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MULTICENTENNIAL CLIMATIC CHANGES IN THE TERE-KHOL BASIN, SOUTHERN SIBERIA, DURING THE LATE HOLOCENE

ABSTRACT. Pollen analysis was carried out on an 80-cm sedimentary section on the shore of Lake Tere-Khol (southeastern Tuva). The section consists of peat overlapping lake loams and covers the last 2800 years. The alternation of dry-wet and cold-warm epochs has been established, and changes in heat and moisture occurred non-simultaneously. The first half of the studied interval, from 2.8 to 1.35 kyr BP was relatively arid and warmer on average. Against this background, temperature fluctuations occurred: relatively cold intervals 2.8–2.6 and 2.05–1.7 kyr BP and relatively warm 2.6-2.05 and 1.7-1.35 kyr BP. The next time interval 1.35-0.7 kyr BP was relatively humid. Against this background, the temperatures varied from cold 1.35-1.1 kyr BP to relatively warm 1.1–0.7 kyr BP. The last 700 years have been relatively cold with a short warming from 400 to 250 years ago. This period included a relatively dry interval 700–400 years ago and more humid climate in the last 400 years. The established climate variability largely corresponds to other climate reconstructions in the Altai-Sayan region. The general cooling trend corresponds to an astronomically determined trend towards a decrease in solar radiation in temperate latitudes of the Northern Hemisphere, and the centennial temperature fluctuations detected against this background correspond well to changes in solar activity reconstructed from 14C production and the concentration of cosmogenic isotopes in Greenland ice. Against the general tendency towards aridization, alternating wet and dry phases correspond well to changes in the activity of the Asian monsoon, established by the oxygen-isotope composition of speleothems in South China.

KEY WORDS: Late Holocene, short-term climate changes, Little Ice Age, Medieval Warm Period, pollen analysis, south-eastern Tuva

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INTRODUCTION

Many paleoclimatic studies over the last two decades have addressed the natural climate variability during the present Holocene interglacial (Mann and Jones 2003; Mayewsky et al. 2004; Wanner et al. 2008; Marcott et al. 2013; and other). They reconstructed the mean surface air temperature, using a variety of land and marine-based proxy data from all around the world. Overall, the pattern of temperatures shows a rapid rise at the beginning of the Holocene, warm conditions until the middle of the Holocene, and a cooling trend over the last 5000 years. Figure 1a shows an example of temperature anomalies record for the Northern Hemisphere reconstructed by Marcott et al. 2013 for the past 11,300 years. According to this reconstruction, the Early-Middle Holocene (11.3 to 5.0 calibrated kyr BP) warm interval was followed by ~0.7°C cooling through the second half of the Holocene (after 5.0 kyr BP), culminating in the coolest temperatures of the Holocene during the Little Ice Age, about 200 years ago.

Comparison of reconstructions of multicentennial-scale temperature oscillations over the Late Holocene reveals agreement on major climatic episodes, such as the 'Medieval Warm Period' and 'Little Ice Age', but substantial difference in reconstructed temperature amplitude. Thus, reconstruction of the mean Northern Hemisphere temperatures for the past two thousand years by Moberg et al. (2005) shows much larger multicentennial-scale variability than most previous multi-proxy reconstructions, including that by Mann and Jones (2003) (Fig. 1b, c). According to Moberg et al. (2005), high temperatures, similar to those observed in the 20th century before 1990, occurred around 1000-900 years ago, and minimum temperatures that were about 0.7°C below the average of 1961-90 occurred about 400 years ago. This reconstruction suggests significant adjustments to the idea of the climate stability of the Late Holocene. As this large natural variability is likely to continue in future, reconstructing the Late Holocene climate is essential for better understanding of climate variability, and provides necessary background knowledge for improving predictions of future climate changes.

Estimating the global or macroregional changes of the humidity of climate during the Holocene represent an even more complicated problem than that of temperature, as the regional variation is very large. Based on palynological data, M.P. Grichuk (1960) worked out a general scheme of the humidity changes during an interglacial, including the Holocene. According to this scheme, within the warm middle part of each interglacial, the earlier *thermoxerotic* (drier), and the later *thermohygrotic* (more humid) phases can be distinguished, their boundary corresponding to the maximum warming (the interglacial optimum). On the whole, this pattern corresponds rather well to the reconstructed changes in heat and moisture supply during the Holocene in various large regions of northern Eurasia by Khotinski (1977).

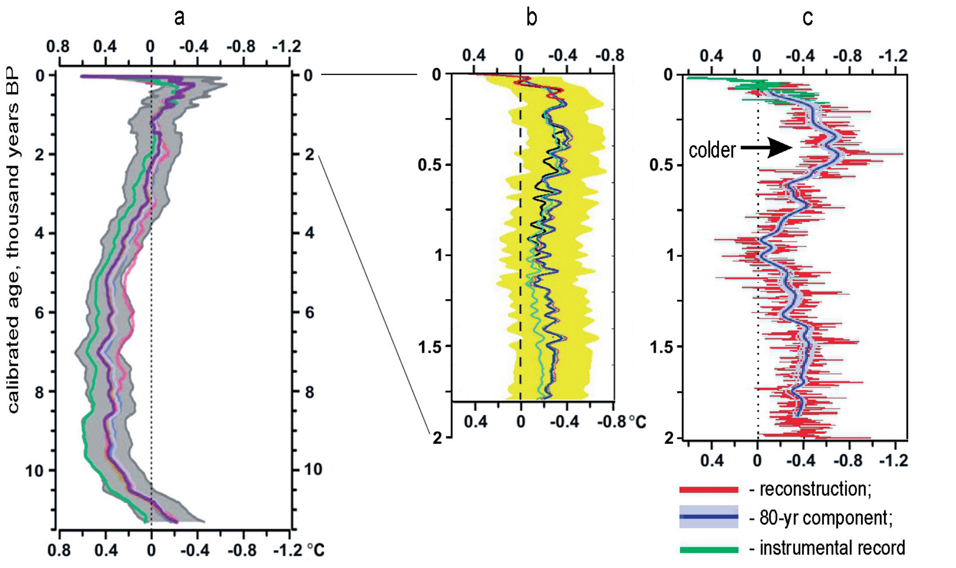

Fig. 1. Northern Hemisphere temperature reconstructions (a) Marcott et al. 2013; (b) Mann and Jones 2003; (c) Moberg et al. (2005). Temperature anomalies in a, b and c are with respect to the 1961–90 average shown by dashed line

The large fluctuations in lake levels, monsoon activity, and regional humidity registered in paleorecords from different regions indicate a considerable short-term variability of the hydrological cycle during the Holocene. Mayewski et al. (2004) concluded that the episodes of rapid climate cooling in high latitudes of both hemispheres within the Holocene were mainly characterized by an intensification of atmospheric circulation and increasing aridity in low latitudes, as the distribution of moisture-bearing winds in the monsoon regions and the carrying capacity for moisture in the atmosphere altered dramatically.

Climate changes in the mountain regions of Southern Siberia and in the adjacent regions during the Holocene

The mountainous areas of southern Siberia (Altai, Sayan and Tuva) are a key region for the analysis of the Holocene climatic changes in Eurasia due to their central location in the continent. They reflect the long-term dynamics of the main pressure fields in the Northern Hemisphere (changes in the depth of the Icelandic Low and the strength of the Siberian anticyclone), associated with the strengthening/ weakening of the Westerlies and the Asian monsoon (Tarasov et al. 2000; Mayewski et al. 2004).

Over the past decades, detailed data on landscape and climate changes during the Holocene have been obtained in the Altai-Sayan region and in adjacent areas of Central Asia.

In the East Sayan Mts., a decrease of temperatures and an increase in the continentality of climate started after 5.5 kyr BP (Bezrukova et al. 2016). The authors explain these changes by weakening of the summer Asian monsoon, strengthening of the Westerlies, and the decrease of summer insolation. Further cooling accompanied by an increase in the aridity occurred in the region about 2.5 kyr BP (Bezrukova et al. 2016). In the southwestern Tuva, the arid climate of the Early Holocene (12-11 kyr BP) has been followed by warming and increasing humidity, which persisted until 5.5-5.0 kyr BP. Later, a process of replacement of forest formations by steppe vegetation caused by cooling and increasing aridity is registered, especially pronounced after 2.0 kyr BP (Blyakharchuk et al. 2007; Blyakharchuk 2008). Analyses of Chironomidae composition in the sediments of the Ak-Khol and Grusha lakes in Tuva indicate four main climatic phases during the Holocene: cold and dry phase 12.1-8.5 kyr BP, warm and dry phase 8.5-5.9 kyr BP, cold and humid phase 5.9-1.8 kyr BP, and cold and dry phase during the last 1.8 thousand years (Ilyashuk and Ilyashuk 2007). Based on the palynological data, Tchebakova et al. (2009) distinguished the following main climatic phases for the Altai-Sayan mountainous region: cold and dry early Holocene, warm and humid climate 8.0-5.3 kyr BP, followed by cooling and drying, so that at app. 3.2 kyr BP the climate was both colder and dryer than the modern one.

In the regions adjacent to the Sayan and Tuva, similar climatic changes were reconstructed for the Holocene, including the most humid conditions in the middle Holocene and increasing aridity in the late Holocene. Thus, based on the multi-proxy studies of the Hoton-Nur basin in northwest Mongolia, Tarasov et al. (2000) and Rudaya et al. (2009) reconstructed an increase in humidity of climate 10.0-10.5 kyr BP, when a transition from steppe to forest steppe occurred in the area, and the beginning of rapid aridization at about 4 kyr BP. In the Baikal region, the transition from more humid conditions to more arid and continental climate took place 6-7 kyr BP (Bezrukova et al. 2014; Reshetova et al. 2013; Sharova et al. 2015). A somewhat different sequence of climate changes was reconstructed for the area west of the Baikal Lake. According to the palynological data on the Khall lake sediments (Bezrukova et al. 2013), 5 to 4 kyr BP the precipitation in the region was higher than today. A subsequent aridization reached its maximum approximately 2.5 kyr BP. Dry conditions persisted there during the entire Late Holocene, with the only increase in humidity 700 to 450 years ago. Dirksen et al.

(2007) reconstructed changes in humidity of climate during the Holocene using pollen data on the sediments of two lakes in the Minusinsk depression and on the Yenisei River floodplain. They distinguished two main phases, a dryer early one 11.7-7.6 kyr BP, and a later more humid phase after 7.6 kyr BP. Within the latter, two relatively dry intervals were identified: 3.6-2.8 kyr BP and 1.5 kyr BP – present (Dirksen et al. 2007).

Therefore, according to the majority of reconstructions, within the mountain regions of Southern Siberia and in the adjacent region of Central Asia three main climatic phases can be distinguished within the Holocene. The Early Holocene was characterized by low temperatures and humidity; the Middle Holocene climate was both the warmest and the most humid. The time of transition to the third phase differs considerably over the larger area, but in the Altai, Sayan, and Tuva Mts. the climate amelioration of the Middle Holocene gave way to a cooling along with increasing continentality and aridity in the last 5.5-5.0 kyr BP. These processes became especially pronounced after 2.0 kyr BP. They brought about the decline of forest and a greater spread of steppe vegetation.
However, the data on short-term climatic oscillations in the late Holocene for this territory are still scarce.

STUDY AREA
Physiography and vegetation

A promising method for studying landscape and climatic changes of the multicentennial rank is a detailed pollen analysis of sediments with a stable accumulation regime, with high contents and good preservation of microfossils, reliably dated by radiocarbon method. As a research object, we chose a section of the lake and mire sediments at the shore of the Tere-Khol Lake in southeastern Tuva (Fig. 2).

Tere-Khol Lake is situated in the intermountain depression of the same name (50°37´N, 97°24´E). The bottom of the Tere-Khol depression lies at the height of about 1300 m above sea level, within the belt of mountain larch and larch-Siberian pine forests. The Tere-Khol depression is located at the transition between the forest and steppe zones, near the southern boundary of the permafrost. Permafrost exists in the bottom of the Tere-Khol basin due to the average annual temperature of -6°C, severity and low snowiness of winters. Part of the basin around the lake and along the rivers flowing from it is paludified and covered by reed, sedge and grass swamps and shrub thickets (mainly of *Salix* spp.). Larch forests of *Larix sibirica* with well-developed shrub and grass layers, as well as meadows, stretch along rivers and streams. Spruce-larch forests cover the southern shore of the lake. The slopes of the mountains surrounding the Tere-Khol depression are occupied with larch forests with the participation of *Pinus sibirica*. In the lower parts of the steep southern slopes and on well-drained patches of the bottom of the depression, steppe communities with rich species composition of forbs are developed (Sobolevskaya 1950). The upper limit of the belt of Siberian pine-larch forests on the Sangilen ridge, lying to the south of the depression, is situated at altitudes of 2200-2300 m above sea level (Koropachinski 1975). Above this belt the mountain tundra with areas of subalpine shrubs and alpine meadows occur.

Panin et al. (2012) studied the history of the development of the Tere-Khol Lake in the Holocene. Based on the multi-proxy data on lake sediments, they distinguished three intervals of high water level and three intervals of low water level, including the one from 2000 to 100 years ago, corresponding to the maximum aridity of climate for the entire Holocene. Overall, the 20th century was marked by a greater water supply to the lake. N.S. Bolikhovskaya performed a pilot palynological study of the upper 120 cm of the Tere-Khol Lake sediments accumulated since approximately 6 kyr BP (Bolikhovskaya and Panin, 2008). The composition of the pollen spectra indicate predominance of mountain taiga similar to the modern vegetation in the Tere-Khol depression. Changes in participation of species characteristic of subalpine and mountain steppe communities reflect short-term changes in temperature and humidity.

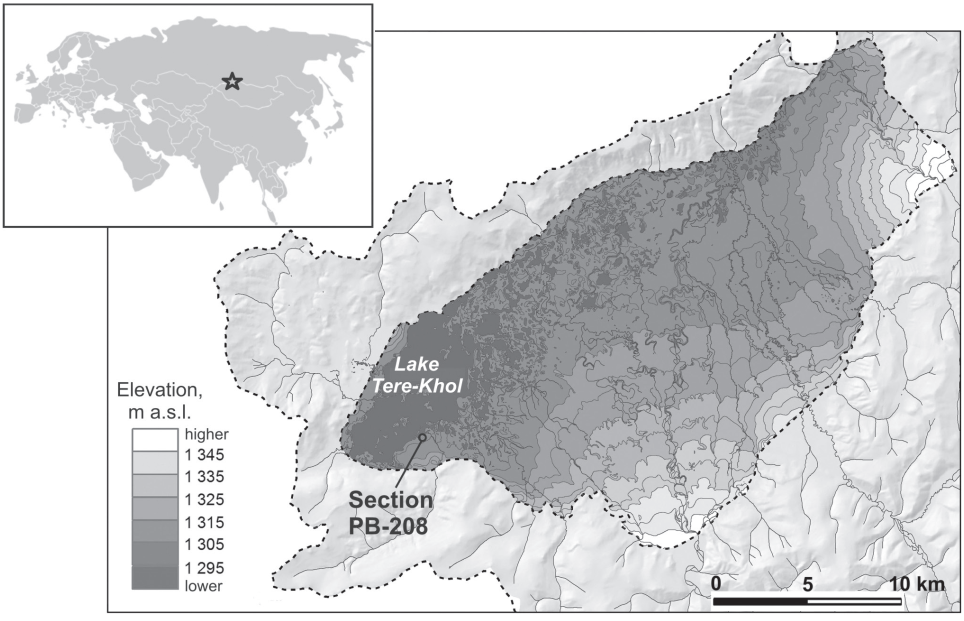

Fig. 2. Location map of Lake Tere-Khol and section PB-208

Unfortunately, the shallowness of the lake (average and maximum water depth are 0.6 m and 2.0 m respectively) provides conditions for its freezing to bottom during the most severe winters. Therefore, the upper part of lacustrine deposits may have been subject to repeated freeze/thaw cycles in the past that could cause sediment mixing. That is why the lacustrine sediments cannot provide a reliable archive for detailed reconstructions of the Late Holocene.

Study site

To study the Late Holocene environmental changes, we selected section PB-208 (50.61032N, 97.40346E) located 50 m from the southern bank of Lake Tere-Khol 1.5 m above its water level (Fig. 2).

In the upper part, section PB-208 includes dark-brown highly decomposed grass and sedge peat with abundant fragmented and entire shells of terrestrial Gastropods without visible mineral admixture, except for a single interlayer containing fragments of schist 6x3x0.3 cm at the depth of 32 cm. The debris were probably brought to the site by lake ice during a spring flood. Total thickness of peat is 49 cm. Underlying deposits are lacustrine sandy silt. Below the depth of 80 cm sediments are permanently frozen.

METHODS

26 samples from section PB-208, 1 cm thick each, at 2 to 3 cm intervals, were subsampled for pollen analysis and processed using the pollen extraction technique of Grichuk (1940): the processing included heavy liquid (cadmium iodine) separation. A minimum of 400 pollen grains and spores per sample was counted. Relative frequencies of pollen of trees and shrubs were calculated based upon the arboreal pollen sum (AP) to make it easier to trace changes in the composition of forest and shrub communities. Pollen percentages of herbaceous plants were based upon the non-arboreal pollen sum (NAP), and those of aquatic plants were based upon the total terrestrial pollen sum, as well as percentages of spores.

Geochronology of the section was established by radiocarbon method (Table 1). Three accelerated mass-spectrometry (AMS) dates on macrofossils and one AMS date on total carbon (TOC) from lacustrine silts were produced in the Institute of Geography RAS (lab index IGANAMS). At the base of peat layer, one scintillation date was provided by the Saint-Petersburg University laboratory (index LU). The dates have been calibrated using OxCal v 4.3.2 (Bronk Ramsey, 2017) and IntCal13 atmospheric curve

(Reimer et al. 2013). Age-depth model was calculated and visualized in OxCal v 4.3.2 (Bronk Ramsey, 2017).

RESULTS

The series of radiocarbon dates from section PB-208 (Table 1) permitted to construct the age-depth model (Fig. 3), which shows that the accumulation of peat below the depth of 10 cm and underlying sandy loam occurred at a rather constant rate of 0.27 mm/yr (26.7 cm per 1000 years). Extrapolation of this rate to the bottom of the section (80 cm) provides the estimation of the total duration of sedimentation at 2.8 thousand years.

Table 1. Radiocarbon dates and calibrated ages for the PB-208 section

Depth, cm	Dated material	^{14}C age	Cal BP* ±1σ	Cal BC/AD, yr	Lab. No.
9.5	plant macrofossils	40±20	75±60	AD 1875±60	IGANAMS-5170
25.5	plant macrofossils	670±20	625±40	AD 1325±40	IGANAMS-5171
38.5	plant macrofossils	1160±20	1085±55	AD 865±55	IGANAMS-5172
48-49	peat	1680±100	1595±120	AD 355±120	Lu-6052
57.5	gyttja (TOC)	1950±20	1900±25	AD 50±25	IGANAMS-5173

**counting from AD 1950*

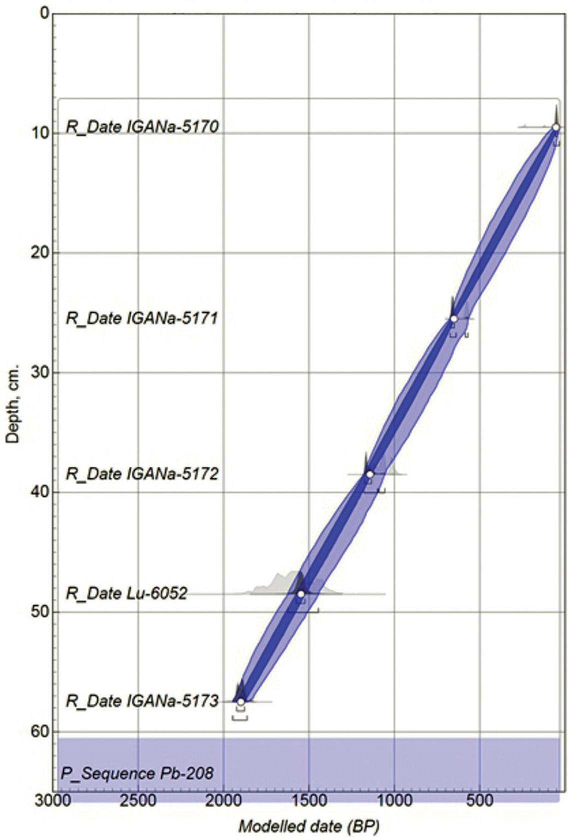

Fig. 3. Age-depth model for the PB-208 section

Based on the changes in the composition of the pollen spectra in section PB-208, we identified six local pollen zones (LPZ) (Fig. 4).

Among arboreal pollen (AP), *Pinus sibirica* and *P. sylvestris* pollen dominate. The latter does not grow in the Tere-Khol depression; the part of its modern range closest to the site is about 100 km to the north (Sokolov et al. 1977). Pollen of *Abies sibirica* occur in minor quantities throughout the entire sequence. Its present geographical range in Tuva is similar to that of Scots pine. Pollen contents of spruce are relatively stable (5-7% of AP) and are adequate to the role of *Picea obovata* in the local vegetation, where it participate larch and mixed taiga forests.

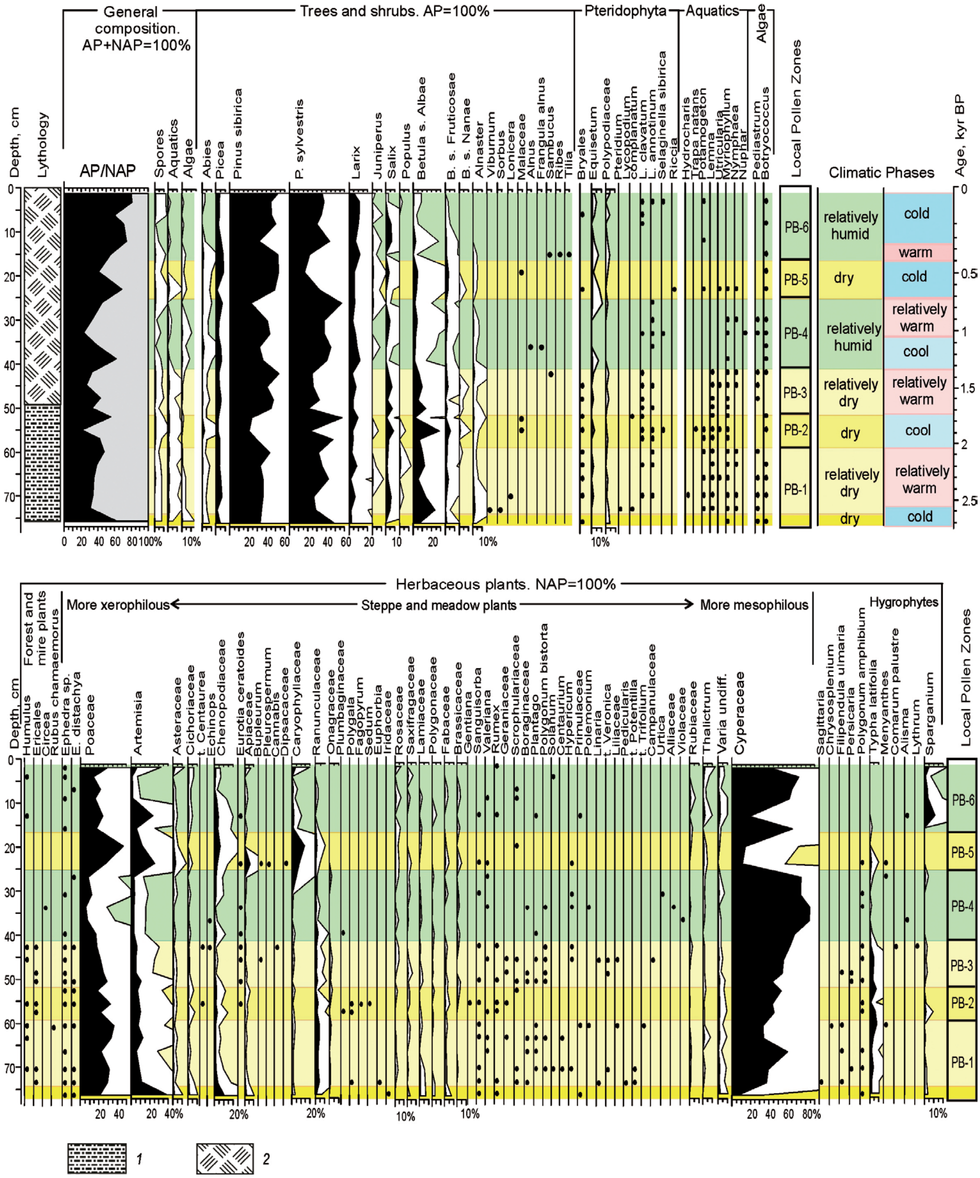

Fig. 4. Section PB-208 percentage pollen diagram. Clear curves represent x5 exaggeration of base curves. Analyses by O. Borisova. 1 – silt and sandy silt deposits, 2 – grass and sedge peat

Low resistance of larch pollen to deterioration in the sediments is probably the main cause of relatively low percentages of *Larix* in pollen spectra. The content of *Larix* pollen in the surface sample of section PB-208 is only 5% of AP, although *L. sibirica* dominates in the forests on the slopes of the Tere-Khol depression. In general, the composition of pollen and spores throughout the section reflects a predominance of mountain taiga similar to modern vegetation in this area. Changes in the abundance of pollen of the main forest-forming species (*Larix, Pinus sibirica, Picea, Betula* sect. *Albae,* etc.), in combination with pollen of microthermal shrubs (*Betula* sect. *Fruticosae, Alnaster fruticosus, Juniperus* spp., etc.), or more thermophilous species of trees and shrubs, allow tracing the altitudinal shifts of the vegetation belts caused by relative warming or cooling.

In the layers with the highest abundance of the non-arboreal pollen (NAP) (up to 40-60%), 60-75% belong to Cyperaceae family, which is probably locally produced by species of sedges growing on the waterlogged ground along the water margin. Poaceae pollen is also abundant (20-30% of NAP). The presence of phytoliths of the characteristic shape suggests that a considerable part of the grass pollen in the lower, sandy clay part of the section might belong to reed (*Phragmites communis*), still widely spread on the shores of the Tere-Khol Lake. Among NAP, there are quite high contents of Chenopodiaceae and *Artemisia*. Presence of pollen of typical xerophytes (*Ephedra, Eurotia ceratoides, Polygala,* etc.) indicate that there were mountain steppe communities on south-facing slopes. A great variety of NAP species indicates that during drier phases, meadows and meadow-steppes occupied larger part of the depression than at present. During the relatively humid phases, the participation of more mesophilous herbaceous plants in the steppe communities increased.

The presence of pollen of aquatic plants typical of stagnant and weakly flowing shallow lakes (*Lemna, Myriophyllum, Potamogeton, Utricularia, Nymphaea,* etc.), algae (*Pediastrum* and *Botryococcus*), and various hygrophytes (*Typha latifolia, Sparganium, Polygonum amphibium* and other) in LPZ PB-1-3 indicates that the accumulation of sediments took place in the coastal part of the lake, which at that time extended farther inland at the site. Changes in the composition of the pollen of hydro- and hygrophytes reflect the process of shallowing and overgrowing of the marginal part of the lake and the formation of the mire, where about 1.7 kyr BP the accumulation of peat has begun.

The composition of AP in LPZ PB 1-3 suggests that larch forests occupied then not only the slopes of the Tere-Khol depression, but also a considerable part of its bottom. On the sufficiently humid and fertile soil, spruce participated in these forests. Siberian pine grew in the upper part of the mountain forest belt, as at the present time. The role of tree birch in the taiga forest composition was then greater than at present. Along the rivers, on the margins of the mires, and in the forest undergrowth, *Betula* sect. *Fruticosae* and, more seldom, *Alnaster fruticosus*, occurred. Pollen of these microthermal shrubs could be transported to the site from the subalpine belt of the Sangilen mountains. Rare pollen grains of *B.* sect. *Nanae*, yet another shrub which grows in the subalpine and alpine belts, occur in the lower part of section PB-208.

In the upper part of the section (LPZ PB-4-6), the pollen percentage of tree birch, characteristic of the lower part of the forest belt in the region, decreases, while the amount of larch pollen increases. The pollen content of *Pinus sibirica*, which forms the upper treeline in the mountains of the region, also increases. In this part of the section, the pollen of *Juniperus* is constantly present. Both species of juniper, characteristic of the region (*J. sibirica* and *J. pseudosabina*), grow in subalpine Siberian pine and larch woodlands and on stony patches in high mountains. Overall, these changes are indicative of the colder conditions compare to the lower part of the section.

LPZ PB-4 is characterized by the largest content of *Pinus sylvestris* pollen, the increase of Cyperaceae pollen (up to 80% of NAP) and diversity of forbs, as well as by the presence of pollen of mesophilous arboreal species (*Alnus* and *Frangula*). Relatively thermophilous aquatic plants, such as *Nymphaea* and *Nuphar*, also occurred at the site.

At the transition from LPZ PB-4 to PB-5, the proportion of Cyperaceae pollen decreased sharply (to 15% от NAP), and the pollen of *Artemisia* and Poaceae reached their highest abundances for the entire sequence. The proportion of Chenopodiaceae, Asteraceae, Apiaceae, Caryophyllaceae, and Ranunculaceae also increased. Within LPZ PB-5, pollen of typical steppe xerophytes (*Eurotia ceratoides, Bupleurum,* and *Pleurospermum*) occur. Larch pollen curve decline, while pollen of *Betula* sect. *Nanae* and *Alnaster fruticosus* is registered here again. Probably, the water content at the mire decreased, as of the plants growing on the waterlogged peaty ground only pollen of *Sparganium, Alisma plantago-aquatica* and *Equisetum* spores are found in this layer. These changes in pollen spectra indicate dry and cold conditions and increasing role of the mountain steppe communities at the site.

In the lower part of LPZ PB-6, rare pollen grains of relatively thermophile shrubs *Sambucus* and *Ribes*), as well as a single pollen grain of *Tilia*, were registered. The proportion of AP reaches its maximum for the entire sequence – 80% of the total terrestrial pollen. In the upper part of the zone, pollen curves of *Abies, Picea*, and *Betula* sect. *Albae* decline. The role of Siberian pine in the larch communities increased, as suggested by the highest proportion of *Pinus sibirica* pollen for the entire sequence (up to 50% of AP). Cyperaceae pollen contents rise again almost to the level of LPZ PB-4, while percentages of *Artemisia* decrease sharply. Pollen of meadow and steppe herbaceous plants of Caryophyllaceae, Asteraceae, Apiaceae, Cichoriaceae, Rosaceae, and other families occur in this layer, but the diversity of forbs here is lower than in LPZ PB-1-3. Proportion of *Artemisia* pollen in LPZ PB-6 is up to 5% of NAP; rare pollen grains of Chenopodiaceae and *Ephedra* are also registered there. Of plants growing on the moist ground, pollen of *Sparganium* and *Alisma plantago-aquatica*, as well as spores of *Equisetum* and club moss species, *Lycopodium clavatum* and *L. annotinum,* are found.

DISCUSSION AND CONCLUSIONS

The boundary position of the site in combination with altitudinal belts and exposure differences in vegetation associated with the mountain relief of the surrounding area lead to a distinct reflection of low-amplitude and short-term climatic variations in the composition of pollen spectra.

Changes in vegetation in the Tere-Khol depression and surrounding mountains over the last 2.8 thousand years, reconstructed from the palynological data on section PB-208, reflect the alternation of wetter and drier phases and relative warmings/coolings lasting several hundred years each, which occurred against the general background of cold and dry climate of the Late Holocene. The formation of deposits in the lower part of the section (up to about 1350 yr BP) occurred in more arid conditions than modern ones. The drier phases several hundred years long were at the same time colder, which means an increase in the continentality of climate during these intervals. The most dry and cold conditions are reconstructed for the earliest part of the sequence (LPZ PB-1, 2.8-2.6 kyr BP).

At the time of peat accumulation in the upper part of the section (LPZ PB-4-6) (1350 yr BP – present), the reconstructed conditions were generally colder than during the previous part of the Late Holocene. During this period, the correspondence of the phases of cooling and drying mentioned above altered: the cooler intervals partly corresponded to relatively moist conditions. The duration of warm phases decreased with increasing differences between warm and cold intervals. The most pronounced dry and cold phase was from 700 to 400 yr BP (LPZ PB-5). This interval separated two relatively warm and humid phases: from 1100 to 700 yr BP and from 400 to 250 yr BP. The lessening of the climate continentality during the warm phases is emphasized by the largest content of *Pinus sylvestris* pollen, by the presence of pollen of mesophilous shrubs and forbs. In the last 250 years, there has been a new cooling, although it was not accompanied by noticeable aridization. The composition of the pollen spectra in LPZ PB-6 shows that the modern climate differs from the cryoxerotic phase 700-400 years ago by less seasonality and slightly higher humidity of climate.

Thus, changes in the vegetation cover in the Tere-Khol depression and in surrounding mountains over the last 2.8 thousand years, reconstructed from the palynological data from section PB-208, reflect the alternation of wetter and drier phases, as well as relatively warm and cold phases, that were several hundred years long, in the context of the cold dry climate of the Late Holocene (see Fig. 4).

Comparison of the short-term oscillations reconstructed for the Tere-Khol depression (SE Tuva mountains) with other reconstructions obtained for the Late Holocene in the Altai-Sayan-Tuva region shows certain common features. Thus, palynological data on the Uzun-Kol Lake situated in the central Altai (Blyakharchuk et al. 2004) indicate an arid phase 1.7 to 1.3 kyr BP and the cooling accompanied by drying after 700 years ago. The climate reconstructions based on the Lake Teletskoye pollen record (NE Altai Mts) (Rudaya et al. 2016) show that a short period of cooling occurred between 1.4 and 1.3 kyr BP. Lower July temperatures are also reconstructed for 0.55-0.2 kyr BP; however, a general cooling trend that led to this minimum began about 0.85-0.8 kyr BP. Blyakharchuk and Chernova (2013), based on the palynological data on the Lugovoe Mire in the West Sayan Mts, reconstructed two dry intervals, 2.2-1.5 kyr BP and 0.7-0.2 kyr BP. These dry phases are similar to the ones reconstructed in this study for SE Tuva. Agatova et al. (2012) identified two main stages of the glaciers' advance in the SE Altai Mts: 2.3-1.7 kyr BP and 0.7-0.15 kyr BP. They pointed out that the thermal minimum in the middle of 19th century was the greatest in the last millennium. The beginning of *pingo* formation in the Chuya Depression in central Altai is dated to 2.25 kyr BP (Blyakharchuk et al. 2004), thus indicating the Late Holocene stage of permafrost aggradation.

The warmings/coolings and oscillations of humidity reconstructed from the palynological data on section PB-208 are depicted in Figure 5 on the time-scale to facilitate their comparison with the temperature reconstruction for the Northern Hemisphere by Moberg et al. (2005) and with the proxy-data, which reflect both the short-term climate changes and their probable drivers.

According to the estimations of Northern Hemisphere mean temperature variations by Moberg et al. (2005), the highest temperature for the past two thousand years was reached between AD 1000 and 1100, during the so-called "Medieval Warm Period", and the greatest cooling occurred around AD 1600, during the "Little Ice Age" (Fig. 5a). Based on the similarity of the paleotemperature curves and changes in the intensity of solar radiation reconstructed from the contents of 14C and 10Be isotopes (Wanner et al. 2008), it can be assumed that the temperature fluctuations were mainly due to the changes in solar activity (Fig. 5c). Bond et al. (2001) demonstrated that ice rafted debris (IRD) were deposited in the North Atlantic by southerly drifting icebergs. Higher IRD numbers indicate cooler time intervals, often called "Bond events" (Fig. 5d).

Warm/cold fluctuations, reconstructed from palynological data on section PB-208, are similar to those described above in their direction, duration and time of manifestation, but less pronounced.

Comparison of paleoclimate records with climate forcing time series suggests that changes in insolation related both to Earth's orbital variations and to solar variability played a central role in the global scale changes in climate of the Holocene (Mayewski et al. 2004). Solar variability (fluctuations in solar output) superimposed on long-term changes in insolation (Bond et al. 2001; Mayewski et al. 2004) seems to be the most likely forcing mechanism for the rapid climate changes.

Data on changes in the isotope composition of oxygen in the calcite of stalagmite from the Dongge cave in southern China (Wang et al. 2005) with a high (up to one-year) time resolution show that, apart from the decrease of the monsoon strength from 7.0 to 0.5 kyr BP, separate episodes of a particularly severe fall in the Asian monsoon activity occurred in phase with the ice-rafting events in the North Atlantic (Wang et al. 2005; Wanner et al. 2008). The relatively humid/dry phases inferred from the PB-208 pollen record, which manifested themselves against the general background of climate aridization in the mountainous regions of southern Siberia in the Late Holocene, correspond fairly well to the phases of Asian monsoon strengthening/weakening.

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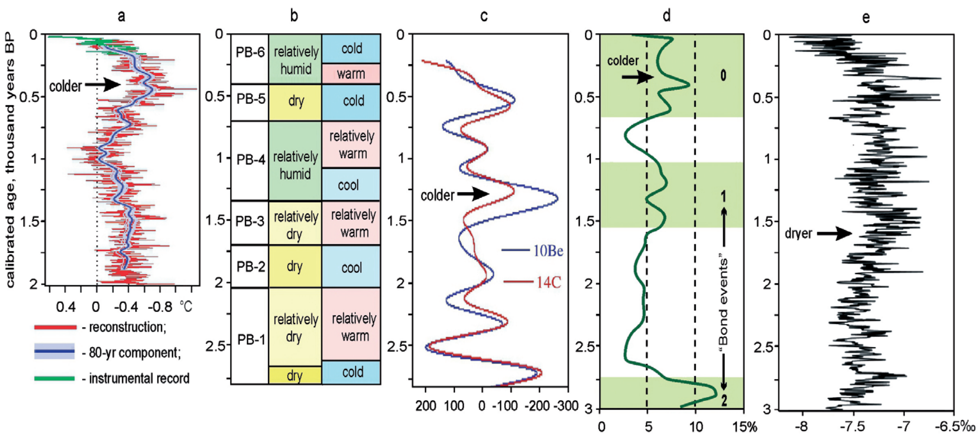

Fig. 5. Short-term climatic oscillations in the late Holocene indicated by different paleodata. a. Multi-proxy reconstruction of Northern Hemisphere mean temperature variations AD 1–1979 with its >80-yr component AD 133–1925, and the instrumental record (Moberg et al. 2005); b. Fluctuations in temperature and humidity inferred from palynological data on section PB-208; c. Reconstructions of the solar activity (in relative units) based on ^{10}Be concentrations measured in the GRIP ice core and ^{14}C production rate (Wanner et al. 2008); d. Changes in the quantity of the ice rafted debris in North Atlantic (Bond et al. 2001); e. Oxygen isotope record from Dongge Cave speleothem in southern China (Wang et al. 2005)

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