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Reconstruction of Palaeoecological and Palaeoclimatic Conditions of the Holocene in the South of the Taimyr according to an Analysis of Lake Sediments

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Abstract—A sediment core from Khatanga-12 Lake (Taimyr Peninsula, Krasnoyarsk krai) has been studied. The 131.5-cm-long core covers ca. 7100 years of sedimentation. Chironomid analysis, a qualitative reconstruction of the paleoenvironment in the region, and a quantitative reconstruction of variations of the mean July air temperature and in the water depth of the lake have been performed using Northern Russia chironomid-inferred mean July temperature models (Nazarova et al., 2008, 2011, 2015). Khatanga-12 Lake was formed during the Middle Holocene warming as a result of thermokarst processes. The development of the lake ecosystem at different stages of its development was influenced by climatic and cryolithogenic factors. The Middle Holocene warming, which occurred around 7100–6250 cal. years BP, activated thermokarst processes and resulted in the formation of the lake basin. Later, between 6250 and 4500 cal. years BP, a period of cooling took place, as is proved by chironomid analysis. The bottom sediments of the lake during this period were formed by erosion processes on the lake shores. The reconstructed conditions were close to the modern after 2500 cal. years BP.

Keywords: Chironomidae, paleolimnology, Holocene, climate reconstructions, Russian Arctic region, Khatanga

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INTRODUCTION

The development of polar ecosystems under the continuously changing climate conditions is an important problem of paleoclimatic and paleoecological investigations (Hoff et al., 2015; Fritz et al., 2016). Despite the environmental development that has been reconstructed in almost the entire northern hemisphere (Mayewski et al., 2004; Schirrmeister et al., 2011; Meyer et al., 2015; Rudaya et al., 2016), paleoecological and paleoclimatic data on the Siberian sector of the Arctic region are still insufficient (Nazarova, 2012; Palagushkina et al., 2012; Nazarova et al., 2013a, b; Frolova et al., 2013, 2014; Solovieva et al., 2005, 2008).

Aquatic organisms, including *Chironomidae* (Insecta: Diptera) (Solovieva et al., 2005; Nazarova et al., 2015), are the best biological indicators for the quantitative reconstructions of changes in the air temperature, because their distribution and development are significantly dependent on temperature (Nazarova et al., 2008; Self et al., 2011). The chitinized structures of chironomids are well-preserved in lake sediments (Nazarova et al., 2008) and easily identified (*Biologicheskie indicatory v paleobiologicheskikh issledovaniyakh*..., 2013). The methods of qualitative and quantitative reconstructions have been elaborated in detail (Brooks, 2006; Nazarova et al., 2015) and used worldwide in paleoclimatic and paleoecological studies (Larocque et al., 2001; Smol et al., 2005; Barley et al., 2006).

In 2011–2013, within the framework of Russian–German cooperation, several expeditions were organized to the region of the Khatanga River (southeast of the Taimyr Peninsula), during which surface and core samples of lake sediments were taken, on which lithostratigraphic, granulometric, and spore palynilogical analyses, and radiocarbon dating were performed (Klemm et al., 2015). The aim of the present study is to reconstruct the environmental conditions of the Holocene in the southeastern part of the Taimyr Peninsula based on the micropaleontological analysis of lake sediments using the statistical chironomid models

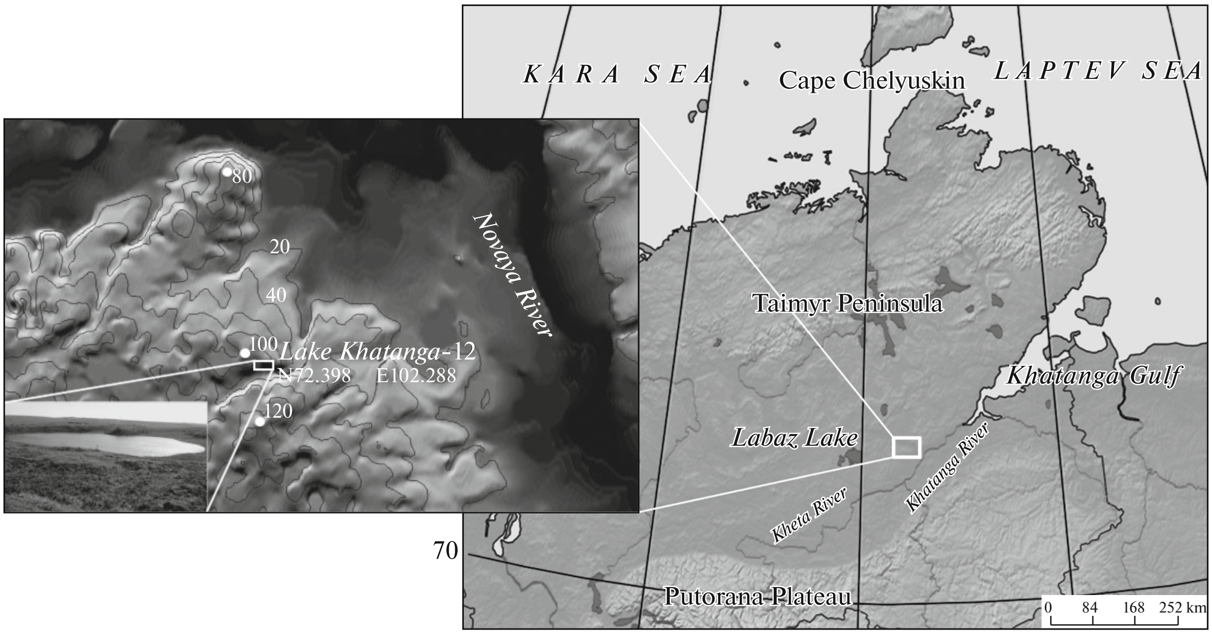

Fig. 1. Geographical location of Khatanga-12 Lake, Taimyr Peninsula.

for the reconstruction of the mean July air temperature and the water depth in lake.

MATERIALS AND METHODS

Khatanga-12 Lake (no official name; 72.50° N, 102.29° E; 60 m a.s.l.) is located on the right bank of the midstream of the Khatanga River (Fig. 1). The lake is small: length 200 m, width 150 m, and maximum depth 14.3 m; area 2.4 ha. Water input occurs through the atmospheric precipitation. The lake basin was formed as a result of thermokarst processes, which are also observed today (bank erosion). The lake has no permanent tributaries. A brook begins on the western shore and falls into the Novaya River, a tributary of the Khatanga River. The lake is oligotrophic (Klemm et al., 2015). The valley of the Khatanga River is located in the southern part of the Taimyr Peninsula, on the North Siberian lowland (Fig. 1). The climate of the studied region is Subarctic, characterized by a short and cool summer (the mean temperature of July is +13.0°C) and a long winter (the mean temperature of January is –31,5°C); the annual precipitation rate is 250 mm, falling mostly in summer (New et al., 2002). The vegetation is predominantly tundra. Almost the entire peninsula is underlain by permafrost.

Collection and processing of samples. The studied core of bottom sediments with a length of 131.5 cm was taken from the depth of 14.3 m using a gravity corer (UWITEC). A total of 15 core samples were dated by the radiocarbon method in the Radiocarbon Laboratory (Poznan, Poland). Based on the results of dating, an age model was constructed using a Bacon 2.2 software package (Blaauw, 2011) in the R program (R Development Core Team, 2013); radiocarbon years were calibrated using the IntCal13 calibration curve. The analyzed core covered the period from 7100 years (Klemm et al., 2015). The age model was presented in more detail by Klemm et al. (2015).

A total of 28 samples were analyzed. Two of them contained only single head capsules and were not taken into account during the reconstruction, but they were considered during the description of stratigraphic zones. The processing of samples for chironomid analysis was carried out by the standard method (Brooks et al., 2007). From 45 to 67 head capsules were picked up from each sample. The permanent slides of head capsules were made hydrometric under the cover glasses with a diameter of 6 mm. Chironomids were identified using modern identification manuals (Wiederholm, 1983; Brooks. et. al., 2007) and the collection of chironomids from the Alfred Wegener Institute (AWI), Potsdam (L.B. Nazarova). Due to the known difficulties in identifying fossilized chironomids, they were identified to the generic level or to the morphotype name (for example, *Psectrocladius psilopterus*-type, *P. sordidellus*-type, and *P. barbimanus*-type), which are referred to below as "taxon" (Brooks et al., 2007).

The stratigraphic diagram was made in the C2 program (Version 1.5) (Juggins, 2007). To study the general trends in the species composition, the method of principal component analysis (PCA) (ter Braak and Prentice, 1988) was used. The statistically significant zones were defined using the BSTICK and ZONE (Lotter and Juggins, 1991; Bennett, 1996) programs

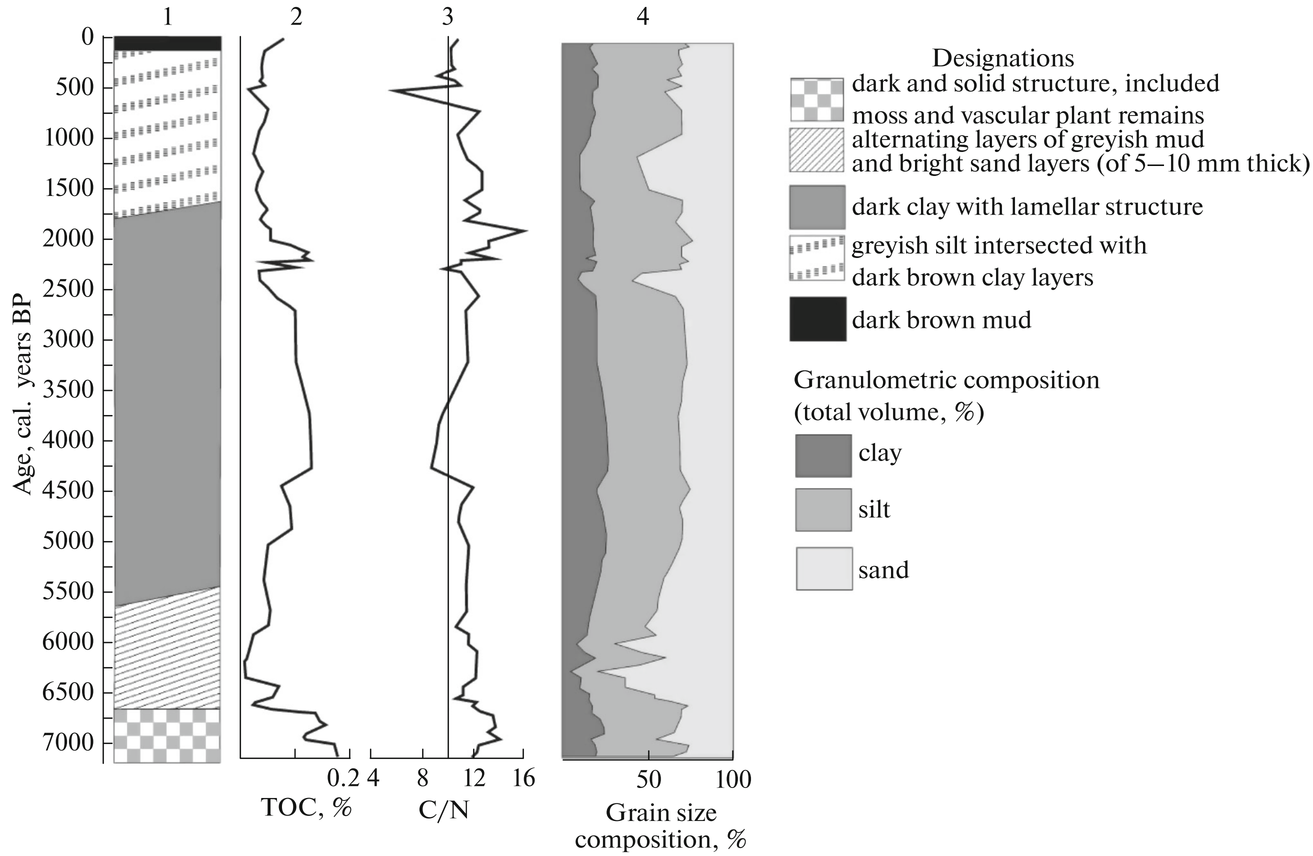

Fig. 2. Results of a lithological, granulometric, and geochemical analyses of the sediment core from Khatanga-12 Lake: (1) Lithostratigraphic analysis of the sediment core; (2) TOC, % is the total organic carbon, %; (3) C/N is the percentage ratio of organic carbon and nitrogen contents in the bottom sediments; and (4) granulometric composition of the bottom sediments.

and axes 1 and 2 of PCA. The biodiversity and evenness of chironomid communities were assessed using Shannnon's indices (H) (Shannon and Weaver, 1963) and Pielou's indices (I) (Pielou, 1966). Qualitative reconstruction was based on calibration data bases of the lakes from Eastern Siberia and the Russian Far East (Nazarova et al., 2008, 2011, 2015). Reconstruction of the mean July air temperature (*T* July) and the water depth (WD) was performed using the Russian chironomid models (Nazarova et al., 2011, 2015).

RESULTS

The sediments are mainly silty clays. The clays have a higher density at the bottom of the core and contain inclusions of mosses and plant remains. The mass fraction of organic carbon varies from 0.7 to 17.8%. The sedimentation rate is about 0.025 cm/year, decreasing to ~0.01 cm/year in the interval between 5400 and 2600 cal. years BP, which corresponds to a horizon of 67–81 cm (Fig. 2). No disturbances were revealed in the sedimentation process (Klemm et al., 2015).

A total of 1208 chironomid head capsules belonging to four subfamilies were identified in the studied samples: Chironominae, Orthocladiinae, Tanypodinae, and Diamesinae. The dominant taxa belong to two subfamilies: Chironominae of the tribe Chironomini (*Sergentia coracina*–type) and Tanytarsini (*Micropsectra insignilobu*–type) and Orthocladiinae (*Zalutshia* type B, *Heterotrissocladius grimshawi*–type, *Heterotrissocladius marcidus*–type). No species occurs in all samples. The most common species are *Zalutshia*-type B, *Sergentia coracina*–type, and *Tanytarsus mendax*–type, which occur in all zones. The evenness of chironomid communities (Pielou index) is high during almost the entire period. However, a slight decrease is registered in the period from 4000 to 2000 cal. years BP, which may be associated with changes in the conditions during this period. A slowdown of sedimentation is observed during this period. The reconstructed conditions are characterized by a certain increase in the acidification of the lake.

In the studied sediment core, four statistically significant zones have been identified (Fig. 3).

Ch I (7100–6250 cal. years BP). Lake sediments are mainly silty clays mixed with sand and interlayers of dark organogenic clays having a higher density with moss and macroresidue inclusions (Fig. 2). The C/N ratio in lake sediments is not above 15 (Fig. 2).

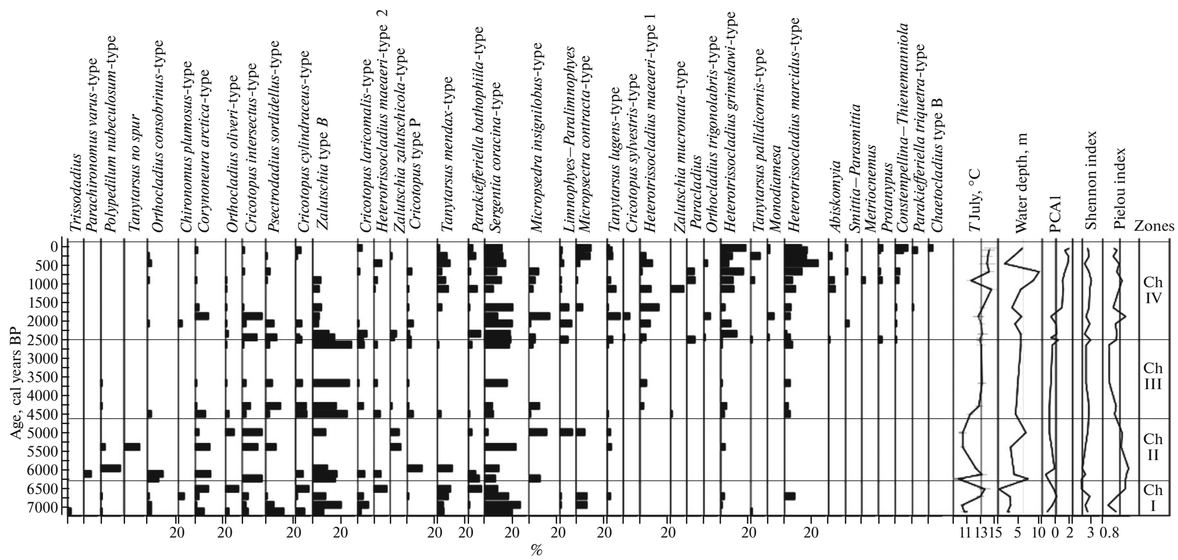

Fig. 3. Stratigraphic distribution of chironomid taxa in the bottom sediments of Khatanga-12 Lake, reconstructed mean temperatures of July (*T*, °C) and water depth, PCA 1.

The Rb/Sr ratio varies in the range of 0.2–0.5 (Klemm et al., 2015). The abundance of dominant chironomid taxa (*Sergentia coracina*–type and *Zalutschia zalutschicola*) varies within this zone (Fig. 3). The following taxa associated with macrophytes are present in the chironomid communities: *Psectrocladius sordidellus*–type, *Cricotopus intersectus*–type, *Cricotopus cylindraceus*–type, *Cricotopus laricomalis*–type. The Shannon index (showing the biodiversity of chironomid communities) varies from 1.98 to 2.80; the evenness of communities (Pielou index) varies from 0.59 to 0.90. The reconstructed temperatures change from 10.5 to 13.0°C. The reconstructed depths are about 2 m.

Ch II (6250–4500 cal. years BP). From the beginning of the period until 5500 cal. years BP, an increase in the sedimentation rate is observed. The granulometric composition is dominated by silt. The structure of bottom sediments is characterized by a decrease in the total organic carbon (TOC) content. Simultaneously (about 5500 cal. years BP), the coarse-grain, sandy, fraction is substituted with the finely dispersed fraction in the lithology of lake sediments (Fig. 2). The abundance of phytophilic taxa (*Cricotopus* and *Zalutschia*) in the chironomid communities increased. On the whole, cold-water stenotherm taxa *Sergentia coracina*–type, *Zalutschia*-type B, *Micropsectra insignilobus*–type, etc., prevail (Fig. 3). The biodiversity in chironomid communities varies from 1.98 to 2.50. The evenness of communities (Pielou index) varies from 0.83 to 0.96. The reconstructed July temperatures vary from 9.7 to 13.11°C. The reconstructed water depths are 3–7 m.

Ch III (from 4500 to 2500 cal. years BP). TOC content in the lake sediments increases. The C/N ratio almost does not change, even decreases slightly about 4500–3750 cal. years BP. The species of cold and moderate conditions preferring macrophytes are dominant (*Zalutschia*-type B, *Limnophyes–Paralimnophyes, Cricotopus intersectus*–type) (Fig. 3). The biodiversity of communities remains high (H) (2.41–2.74); the evenness decreases (0.59–0.74). The reconstructed temperatures vary from 11.4 to 12.9. The reconstructed depths are 4–5 m.

Ch IV (from 2500 cal. years BP to the present time). The two periods of sedimentation changes are registered in the composition lake sediments (Fig. 2): 2500–2250 cal. years BP and between 1500 and 1000 cal. years BP, during which an increase in the sandy fraction and a sharp decrease in the organic content are observed in the composition of the sediments. Dark brown finely dispersed clay is substituted about 1500 cal. years BP with grayish silty clay having dark brown interlayers. The role of *Sergentia coracina*–type and *Zalutschia*-type B in the chironomid communities becomes significantly less important. *Heterotrissocladius marcidus*–type, *Heterotrissocladius grimshawi*–type, and *Heterotrissocladius maeaeri*–type 1, all profundal and tolerant to acidification, become the dominant taxa (Fig. 3). The biodiversity and evenness of communities increase (Shannon index 2.60–3.01; Pielou index 0.70–0.90). The reconstructed July temperatures vary from 12.8 to 14.3°C. The average depth is about 5 m. Considerable fluctuations in the depth, from 3 to 9 m, were reconstructed during this period.

DISCUSSION

The period from 7100 to 6250 cal. years BP is an early stage in lake development. The content of carbon and nitrogen (C/N) in the lake sediments indicates a large proportion of the allochthonous component in the sediments (up to 15), and the revealed fluctuations in the Rb/Sr ratio reflect the deepening of the lake as a result of the thermokarst processes (Klemm et al., 2015). The chironomid taxa (*Sergentia coracina*–type and *Zalutschia zalutschicola*) that were dominant during that period are relatively deepwater and react to the water level dynamics: their number reduces as the lakes becomes shallower. The presence of phytophilic taxa indicates palludification and overgrown areas along the lake shores.

Up to 6750 cal. years BP, the reconstructed T July are lower than the modern ones. Following 6750 cal. years BP, they become higher than the modern level. This period corresponds to the final stage of the Middle Holocene warming. About *ca* 6250 cal. years BP, the reconstructed temperatures show a short cooling. Simultaneously, according to the data of an analysis of the chironomid communities, there is a short increase in the lake depth, which is probably caused by the enhancement of thermokarst processes and, as a result, the lake deepening. The change in sedimentation is registered in the lithostratigraphy of bottom sediments: the big-grain sandy material carried from the drainage basin prevails, probably as a result of the bank erosion. In the plant communities, there is also a reaction to the short cooling: the pollen spectra show an increase in the content of *Betula nana* pollen and herbaceous plants, as well as a decrease in the content of *Larix* and *Alnus viridis* pollen. An increase in the content of *Menyanthes trifoliata* and sedge pollen indicates the process of palludification (Klemm et al., 2015).

During the Middle Holocene warming, warm and wet conditions were established on the territory of North Siberia, which favored the active development of thermokarst processes. As a result of the latter, the basin of Khatanga-12 Lake was formed.

The period of 6250–4500 cal. years BP. The observed increase in sedimentation rate, prevalence of silty clays, and the decrease in the content of total organic carbon (TOC) as well as the shift in the lithological structure of bottom sediments from the big-grain, sandy, fraction to the finely dispersed fraction (about 5500 cal. years BP) must be a consequence of the lake deepening and the decrease of the sedimentation rate (Fig. 2). An increase in the abundance of phytophilic and cold-water stenotherm taxa indicates the ongoing development of a macrophyte belt in the shore area, which is also proved by palynological data: there is a gradual increase in the proportion of sedge plants in palynospectra (Klemm et al., 2015). During this period, according to the results of the chironomid analysis, we registered some cooling that influences the state of the lake ecosystem.

This period corresponds to the Neoglacial cooling, which was observed in various Eurasian and North American regions (Gribbin and Lem, 1980; Grove, 2004). The climate is cool and moist. The period from 7500 to 5300 cal. years BP was warm, but in some regions, such as Greenland, the Alps, Colorado mountains, and the tropics of Latin America, glaciation began around *ca* 6600–6000 cal. years BP. The beginning of the new stage of glacier expansion on the global scale (Neoglacial) occurred in the second half of the Holocene. It coincides with the southward shift of the northern border of forests and the cooling of Arctic waters (MacDonald et al., 2000).

The period from 4500 to 2500 cal. years BP. An increase in the TOC content and a stable C/N ratio during this period proves the dominance of autochthonous sedimentation as a result of an increase in the bioproductivity of the lake (Fig. 2). The water depth in the lake is quite stable. The species diversity of chironomids is higher than during the previous periods. The species of cold and moderate conditions preferring macrophytes are dominant (*Zalutschia*-type B, *Limnophyes–Paralimnophyes*, *Cricotopus intersectus*–type) (Fig. 3).

According to the spore–pallynological analysis, the plant communities during this period are characterized by a gradual decrease in the share of aboreal species and the formation of tundra vegetation: the content of pollen produced by aboreal plants decreases; the content of pollen produced by dwarf birch and herbaceous plants increases. A shift of larch taiga to forest tundra (about 3500 cal. years BP) is observed (Klemm et al., 2015).

Beginning from 2500 cal. years BP, fluctuations are registered in the climatic conditions, as well as instability in the development of environmental conditions. Significant changes are registered in the structure of plant communities: a shift from forest to shrub tundra is observed around *ca* 2250 cal. years BP; the range of larch gradually reduces (Klemm et al., 2015).

The more important role of profundal and acidification-tolerant taxa in the chironomid communities during this period (*Heterotrissocladius marcidus*–type, *Heterotrissocladius grimshawi*–type, and *Heterotrissocladius maeaeri*–type 1) must be associated with an increase in the lake depth and an intensification in the input of humic acids with the surface runoff (Ellenberg et al., 1992; Laing et al., 1999), which, in turn, confirms the land-cover development in the drainage basin.

The reconstructed climatic conditions are close to modern ones. The increase in the air temperature was reconstructed between 2000 and 1200 cal. years BP. Later, around *ca* 1200–900 cal. years BP, a short cooling took place.

CONCLUSIONS

The results of the investigation of a sediment core from Khatanga-12 Lake provided new data on the development of paleoecological conditions of the Russian Arctic using the first Russian statistical temperature and water depth chironomid-based models. The qualitative and quantitative reconstructions of climatic conditions in the Holocene for the southeastern part of the Taimyr Peninsula were performed. The periods in the development of the ecosystem of a typical for the studied region thermokarst lake and their relation to climate changes were identified. The ecosystem of Khatanga-12 Lake was influenced at different stages of its development by various climatic and cryolithogenic factors.

The period of 7100–6250 cal. years BP is the early stage of the lake development. The lake ecosystem is greatly influenced by thermokarst processes associated with the high moisture availability and relatively warm climatic conditions. During this period, the fauna mainly reacts to the instability of limnological conditions.

6250–4500 cal. years BP: the period of cooling; the species composition is characterized by the presence of cold-water stenothermic taxa. The autochthonous processes slow down and bottom sediments are formed by erosion processes on the shores. The lake depth increases.

4500–2500 cal. years BP: the period is characterized by an increase in the mean July air temperature. The water level in the lake becomes stable and eutrophication processes develop.

From 2500 cal. years BP, the proportion of total organic carbon (TOC) in bottom sediments increases and the share of psephytic material decreases due to the slowing of thermokarst processes. The trophicity of the lake increases. The reconstructed conditions are close to modern.

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