences, ul. Lermontova 128, Irkutsk, 664033, Russia*

Received 30 July 2013; accepted 11 October 2013

Abstract

The paper is focused on the regularities and character of the response of the regional landscapes of the Angara–Lena Plateau to variations in the global climate system during the Holocene. They were revealed by integrated studies of four peat bogs of the plateau—an important area for the understanding of the environmental dynamics in the entire Baikal region. Age models for the records obtained were provided by 16 radiocarbon dates. A spatiotemporal correlation of spore–pollen indices with the trend of $\delta^{18}O$ records from the global stratotypes was used to find out the possible causes of changes in the landscapes and climate of the Angara–Lena Plateau in the context of past changes in the global climate system. The plateau environment showed a dramatically varying response to global climate variations in the Middle–Late Holocene. Moreover, the observed intervals of reorganization in the regional environment took place in a quasi-millennial regime, in accordance with global climate rearrangement. However, not all the studied regions of the Angara–Lena Plateau exhibited a synchronous or analogous response to global environment change. This emphasizes the complicated character of regional climate manifestations in the Holocene and necessitates the use of paleogeographical data from a wider range of territories.

Keywords: pollen analysis; peat deposits; Holocene; dynamics of regional climate and landscapes; interregional correlation; Angara–Lena Plateau

Introduction and problem formulation

In the last few decades, studies have shown considerable instability in the climate of the recent interglacial—the Holocene. The intervals of change in the Holocene environment and their age boundaries were reflected in different natural records of climate change, and part of them received the status of Holocene global stratotypes (Bond et al., 2001; Svensson et al., 2008; Wang et al., 2005). The conventional Blytt–Sernander system for the European Holocene includes five stages (ka): Preboreal (11.5–10.5), Boreal (10.5–7.8), Atlantic (7.8–5.7), Subboreal (5.7–2.6), and Subatlantic (2.6–present) (Roberts, 1998). However, researchers now prefer to divide the evolution of the Holocene environment into three periods: Early (11.7–8.0 ka), Middle (8.0–2.5 ka), and Late (the last 2.5 kyr) (Roberts, 1998). The Holocene optimum in different regions of the Northern hemisphere took place at (10)9–(7)6 ka (Roberts, 1998). The climate cooling which began at 6000–4000 years BP is regarded as the start of the Neoglacial Holocene (Crockford and Frederick, 2007). Also, the climate variations which took place at 7–6 ka led to a global transformation of vegetation. This is clearly evidenced by pollen records from the sediments of the Western Alps (Fauvart et al., 2012), Spain (Jiménez-Moreno and Anderson, 2012), Mongolia (Fukumoto et al., 2012), China (Chen et al., 2013), and some other regions. During the Holocene postoptimum, the ice sheets which caused dramatic changes in the Earth's environment and climate in the last glacial period waned to the present size (Dyke and Prest, 1987). The present level of the World Ocean was also reached at ~6 ka and has shown only slight fluctuations since then (Horton et al., 2007). However, a summary of more than 50 global paleoclimate records from both hemispheres yields five periods of significant climate changes during the postoptimum time: 6.0–5.3, 4.2–3.8, 3.2–2.4, 1.2–1.0, and 0.60–0.15 ka (Mayewski et al., 2004).

Analysis of palynostratigraphic data on the Baikal region revealed three long periods of climate and vegetation change: (a) 11.7–9.5 ka, with low atmospheric humidity, lower average winter and summer temperatures than present ones, and

* Corresponding author.
E-mail address: bezrukova@igc.irk.ru (E.V. Bezrukova)

http://dx.doi.org/10.1016/j.rgg.2014.03.004

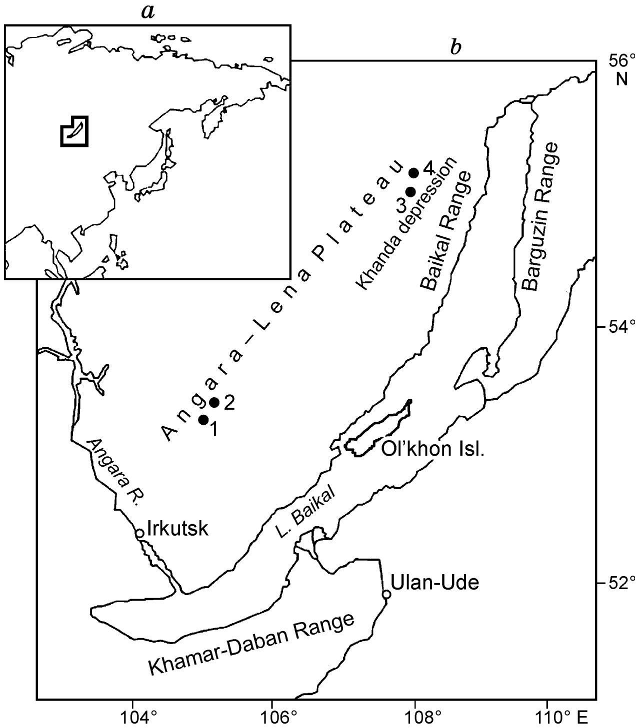

Fig. 1. Sketch map of North Asia and the Baikal region (*a*), with study areas (*b*). The location of the study areas is shown by black circles: 1, Khyndyrkul tract; 2, Lake Valley; 3, Khanda-1 peat bog; 4, Khanda-2 peat bog.

predominant forest tundras; (b) 9.5–6.5 ka, the most favorable period for the development of dark coniferous fir-tree taiga with the maximum average annual precipitation and the highest average winter temperature in the Holocene; and (c) 6.5 ka–present, when the values of all the above-mentioned climate parameters decreased with respect to those in the previous period and light coniferous forests began to predominate (Bezrukova et al., 2010; Demske et al., 2005; Tarasov et al., 2007, 2009).

To test this Holocene periodicity for Baikal, biostratigraphic data on its other large regions were required. One of them is the Angara–Lena Plateau, which occupies most of Cisbaikalia as the main structural and morphologic element of its topography. This region is key to the understanding of the evolution of the Baikal environment because of the predominance of primary boreal forests (taiga). As they are on the way of western moisture-bearing air masses, they retain a considerable part of moisture, thus reducing the amount of precipitation in the Baikal region and ensuring the accumulation of water resources in the Baikal Trough. The landscapes of the Angara–Lena Plateau are located on permafrost, which makes them sensitive to climate change. Nevertheless, the change in the environment and climate of this region remained almost unknown till now. The present study is concerned with the regularities in the reaction of the plateau landscapes and climate to regional climate change caused by the Holocene transformations of the global climate system. To meet this objective, we carried out the first integrated study of peat bogs in this region.

Materials and methods

Southeastern Angara–Lena Plateau. The Khyndyrkul tract is located in the southern part of the plateau (Fig. 1), in the upper reaches of the valley of the Ilga River, left tributary of the Lena River (53°30′45.15″ N; 104°48′51.76″ E). The area is characterized by the sparse patchy distribution of frozen rocks, waterlogging, the presence of long-term and seasonal frost mounds, and extreme continental climate. According to the data of the Bayandai weather station, the average temperature of January is –22.9 °C; that of July, +16.8 °C; and the average annual precipitation is ~350 mm. The present vegetation in the area is dominated by forests of *Pinus sylvestris*, *Larix* sp., and *Betula sect. Albae*, part of which substituted dark coniferous taiga. Dark coniferous forests with *Pinus sibirica*, *Picea obovata*, or, more rarely, *Abies sibirica* occupy small areas. The frost peat mound itself is covered with birch-forb vegetation, and the bog sustains sedge-grass communities with *Betula sect. Nanae*.

The Lake Valley tract (Fig. 1) is located 5 km north of the Khyndyrkul peat bog (53°30′43.47″ N; 104°48′35.68″ E). The climate and vegetation in this area are almost identical to those in the Khyndyrkul tract.

Northeastern Angara–Lena Plateau. We studied two peat bogs in the upper reaches, on the right bank of the Khanda River, left tributary of the Kirenga River. The Khanda-1 section (55°44′30.60″ N; 106°58′0.38″ E) is localized at the second bottom, where the peat bog is undermined by the river. The Khanda-2 section (55°59′50.60″ N; 106°59′40.38″ E) is localized at the second bottom of the river, 7 km north of the first peat bog. The studied peat bogs are located in the Khanda basin, whose sides have an altitude of up to 250 m more than the bottom. The area is marked by extreme continental climate, with a long cool winter and a short warm summer. Owing to winter inversions, the temperature here decreases to –45 to –50 °C, ensuring the existence of permafrost. According to the data of the closest Davan weather station, the average temperature of January is –26.1 °C; that of July, +14.2 °C; and the average annual precipitation is from 300 to 400 mm (Galazii, 1993).

The vegetation of the basin sides and bottom is very different. The western slope is dominated by spruce–Siberian pine forests with larches, and the eastern one sustains Siberian pine–larch and Scots pine–larch forests with dwarf birches. Vast expanses of primary forests on the basin sides were destroyed by fires and then replaced by larches and birches. The basin itself is occupied by stunted larch forests, and sand deposits in this area sustain Scots pine forests. The surfaces of both peat bogs have similar vegetation—sparse larch forests with *Betula sect. Nanae*, Cyperaceae, and *Sphagnum* sp.

Sampling process. The peat bog in the Khyndyrkul tract was drilled into using an Instorf sampler. Three other peat bogs were sampled in situ by cutting peat monoliths (5 × 5 × 5 cm) out of cleared outcrops.

Radiocarbon dating. The age models for the peat profiles are based on 16 radiocarbon dates (Table 1). The radiocarbon ages were converted to calendar years BP using the CalPal

Table 1. Results of radiocarbon dating for the studied peat sections

Section	Depth of the dated layer from the section surface, cm	^{14}C age, years starting from 1950	Calibrated age, years BP	Sedimentation rates, mm/yr
Khyndyrkul	80	1115 ± 100	1057 ± 106	0.7
	122	2300 ± 105	2346 ± 162	0.3
	184	3700 ± 120	4066 ± 168	0.4
	214	4530 ± 120	5190 ± 185	0.3
Lake Valley	20	565 ± 35	588 ± 41	0.4
	40	1065 ± 45	994 ± 47	0.5
	70	1315 ± 65	1232 ± 58	1.3
Khanda-1	10	130 ± 40	140 ± 101	0.7
	70	1870 ± 120	1804 ± 144	0.4
	123	2800 ± 120	2965 ± 148	0.5
	145	3450 ± 80	3722 ± 102	0.3
	190	4080 ± 90	4621 ± 147	0.5
	228	5230 ± 130	6007 ± 163	0.3
Khanda-2	10	260 ± 45	302 ± 114	0.3
	60	2115 ± 65	2133 ± 114	0.3
	112	2915 ± 55	3074 ± 87	0.65

software (Danzeglocke et al., 2013). Calibrated values will be used thereafter. The rates of peat accumulation between the dated layers were calculated (Table 1). The age of spore–pollen zones was calculated by linear interpolation between the dated levels.

The spore–pollen analysis of the samples was carried out at the Vinogradov Institute of Geochemistry. In the core from the Khyndyrkul peat bog, every fifth centimeter was sampled; in the Lake Valley section, every tenth; in the Khanda-1 section, every fifth; and in the Khanda-2 section, every second. For spore–pollen diagrams, the percentage of individual pollen taxa from every sample was calculated from the total amount of pollen (100%). The spore percentage for cryptogam plants was calculated from the total amount of counted pollen and spores.

Results and interpretation

The Khyndyrkul peat bog is 230 cm thick. The lower layer (230–190 cm) of strongly decomposed dark brown peat is overlain (190–134 cm) by still darker peat showing different degrees of decomposition. The interval 134–20 cm is dominated by strongly decomposed dark brown peat. The 20 cm thick upper layer is pierced with the roots of present-day shrubs and herbs. With regard to the sedimentation rates, the dating permits us to estimate the age of the peat base at 6300 years. The average time resolution of the spore–pollen record is 170 years. The spore–pollen diagram for the Khyndyrkul peat bog is divided into three local pollen zones and two subzones: Khdr-3, Khdr-2, Khdr-1b, and Khdr-1a (Fig. 2). The lower zone Khdr-3 (230–203 cm, 6300–5000 years BP) is characterized by the predominance of tree pollen, similar contents of Scots pine *Pinus sylvestris* and Siberian pine *Pinus sibirica* pollen, a high content of spruce *Picea obovata* pollen, and maximum contents of the pollen of tall birches *Betula sect. Albae* and xeromesophyte herbs: wormwood *Artemisia*, buttercups Ranunculaceae, and roses Rosaceae. The spore–pollen spectra (SPS) for the Khdr-2 zone (203–120 cm, 5000–2300 years BP) reflect an increase in the contents of herbs, particularly sedges Cyperaceae and grasses Poaceae. The abundance of fir *Abies sibirica* and larch *Larix* sp. pollen also increases considerably with respect to that in the previous zone. Pollen of xeromesophyte herbs almost disappears from the SPS for the Khdr-2 zone. In the SPS for the Khdr-1b subzone (120–23 cm, 2300–300 years BP), the abundance of *Pinus sylvestris* and *Picea obovata* pollen increases considerably, whereas that of *Abies sibirica* and Cyperaceae pollen decreases. In the SPS for the Khdr-1a subzone (23–0 cm, ~300 years–present), the percentage of tall birch *Betula sect. Albae*, dwarf birch *Betula sect. Nanae*, willow *Salix* sp., alder *Duschekia fruticosa*, and Ericaceae pollen increases dramatically.

The low sedimentation rate in the Khyndyrkul section at depths of 230–203 cm (6300–5000 years BP) (Table 1), the high degree of peat decomposition, and the maximum content of xeromesophyte herbs suggest unfavorable conditions for peat accumulation in an insufficiently humid climate. The increase in the accumulation rates of the overlying layer at 5000–2300 years BP and the appearance of *Abies sibirica* pollen imply the onset of a more humid and less continental climate and the expansion of dark coniferous forests. The increase in the abundance of *Pinus sylvestris* pollen and the decrease in the contents of *Abies sibirica* and Cyperaceae pollen suggest worse conditions of peat accumulation, a lower

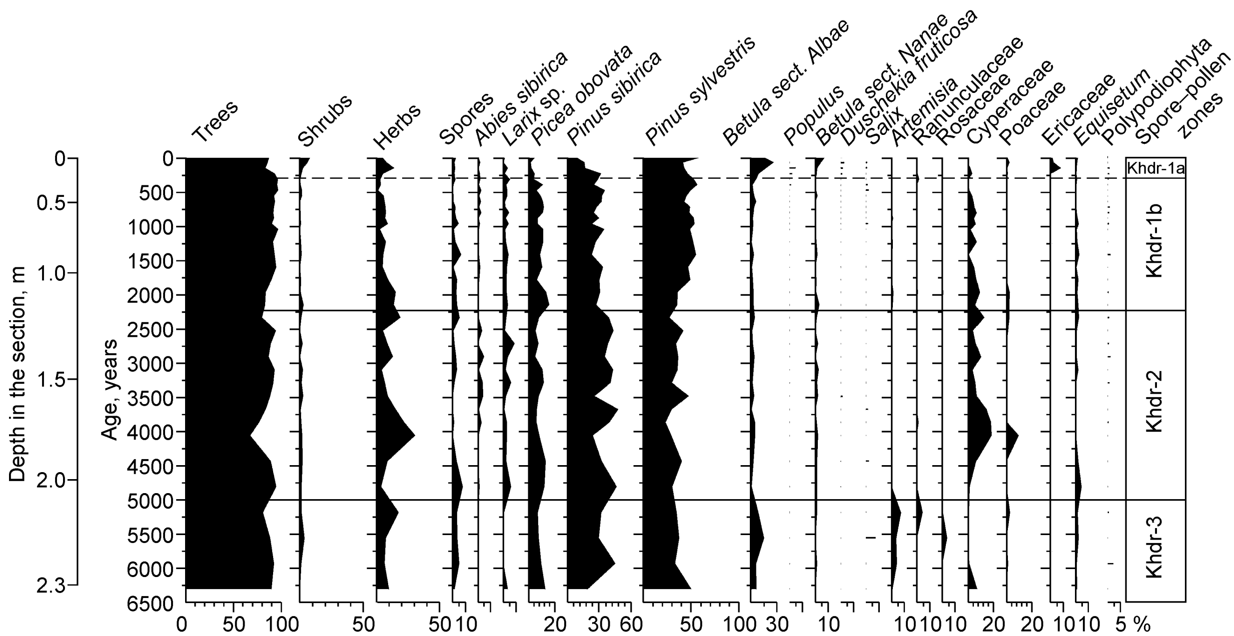

Fig. 2. Spore–pollen diagram for the Khyndyrkul peat bog. Taxa whose pollen makes up no more than 5% are shown by histograms without a vertical axis.

moisture content, and a more continental climate at 2300–1000 years BP.

The high sedimentation rates after 1000 years BP reflect a cool humid climate, favorable to peat accumulation. The increase in the abundance of *Betula sect. Albae*, shrub, and Ericaceae pollen in the last few centuries might be due to the destruction of the primary vegetation by fires. The latter might have caused the development of permafrost and the transition of the bogs to the oligotrophic state.

The total thickness of **the Lake Valley peat bog** is 90 cm. The lower layer (0–40 cm) consists of silty alluvium overlain by a 40-cm peat layer. The interval 40–15 cm consists of strongly decomposed dark brown peat. The upper 15 cm consist of more light-colored peat of medium decomposition with the roots of present-day shrubs and herbs.

In the age model for the section, the base of the peat deposits is dated at 994 ± 47 years. The extrapolation of the sedimentation rate to the section base suggests that the age of the alluvial base is ~1400 years. The average time resolution of the spore–pollen record is 150 years. The SPS for the peat bog shows one pollen zone with three subzones, designated as DO-1c–DO-1a (Fig. 3).

The SPS for the DO-1c subzone (90–40 cm, 1400–1000 years BP) is dominated by *Pinus sylvestris*, *Pinus sibirica*, and *Picea obovata* pollen. Also, *Abies sibirica* and *Larix* pollen is observed. Spores of cryptogams are abundant, particularly *Botrychium virginianum*-type and *Selaginella selaginoides*. The SPS for the DO-1b subzone (40–5 cm, 1000–150 years BP) is dominated by *Pinus sylvestris* and Cyperaceae pollen. In the SPS for the DO-1a subzone (5–0 cm, 150–present), the content of *Betula sect. Nanae* pollen increases and that of Cyperaceae pollen decreases.

The predominance of tree pollen in the SPS for the lower subzone DO-1c indicates the predominance of forests near the peat bog at 1400–1000 years BP. The maximum contents of *Abies sibirica*, *Picea obovata*, and *Pinus sibirica* pollen and Polypodiophyta spores suggest considerable participation of dark coniferous forests in a humid, temperate continental climate. This is evidenced by the highest sedimentation rate.

The portion of dark coniferous forest communities decreases at 1000–150 years BP, whereas that of light coniferous larch and Scots pine forests increases. If we consider the high aerodynamic properties of *Pinus sylvestris* pollen and the very low ones of *Larix* pollen, *Larix* might have constituted a larger portion of the forest than it is shown by the SPS. The manifold increase in the abundance of Cyperaceae pollen indicates the development of a fen on the floodplain at ~1000 years BP. The development of the fen (i.e., waterlogging) might have been an important cause of the decrease in the portion of dark coniferous spruce and Siberian pine associations.

In the last 150 years, there has been an expansion in the area of dwarf birches, which are typical of small river valleys with frozen ground. The manifold decrease in the content of Cyperaceae pollen suggests the development of a raised bog with predominant atmospheric feeding.

The section of **the Khanda-1 peat bog** is 232 cm thick. The 5-cm lower interval in the stratigraphic section is composed of frozen bluish light gray silty and sandy fluvial alluvium. The rest of the section consists of peat showing different degrees of decomposition. The uppermost peat layer (0–5 cm) is composed of fallen leaves and moss. The interval 5–36 cm is poorly decomposed light brownish gray peat with roots in the upper part. The layer 36–80 cm is made up of dense light brown peat of medium decomposition. The layer 70–78 cm is frozen dense dark brown peat of medium decomposition. The interval 80–160 cm consists of strongly decomposed frozen dark gray-brown peat. A layer of strongly decomposed frozen dark gray-brown peat is observed at depths

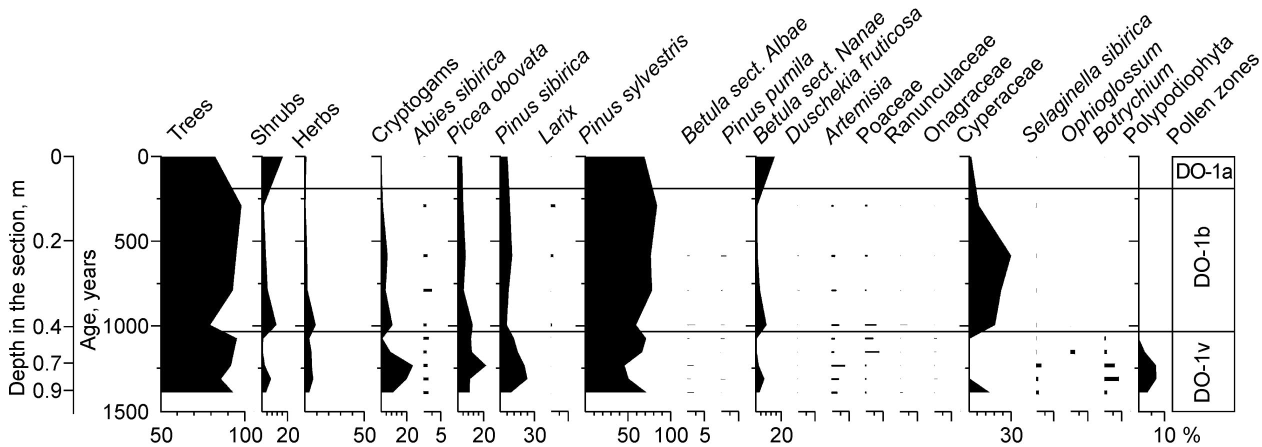

Fig. 3. Spore–pollen diagram for the Lake Valley peat bog.

of 160–227 cm. The peat–alluvium contact is smooth and well-defined.

According to the age model, the basal peat layer began to accumulate at ~6200 years BP. The average time resolution of the spore–pollen record is 150 years. The diagram for the Khanda-1 peat bog shows four pollen zones: Khnd-1–Khnd-4 (Fig. 4).

The SPS for the Khnd-4 zone (232–210 cm, 6200–5400 years BP) is dominated by tree pollen and shows similar contents of *Pinus sylvestris* and *Pinus sibirica* pollen. The base of the zone has the maximum content of *Picea obovata* pollen and high contents of *Betula sect. Nanae* and Poaceae pollen. The Khnd-3 zone (210–115 cm, 5400–2800 years BP) has lower contents of *Picea obovata* and *Pinus sibirica* pollen and higher contents of *Abies sibirica* and *Pinus sylvestris* pollen than the previous zone.

The SPS for the Khnd-2 zone (115–25 cm, 2800–600 years BP) is characterized by a gradual decrease in the abundance of *Pinus sylvestris* pollen and an increase in the abundance of *Pinus sibirica* and *Betula sect. Nanae* pollen. *Abies sibirica* and *Picea obovata* pollen is observed constantly in small amounts.

The SPS for the Khnd-1 zone (25–0 cm, the last 600 years) shows a considerable increase in the abundance of *Pinus sibirica* and *Larix* pollen and *Sphagnum* spores.

The persistence of tree pollen in the SPS for the Khanda-1 section indicates the existence of forests all through the peat bog formation. However, the late Middle Holocene (6200–5400 years BP) was characterized by the predominance of dark coniferous spruce and Siberian pine forests with ferns and Lycopodiaceae in the herbaceous cover. Dwarf birches, Ericaceae, and sphagnum mosses were a considerable part of the local vegetation. Spruces might have made up valley forests and be part of the forests of the Khanda basin. The dramatic decline of the role of spruces after 6000 years BP in the forest vegetation of the Angara–Lena Plateau took place at approximately the same time as the decline of the spruce component in the forests of the entire Baikal region (Bezrukova et al., 2005), implying the common cause of these processes.

The increase in the content of *Pinus sylvestris* pollen in the SPS for the Khnd-3 zone, along with the significant decrease in the abundance of *Pinus sibirica* and *Picea obovata* pollen, suggests that Scots pines began to play a more important role in the forest vegetation of the region at 5400–2800 years BP. The area occupied by dwarf birches in the local vegetation expanded at 4800–3800 years BP. The maximum contents of *Sphagnum* spores at 3800–2800 years BP and increased contents of Cyperaceae pollen at 2800–1800 years BP indicate variability in the bog regime (transition to the mesooligotrophic stage). Sedge communities typical of eutrophic bogs predominated during periods of rising water level in the peat bog.

The gradual decrease in the abundance of *Pinus sylvestris* pollen and, vice versa, the increase in the contents of *Pinus sibirica* and *Picea obovata* pollen in the SPS at 2800–600 years BP suggest an expansion of dark coniferous forests in the northwestern Angara–Lena Plateau. The SPS for the sediments which have accumulated over the last ~600 years suggest continuing expansion of the areas occupied by Siberian pines and particularly larches. The local vegetation of the peat bog was dominated by sphagnum mosses. The synchronous maximum contents of *Artemisia* and Ericaceae pollen at ~500 years BP might reflect a short-term change in the trophicity of the peat bog.

The section of **the Khanda-2 peat bog** is 112 cm thick. The bog surface is covered with a sparse larch forest dominated by dwarf birches, Ericaceae, sedges, and sphagnum mosses. The upper peat layer (0–10 cm) consists of fallen leaves and moss. The underlying layer 10–35 cm is composed of brownish gray peat. The interval 35–80 cm is dark brown peat of medium decomposition. The interval 80–112 cm is strongly decomposed frozen dark gray-brown peat.

The age of the peat base is ~3200 years. The average time resolution of the spore–pollen record is 60 years. The spore–pollen diagram for the peat bog shows one local pollen zone with three subzones: Khnd-2$_a$–Khnd-2$_c$ (Fig. 5).

The SPS for the Khnd-2$_{1c}$ subzone (112–86 cm, 3200–2600 years BP) is characterized by unstable contents of tree pollen and the highest contents of *Sphagnum* spores and

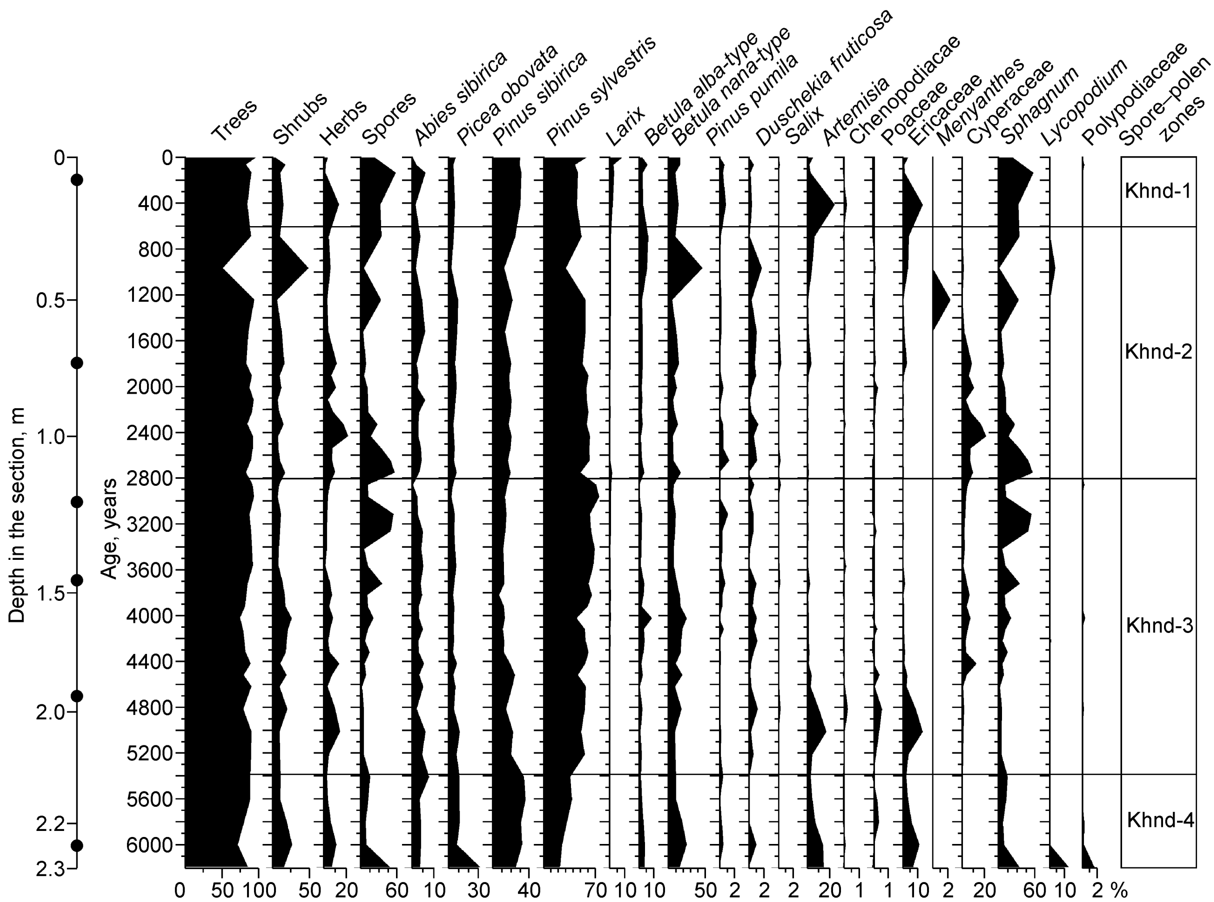

Fig. 4. Spore–pollen diagram for the Khanda-1 peat bog.

Cyperaceae pollen. The trees are dominated by *Pinus sylvestris* and *Larix* pollen. The Khnd-2_{1b} subzone (86–36 cm, 2600–1300 years BP) has higher contents of *Pinus sylvestris*, *Picea obovata*, *Abies sibirica*, and *Pinus sibirica* pollen than the previous subzone. The Khnd-2_{1b} subzone is marked by the appearance and permanent presence of *Pinus pumila* pollen. As regards the herbs, the sediments aged 2.6–2.4 ka have maximum contents of bog-beans *Menyanthes* and pondweed *Potamogeton* pollen. The abundance of *Pinus sylvestris*, *Abies sibirica*, and *Pinus sibirica* pollen decreases gradually in the SPS for the Khnd-2_{1a} subzone (36–0 cm, the last 1200 years).

The environment favored the accumulation of the frozen lower dark gray-brown layer at 3200–2600 years BP, which might have been due to the development of a sphagnum bog. The spread of sphagnum mosses, which retain a large amount of moisture, creates less favorable conditions for local tree vegetation and might be the cause of the decrease in the forest cover evident from the decreased content of tree pollen in the SPS (Fig. 5).

During the interval 2600–1300 years BP, a series of short-term changes in the local vegetation was expressed in the appearance of bog-beans and pondweed, the expansion of sedge communities (2600–2400 years BP), and the development of dwarf pines. This indicates the knob-and-kettle structure of the bog surface, where communities of bog vegetation developed in water sinks and dwarf pines developed on mounds with permafrost. The importance of spruces, firs, and Siberian pines increased gradually because of warming after 2600 years BP. Approximately at 1300 years BP, dwarf pines almost disappeared from the local vegetation. Firs and Siberian pines began to play an important role in the forest vegetation on the slopes of the Khanda depression at 1300–600 years BP, suggesting the onset of a milder climate than in the previous interval. The increasing portion of Siberian pines and the decreasing portion of firs and Scots pines in the regional vegetation after 600 years BP might have been due to cooling.

Conclusions

As demonstrated above, the studied areas of the Angara–Lena Plateau are dominated by landscapes with primary boreal forests in harsh conditions with permafrost. Their vegetation is known to be very sensitive to environmental and climate changes. To find out possible causes of vegetation change on the Angara–Lena Plateau in the context of past changes in the global climate system, two palynological indices were selected: the abundance of tree pollen and that of dark coniferous tree pollen (Fig. 6). These indices, regarded as indices of relative variations in the climate continentality (Bezrukova et al., 2012), signal changes in the Holocene regional climate.

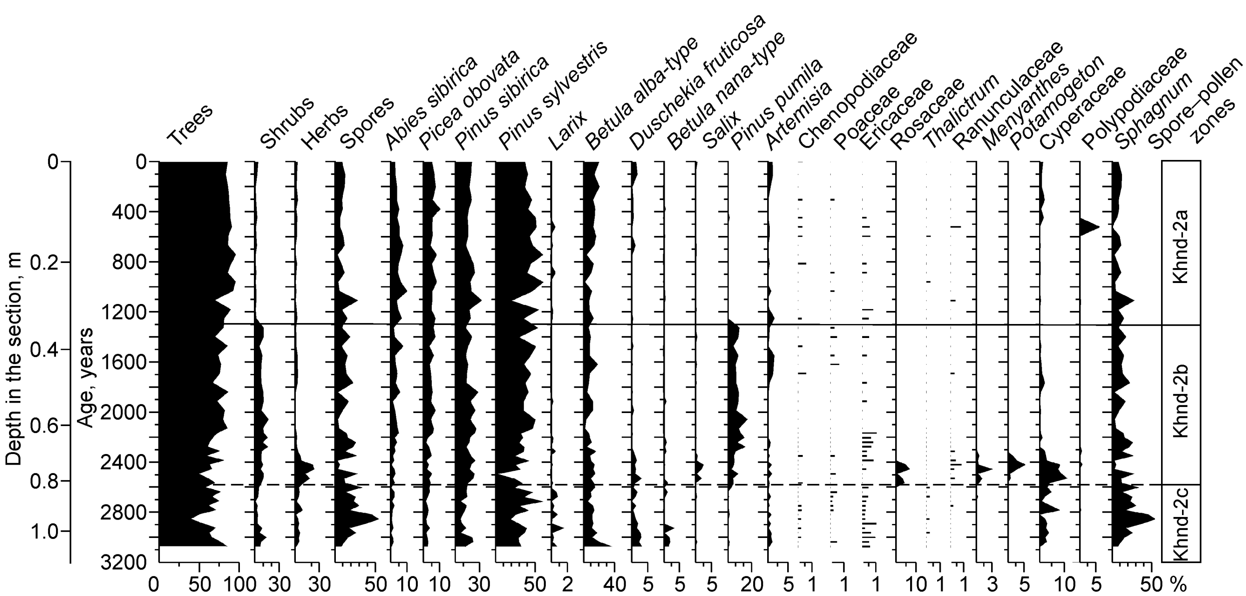

Fig. 5. Spore–pollen diagram for the Khanda-2 peat bog.

The observed variations in both indices are compared with the trend of $\delta^{18}O$ records from the global stratotypes (the Greenland ice sheet (Svensson et al., 2008) and stalagmites of China caves (Wang et al., 2005) and the global dramatic climate changes known in the Holocene (Mayewski et al., 2004). The variability in the abundance of tree pollen suggests the unstable state of forest vegetation in the study area during the Holocene postoptimum. For example, the short episodes of its decrease observed near the Khyndyrkul tract at ~5.3, 4.0, 2.3, and 1.0 ka coincide with periods of dramatic global cooling (Fig. 6). During the same intervals, the importance of dark coniferous forests declined, indicating the development

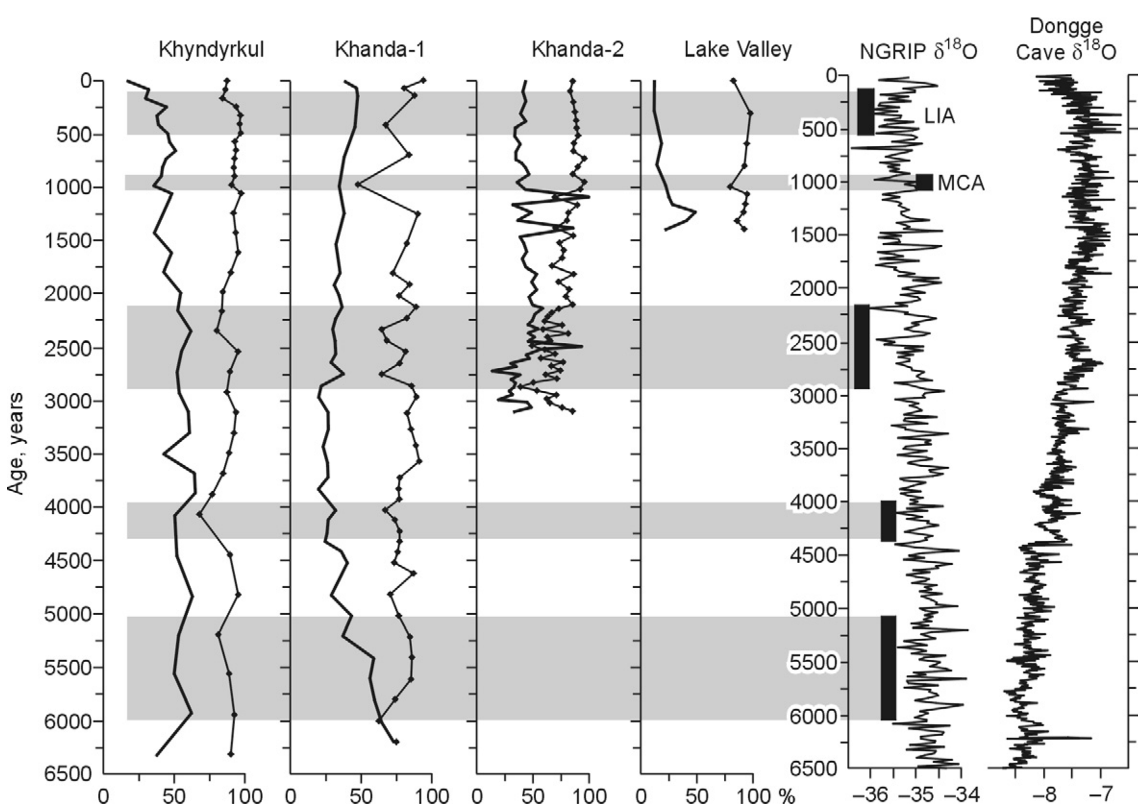

Fig. 6. General variations in the abundance of all tree pollen (line with diamonds) and of the pollen of dark coniferous trees (solid line) compared to the dynamics of $\delta^{18}O$ from the global stratotypes—NGRIP (Greenland ice sheet) (Svensson et al., 2008) and the stalagmites of Dongge Cave (China) (Wang et al., 2005)—and to global cooling episodes over the last 6.5 kyr (vertical black rectangles) (Mayewski et al., 2004).

of a more continental climate in the region. The Little Ice Age did not find any clear expression in the Khyndyrkul tract. The minimum contents of forest vegetation observed in the Lake Valley at 1.1 ka and at present permit correlating the first minimum with the global cooling at 1.1–1.3 ka (Mayewski et al., 2004). The steady decrease in the portion of the dark coniferous forests in the southeastern Angara–Lena Plateau might have multiple causes. One of them is a reaction to the global cooling, which is evident from both global $\delta^{18}O$ records approximately from 6.5 ka (Fig. 6). Another cause might have been increasing anthropogenic burden on the landscapes in this territory.

According to the pollen records from the Khanda depression, the postoptimum deterioration of global climate at 5.9–5.3 ka might have reduced the portion of the dark coniferous forests (Fig. 5). Note that the next cooling at 3.2–2.4 ka caused a gradual increase in this value (Fig. 5). A similar situation is typical of the Khanda-2 site (Fig. 6). The global paleoclimate records show that the activity of the Siberian anticyclone was of similar intensity at 5.9–5.3 and 3.2–2.4 ka; therefore, it remains uncertain why the response of the regional vegetation of the northeastern Angara–Lena Plateau to global cooling was so different. Interestingly, these two global cooling episodes also had different effects on landscapes in Scandinavia. For example, the tree-line became higher at 6–5 ka, simultaneously with the advance of glaciers, but the situation was the opposite during the cooling at 3.5–2.5 ka. This is explained by different amounts of solar radiation (Mayewski et al., 2004).

The deterioration of the global climate at 1.2–1.0 ka in all the studied regions was manifested in short episodes of slight decrease in the portion of forest vegetation and expansion of dwarf birch communities (Fig. 6). Also, the Little Ice Age might have caused another short interval of change in the vegetation structure in all the study regions except the Khyndyrkul tract.

The last 150 years were marked by an increase in the average annual temperature, but the considerable increase in the portion of larch and dwarf birch associations on the Angara–Lena Plateau during the same period, on the contrary, indicates permafrost activity in the region. Apparently, the retarded reaction of cool boreal forests sustained by permafrost does not permit them to respond quickly to the recent warming, which suggests their evolution inertness.

The most important result of the present study is the detection of variability in the regional response of the vegetation and climate of the Angara–Lena Plateau in the Middle–Late Holocene. Moreover, the observed intervals of reorganization in the regional environment took place in a quasi-millennial regime, in accordance with global climate rearrangement. However, not all the studied regions of the Angara–Lena Plateau showed a synchronous or analogous response to global environment change. This emphasizes the complicated character of regional climate manifestations in the Holocene and necessitates the use of paleogeographical data from a wider range of territories.

The study was supported by the Russian Foundation for Basic Research (projects no. 12-05-00476 and 13-05-00193), Baikal–Hokkaido Archaeological Project, and the Siberian Branch of the Russian Academy of Sciences (integration project no. 53).

References

Bezrukova, E.V., Abzaeva, A.A., Letunova, P.P., Kulagina, N.V., Vershinin, K.E., Belov, A.V., Orlova, L.A., Danko, L.V., Krapivina, S.M., 2005. Post-glacial history of Siberian spruce (*Picea obovata*) in the Lake Baikal area and the significance of this species as a paleo-environmental indicator. Quat. Int. 136 (1), 47–57.

Bezrukova, E.V., Tarasov, P.E., Solovieva, N., Krivonogov, S.K., Riedel, F., 2010. Last glacial—interglacial vegetation and environmental dynamics in southern Siberia: Chronology, forcing and feedbacks. Palaeogeogr. Palaeoclimatol. Palaeoecol. 296 (1–2), 185–198.

Bezrukova, E.V., Anderson, D.G., Vinkovskaya, O.P., Kharinsky, A.V., Kulagina, N.V., 2012. Vegetation and climate changes in the Bolshoe Inyaptukskoe Lake Basin (North Baikal Plateau) in the Middle and Late Holocene. Archaeology, Ethnology and Anthropology of Eurasia 40 (3), 2–11.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on north Atlantic climate during the Holocene. Science 294 (5549), 2130–2136.

Chen, F., Liu, J., Xu, Q., Li, Y., Chen, J., Wei, H., Liu, Q., Wang, Z., Cao, X., Zhang, S., 2013. Environmental magnetic studies of sediment cores from Gonghai Lake: implications for monsoon evolution in North China during the late glacial and Holocene. J. Paleolimnol. 49 (3), 447–464.

Crockford, S.J., Frederick, S.G., 2007. Sea ice expansion in the Bering Sea during the Neoglacial: evidence from archaeozoology. The Holocene 17 (6), 699–706.

Danzeglocke, U., Jöris, O., Weninger, B., 2013. CalPal-2007online, http://www.calpal-online.de.

Demske, D., Heumann, G., Granoszewski, W., Nita, M., Mamakowa, K., Tarasov, P.E., Oberhänsli, H., 2005. Late glacial and Holocene vegetation and regional climate variability evidenced in high-resolution pollen records from Lake Baikal. Global Planet. Change 46 (1–4), 255–279.

Dyke, A.S., Prest, V.K., 1987. Late Wisconsinan and Holocene history of the Laurentide ice sheet. Géographie Physique et Quaternaire 41 (2), 237–263.

Fauvart, N., Ali, A.A., Terral, J.-F., Roiron, P., Blarquez, O., Carcaillet, C., 2012. Holocene upper tree-limits of *Pinus* section *sylvestris* in the Western Alps as evidenced from travertine archives. Rev. Palaeobot. Palynol. 169, 96–102.

Fukumoto, Y., Kashima, K., Orkhonselenge, A., Ganzorig, U., 2012. Holocene environmental changes in northern Mongolia inferred from diatom and pollen records of peat sediment. Quat. Int. 254, 83–91.

Galazii, G.I. (Ed.), 1993. Baikal: An Atlas [in Russian]. Federal'naya Sluzhba Geodezii i Kartografii Rossii, Moscow.

Horton, B.P., Culver, S.J., Hardbattle, M.I.J., Larcombe, P., Milne, G.A., Morigi, C., Whittaker, J.E., Woodroffe, S.A., 2007. Reconstructing Holocene sea-level change for the Central Great Barrier Reef (Australia) using subtidal foraminifera. J. Foraminiferal Res. 37 (4), 327–343.

Jiménez-Moreno, G., Anderson, R.S., 2012. Holocene vegetation and climate change recorded in alpine bog sediments from the Borreguiles de la Virgen, Sierra Nevada, southern Spain. Quat. Res. 77 (1), 44–53.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability. Quat. Res. 62 (3), 243–255.

Roberts, N., 1998. The Holocene: An Environmental History, 2nd ed. Blackwell, Malden, Mass.

Svensson, A., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Davies, S.M., Johnsen, S.J., Muscheler, R., Parrenin, F., Rasmussen, S.O., Röthlisberger, R., Seierstad, I., Steffensen, J.P., Vinther, B.M., 2008. A

60 000 year Greenland stratigraphic ice core chronology. Clim. Past 4 (1), 47–57.

Tarasov, P., Bezrukova, E., Karabanov, E., Nakagawa, T., Wagner, M., Kulagina, N., Letunova, P., Abzaeva, A., Granoszewski, W., Riedel, F., 2007. Vegetation and climate dynamics during the Holocene and Eemian interglacials derived from Lake Baikal pollen records. Palaeogeogr. Palaeoclimatol. Palaeoecol. 252 (3–4), 440–457.

Tarasov, P.E., Bezrukova, E.V., Krivonogov, S.K., 2009. Late Glacial and Holocene changes in vegetation cover and climate in southern Siberia derived from a 15 kyr long pollen record from Lake Kotokel. Clim. Past 5 (3), 285–295.

Wang, Y., Cheng, H., Edwards, R.L., He, Y., Kong, X., An, Z.S., Wu, J.Y., Kelly, M.J., Dykoski, C.A., Li, X., 2005. The Holocene Asian monsoon: links to solar changes and North Atlantic climate. Science 308 (5723), 854–857.

Editorial responsibility: M.I. Kuz'min