Dynamics of vegetation cover and quantitative palaeoclimatic reconstructions in the Western Sayan Mountains from the Late Glacial period to the present time according to a palynological study of the Yuzhno-Buybinskoe mire

T A Blyakharchuk
Laboratory of Monitoring of Forest Ecosystems, Institute of Monitoring of Climatic and Ecological Systems, Siberian Branch of the Russian Academy of Sciences, 10/3 Academichesky avenue, 634055, Tomsk, Russia
E-mail: blyakharchuk@mail.ru

Abstract. The aim of this research is an investigation of long-term palaeoclimatic changes. In this paper we present results of a palaeopalynological study of a high mountain peat-lake sediment core from the Yuzhno-Buibynskoe Mire in the Western Sayan Mountains covering the last 13000 cal yrs BP. In addition to qualitative palaeopalynological reconstructions we have performed quantitative reconstructions of T January, T July, and Annual precipitations using our own transfer functions constructed on 118 surface pollen spectra by a method developed by ter Braak and coauthors [16]. The results of the quantitative palaeoclimatic reconstructions have demonstrated three types of climate changes in the study area from the Late Glacial period to the present time: cryo-arid climate in the Late Glacial period from 13000 cal yr BP to 11000 cal yr BP (I), humid moderate cool climate in the Middle Holocene (II) and humid cool climate in the Late Holocene after 5000 cal yr BP (III). The cold climate during the Late Glacial period was caused mostly by low winter temperatures combined with low annual precipitation, while the summer temperatures were equal or even higher than modern ones. This is characteristic for the anticyclone influenced areas. The winter temperatures and annual amount of precipitation considerably increased in all areas of the Altai-Sayan region during the early and middle Holocene times, when Atlantic cyclones reached this area. In the Late Holocene period we observe a gradual return to the climatic parameters of the pre-Holocene time.

1. Introduction
The integration of fossil-based vegetation reconstructions with modeling and projection of future Earth’s climate and vegetation in light of anthropogenic global warming are key topics in the earth sciences [1]. The main source of information on the millennial dynamics of vegetation cover and climate allowing for spatial and temporal reconstructions are the data of paleopalynological studies [2] which, however, very unevenly cover the Earth’s territory. It is well-known that the only possible way to reconstruct the underlying mechanisms of climate change is using spatially extensive networks of paleodata [3]. In the paleoclimatic studies of northern Eurasia, the Siberian region is the least studied. Only for certain regions of Siberia, such as the flat territory of Western Siberia [4] and Baikal region [5], there is currently a fairly representative paleopalynological data base to identify the spatial and temporal dynamics of vegetation and climate in the Late Glacial and Holocene periods. New paleopalynological data are needed for the territories of Siberia that have not been previously studied in this regard. Of particular interest is the central continental region, where different types of climates of Eurasia are in contact (humid with arid, moderate with continental ones). Significant changes in the vegetation cover in such a region reflect global climate change throughout the Eurasian continent. One of these regions is the mountainous area between Lake Baikal and the Altai-Sayan region represented by mountain ranges of the Western Sayan. In this study, we present the first paleopalynological data for the Western Sayan Mts. covering, without interruption, the Late Glacial and Holocene from 13,000 cal. yrs BP up to the present.

2. Study site
The Yuzhno-Buybinskoe Mire (52 ° 50'22"N, 93 ° 31'23"S, 1377 m a.s.l.) is located in the Ergaki nature reserve in the Western Sayan Mountains in southern Siberia (Russia). The mountain relief and boundary location between climatic zones determine the modern appearance of the vegetation cover of the Western Sayan and its changes in the past. The atmospheric precipitation of the region is of Atlantic origin and falls most abundantly on the western and northern macroslopes of the mountain ranges. Geobotanically, the Ergaki reserve is located in the axial West Sayan region of the mountain taiga and subalpine Siberian
cedar (*Pinus sibirica*) taiga forests [6]. Pure Siberian cedar forests or those mixed with fir (*Abies sibirica*) dominate the area. In the valleys there grows spruce. The soils are mountain-taiga humus podzolized ones, and at high altitudes, mountain podzolic ones. The cedar forests are dominated by green moss and bilberry ground covers, and herb-green moss ground cover on the southern slopes. On the steep slopes and scree, cedar forests with *Bergenia crassifolia* are widespread, there are tall herb and wild rosemary-moss forests. Spruce forests (*Picea obovata*) and small areas of mixed taiga from Siberian cedar, spruce and fir grow along the river valleys. Light coniferous forests with Scots pine (*Pinus sylvestris*) and larch (*Larix sibirica*) forests occupy steep slopes along the river valleys. They alternate with stony scree, petrophyte herbal and shrub communities. The modern vegetation cover of the swamp is represented by a treeless sedge-sphagnum-hyphnum plant association with the dominance of *Sphagnum riparium*, *Calliergon stramineum*, *Carex limosa*, and *Oxycoccus palastris*.

### 3. Materials and methods

For spore-pollen analysis, a 600 cm long peat-lake sediment core was collected in the middle of the mire by a hiller corer with a diameter of 5 cm. In the laboratory, sub-samples with a volume of 1 cm$^3$ were taken from the initial 10 cm samples. The sample preparation of the selected sub-samples for spore-pollen analysis was performed by a standard method [7, 9] with a slight modification depending on the nature of the sample. Reference books [9, 8] were used to determine palynomorphs as well as a reference collection taken from the initial 10 cm samples. The sample preparation of the selected sub-samples for spore-pollen analysis of Novosibirsk. All radiocarbon dates were calibrated with the IntCal13 calibration program [11] using the ‘Bacon’ program [12] (Fig. 2), which was implemented in R v.3.2.4 [13].

For quantitative palaeoclimatic reconstructions based on pollen data, we used our own transfer functions (Table 1) compiled by the weighted average method for 120 modern spore-pollen spectra [14] and the corresponding climatic parameters. The optima of pollen taxa with respect to climatic indicators are defined as the weighted average of this indicator in modern pollen samples, and the tolerance as the error of the weighted average [15]. The values of climatic parameters (T January, T January, average annual precipitation) by the optima of pollen taxa in fossil samples were calculated by using a transfer function model proposed by Ter Braak and co-authors [16], which is based on the calculation of the weighted average optimum values of the encountered pollen taxa taking into account their tolerance values. The reconstruction was carried out using the transition functions obtained by calibrating the paleopalynological data on the optima of the transfer functions of annual precipitation, January temperature (T January) and July temperature (T July). Specifically, only the following pollen taxa were used for paleoreconstructions in this work: *Pinus sylvestris, Pinus sibirica, Abies, Picea, Larix, Betula pendula, Betula alba, Betula nana, and Artemisia* as the most informative types of pollen, indicating the latitudinal vegetation zones in Western Siberia and altitudinal vegetation belts in mountains of southern Siberia. For calculations, the program PAST 1.87b and Statistica 6.0 were used.

### Table 1. Transfer functions calculated by the weighted average method for 118 modern pollen spectra of Altai-Sayan region.

| Pollen Type | Pinus sylvestris | Pinus sibirica | Abies sibirica | Picea obovata | Larix sibirica | Betula pendula | Betula alba | Betula nana | Artemisia |
|-------------|------------------|----------------|---------------|--------------|---------------|---------------|-------------|-------------|-----------|
| January temperature transfer function (T January) | | | | | | | | | |
| Optimum     | -22.3696         | -23.9217       | -19.6304      | -23.8789     | -24.4796      | -20.1474      | -21.2699    | -22.4826    | -27.8822  |
| Tolerance   | 5.08748          | 5.44401        | 3.2689        | 5.55169      | 5.77281       | 3.30622       | 4.34073     | 4.85909     | 6.40755   |
| Maximum     | 66.4336          | 66.1538        | 32.5397       | 32.6087      | 11.7647       | 65.415        | 17.7725     | 48.6772     | 85.6079   |
| July temperature transfer function (T July) | | | | | | | | | |
| Optimum     | 16.0256          | 15.2797        | 17.0553       | 15.8173      | 15.2419       | 16.6769       | 16.4126     | 15.5336     | 16.622    |
| Tolerance   | 1.78663          | 1.68745        | 1.62067       | 1.73939      | 1.52726       | 1.45922       | 1.76083     | 1.67788     | 1.65888   |
| Maximum     | 66.4336          | 66.1538        | 32.5397       | 32.6087      | 11.7647       | 65.415        | 17.7725     | 48.6772     | 85.6079   |

*For Annual precipitation transfer function (Annual precipitation)*
4. Results

The spore-pollen diagram of the Yuzhno-Buybinskoe Mire can be clearly subdivided into 5 local spore-pollen zones (LSPZ) which are confirmed also by cluster analysis (Figure 1). The cluster analysis performed using the CONISS program built into the Tilia program for pollen data processing divided the spore-pollen diagram into 5 main clusters, coincided with visually identified 5 local spore-pollen zones (LPZs). We reconstructed the quantitative parameters of the paleoclimate change according to pollen data of the Yuzhno-Buybinskoe Mire (Figure 2) by using the developed transfer functions. On the basis of the defined local spore-pollen zones, we reconstructed the phases of development of the vegetation cover in the Western Sayan Mountains from the Late Glacial time to the present with climatic parameters.

**Figure 1.** Percent spore-pollen diagram of Yuzhno-Buybinskoe Mire. Conventional marks: 1. – gyttja; 2 – water layer; 3 – peat.

1. **Late Glacial phase of spruce-tundra-steppe vegetation** in the Western Sayan Mountains. In the study, the pollen diagram covers the time from 13000 to 11000 cal yrs BP and includes the Younger Dryas interval (12.9-11.6 ka BP). Open steppe landscapes with groves of spruce-larch forest and alpine tundra at higher elevations were common in the vegetation cover of the Western Sayan Mountains at this time. The climate was relatively dry and, possibly, sharp continental. The termination of the YD event was marked by intensive spreading of dwarf birch and *Alnus* shrublands at the account of open steppe vegetation and by replacing of spruce (*Picea obovata*) in the forest stands first by *Pinus sibirica*, and then by *Abies sibirica*. We suppose that this was caused by a progressive increase of precipitation. The evidence of moistening of climate is intensive spread of mosses in mountain landscapes and a sharp decrease of steppe vegetation. In the pollen diagram it is confirmed by a sharp maximum of Bryales spores.

2. **The transitional phase of spreading of Abies sibirica and Pinus sibirica forests** took place 1100-9300 cal yrs BP. Judging by the pollen spectra, the corresponding phase of vegetation development reflects the transition from a more continental arid climate to a warm and humid climate.

3. **The phase of dominance of Abies sibirica forests with admixture of Pinus sibirica** in the Western Sayan Mountains lasted from 9300 to 5400 cal yrs BP. During this long period of 3900 years, the climate remained sufficiently humid to allow *Abies sibirica* forest formation with a tall herb-fern ground cover to dominate in the Western Sayan Mountains. At the same time, Scots pine *Pinus sylvestris* and birch forests with *Betula pendula* spread on the northern low mountain piedmonts.

4. **The phase of Pinus sibirica forests dominance and decline of Abies sibirica** in the forests started about 5400 cal yr BP and lasted until 1100 cal yr BP. During all this time, cedar grass forests with
fir and birch dominated in the mountains of Western Sayan. Scots pine forests grew in the foothills and on the drier slopes of the southern macroslope of the Western Sayan facing the Uyuk and Tuva hollows.

5. The phase of Pinus sibirica forests alternated with Pinus sylvestris. The fifth spore-pollen zone is a zone of pine forest and Siberian cedar (Pinus sylvestris - Pinus sibirica); it stands out at a depth of 130 cm representing the last millennium. The pollen records of these phase were obtained entirely from peat deposits at a depth of 130-0 cm and reflect sharp fluctuations in the vegetation cover of the Western Sayan. The beginning of LIA in the diagram of the Yuzhno Buybinskoye Mire is marked by a maximum spread of Siberian cedar pollen at a depth of 70 cm, which indicates an increase in the climate humidity in this mountainous region.

5. Discussion
Our studies of modern pollen spectra from the Altai-Sayan mountain region [15] showed that in the pollen spectra of the high-altitude tundra-steppe landscapes of south-eastern Altai and south-western Tuva the abundance of Siberian cedar pollen (Pinus sibirica) is overestimated due to long distant Siberian cedar pollen transported from the north. This shifted the climatic optimum of the Siberian cedar pollen in the resulting transfer functions towards a more arid and warmer climate of the southern steppes. Also, due to a long distant drift of the tree pollen into the steppe, the climatic optima of the pollen for other Siberian tree species can be distorted (Table 1). We suppose that this may also distort transfer function paleoreconstructions based on fossil pollen spectra. That is why we consider that relative changes of reconstructed climatic parameters are more reliable and informative than absolute reconstructed temperatures and precipitation.

Figure 2. Results of quantitative palaeoclimatic reconstructions based on spore-pollen data from the Yuzhno-Buybinskoe Mire with the use of transfer functions constructed by the method of weighted average optima from 180 modern pollen spectra from Altai-Sayan region.

In general, the quantitative paleoreconstructions have shown that three types of climate changed in the study area from the Late Glacial to the present time (Fig. 2, I-III): the cryo-arid climate in the Late Glacial from 13500 cal yr BP to 11000 cal yr BP (I), the humid moderate cool climate in the Middle Holocene (II), and the humid cool climate in the Late Holocene after 5000 cal yr BP (III).

6. Conclusions
1. Three types of postglacial climate were clearly manifested in the Altai-Sayan region.
2. Quantitative reconstructions of palaeoclimate in the Western Sayan mountains have demonstrated that the cold climate during the Late Glacial period was caused mostly by low winter temperatures combined with low annual precipitation, while the summer temperatures were equal or even higher than modern ones. This is characteristic for the anticyclone influenced areas. The winter temperatures and
annual precipitation amount considerably increased in all areas of the Altai-Sayan region during the early and middle Holocene times. In the Late Holocene period, we observe a gradual return to the climatic parameters of the pre-Holocene time.

3. Significant restructuring of the global climate system took place during the transition from the Late Glacial time to the Holocene when the climate of the Western Sayan Mts. shifted from an anticyclonic regime to a cyclonic climate regime. Atlantic cyclones began to moisten most of the territory of the Altai-Sayan mountain region.

4. During the Late Holocene period after 6000 cal yr BP the influence of Atlantic cyclones in the Altai-Sayan mountain region decreased and caused more unstable and continental climate in the Western Sayan Mts.

Acknowledgements
This research was supported by the Russian Foundation for Basic Research (project no. 20-55-53015/GFEN_a) and IMCES SB RAS (budget theme no. AAAAA-A16-11604135666-6).

References
[1] IPCC 2013: Summary for Policymakers Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change eds T F Stocker, D Qin, G-K Plattner, M Tignor, S K Allen, J Boschung, A Nauels, Y Xia, V Bex and P M Midgley (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press)
[2] Binney H et al 2017 Vegetation of Eurasia from the last glacial maximum to present: Key biogeographic patterns. Quaternary Science Reviews 157 80-97 http://dx.doi.org/10.1016/j.quascirev.2016.11.022
[3] Harrison A P 1996 Late Quaternary lake-level records from Northern Eurasia Quaternary Research 45 138-59
[4] Blyakharchuk 2012 New palaeopalynological data on the dynamics of vegetation cover and climate of western Siberia and adjacent territories in the Holocene (Novosibirsk: Academic publishing house “GEO”) p 139 (in Russian)
[5] Tarasov P E, Bezrukova E V, Krivinogov 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 Climate of the Past 5 127-51
[6] Smagin V N, L’inskaya S A, Novoseltseva D I, Cherednikova Yu S 1980 Tipy lesov gor yuzhnoy Sibiri (Types of forests of the mountains of southern Siberia) (Novosibirsk: Nauka Press) p 336
[7] Grichuk V P, Zaklinskaya E D 1948 Analysis of fossil pollen and spores and its application in paleogeography (Moscow: Geografizdat Press) p 223 (in Russian)
[8] Moore P D, Webb J A, Collinson M E, 1997 Pollen Analysis (Oxford: Blackwell Science Ltd)
[9] Bobrov A E, Kupryanova L A, Litvintseva M D, Tarasevich V F 1983 Spores of Pteridophytae and Pollen of Gymnospermae and Monocotyledone Flora of European Part of USSR (Leningrad: Nauka Press) p 207 (in Russian)
[10] Grimm E T 2004 TGView Version 2.0.2. Springfield Ill: Illinois State Museum research and Collections Center
[11] Reimer P J et al 2013 IntCal13 and Marine 13 radiocarbon age calibration age curves 0-50,000 yr cal BP Radiocarbon 4 1869-87
[12] Blauuw M and Christen J A 2011 Flexible paleoclimate age-depth models using an autoregressive gamma process Bayesian Analysis 6 457-74
[13] R Core Team 2012 R: A language and environment for statistical computing R Foundation for Statistical Computing Vienna Austria URL: https://www.r-project.org/
[14] Blyakharchuk T A, Eirikh A, Mitrofanova E, Li Hong-Chun Kang, Su-Chen 2017 High resolution palaeoecological records for climatic and environmental changes during the last 1350 years from Manzherok Lake, western foothills of the Altai Mountains, Russia Quaternary International 447 59-74
[15] Lakin G F 1990 Biometrya (Biometrics) (Moscow: Higher School) p 352 (In Russian)
[16] ter Braak C J F, van Dam H 1989 Inferring pH from diatoms: a comparison of old and new calibration methods Hydrobiologia 178 209–23