Consistency of the Iksinskoe bog dynamics with extreme Holocene climate events

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Abstract. This research is devoted to the response of the southern taiga oligotrophic Iksinskoe bog to extreme Holocene climatic events. Based on data of preliminary geological exploration and 14C-dated cores – analogues of this bog, a spatio-temporal model of paludification and vegetation succession from 11 paleosurface chronoslices is created. It has been shown that the global dry cooling events of about 8200, 5900, 4900, and 2800 cal yr BP influenced the bog dynamics. Their direct impact is through the formation of a long-term thawing seasonal frost and permafrost water pressure as well as palsa. Their indirect impact is through a permafrost degradation and a subsequent warming. The cooling of 2800 cal yr BP had the maximum effect due to a drying and cryogenic peat accumulation stopping over a large area of the bog. During the subsequent warming of 2450 and 1900 cal yr BP there was a significant increase in the water content of the bog surface, and a phased oligotrophization of paleophytocenoses took place. The direct and indirect impacts of extremely dry Holocene cooling caused active paludification, catastrophic changes in the paleophytocenoses, high water content of the surface, and reduced the depth of peat deposits of the Iksinskoe bog.

1. Introduction

Assessment of the consistency of changes in the functional state of mires and climate is necessary to develop their forecasts for the coming centuries. This is especially important for the West-Siberian region. Bogs of different natural and climatic zones and even separate parts of the same bog massif have different sensitivity and even the opposite response to specific climatic events. Therefore, to date opinions on the response of this region's bogs to the Holocene climate change are ambiguous and sometimes contradictory.

We have found that different response of the bogs with the presence or absence of permafrost in the cooling periods of the Holocene are connected. In the Holocene, permafrost in mineral soils and peat deposits of forest zone was repeatedly formed. Repeated paleo-cryogenic processes have caused peat accumulation stops [1].

However, to date the influence of paleo-cryogenic processes on the dynamics of bogs outside the cryolithic zone has rarely been taken into account. The fact that the influence of these processes is not taken into account leads to incorrect data on reconstructions of the functional state of bogs and paleoclimate. The existing spatial and temporal models of bog
dynamics are based on the opinion of their mainly endogenous development and a continuous course of the bog formation process [2–4].

In numerous peat cores of the forest zone of Western Siberia, we found a widespread climatogenic type of bog formation process, which differs from the autogenic one primarily by meso- and oligotrophic paludification of carbonate soils and repeated cryogenic stoppages of peat accumulation [1, 5–7]. The main paleostratigraphic boundaries in peat deposits are dated. These paleostratigraphic boundaries are indicators of focal changes in the bog functional state under the Holocene climate. However, the degree and scale of influence of these events on the origin and development of climatogenic bogs have not been sufficiently studied.

The aim of this work is to create a spatio-temporal model of paludification and vegetation succession of a climatogenic massif to reveal the influence of extreme Holocene climate events on these processes.

2. Study area
The object of study is the oligotrophic Iksinskoe bog. The Iksinskoe bog is located in southern taiga of Western Siberia (56°54′ – 56°59′ N, 82°21′ – 83°22′ E). It is the northeastern spur of the Great Vasyugan Bog. It occupies a section of the asymmetric watershed of the Shegarka and Iksa rivers. The watershed has a complex and significant meso- and microrelief differentiation of the surface. Sublatitudinal mineral ridges and local elevations, channels of ancient streams are represented here. The mineral bottom of the Iksinskoe bog is composed of loess-like carbonate loams and clays. The Iksinskoe bog is not connected with groundwater and, therefore, its development was completely dependent on climatic conditions.

The Iksinskoe bog is a complex mire system. It consists of numerous convex forested uplands and heavily watered swamps and hollows of runoff with ridges and pools.

In the northern half of this mire system, an eccentric bog massif with a highly pool-free apex plateau and a radial slope structure made of alternating strips of low ryams and heavily watered troughs of runoff with ridges and pools is represented. It resembles a typical bog massif of the "Narym" type [8], which is in the late stage of development. However, the apex plateau is not a genetic center of the bog massif. It is timed to the flattened top of the highest section of the interfluves. The peat deposits are less thick (2.3–4.5 m) than on the adjacent slopes (up to 5.6 m).

The southern part of the bog is elongated from south to north. Here an eccentric bog massif with predominantly sublatitudinal structure of microlandscapes is represented. The main background is formed by Carex–Scheuchzeria–Sphagnum swamps with pools and rare ridges. This background is disturbed by numerous hollows of runoff with pools and chains of low ryam islands.

3. Methods
The internal bog hydrographic network of deep (up to 2.5–3.0 m) pools was formed at early eutrophic and mesotrophic stages of its development. Less deep pools were formed at the oligotrophic stage.

The spatial-temporal model of the Iksinskoe bog is based on data of a preliminary geological exploration of Site № 6 of the Vasyuganskoe peat deposit. The plan of this deposit (M: 1:100000) was linked to a space image. The geographical coordinates of its 14 profiles and 441 peat sampling points have been determined. For the model of the mineral bottom relief, the surface and depth markings of the peat deposit at the sampling points were taken. Layer-by-layer (after 25 cm) values of the plant macrofossil composition and general technical properties of the peat were used. Paleophytocoenoses by the plant macrofossil composition of the peat layers have been reconstructed.
For chrono-slices of the bog paleosurfaces, spatial-temporal models of the age of the paleostratigraphic boundaries of peat cores – analogues were taken. 29 dated peat cores of the Iksinskoe bog and the neighboring Bakcharskoe bog obtained by the authors in [1, 5-7] and taken from [2–4, 9, 10] are taken as analogues. When selecting an analogue, the location of the peat sampling points within the bog massif, on an element of meso- and microrelief, was taken into account. Search for paleostratigraphic boundaries in peat deposits of the sampling points was carried out on the basis of layer-by-layer values of the botanical composition, the degree of decomposition (R), the ash content (A), and the natural humidity content (Hnat.) of the peat.

The layer-by-layer and total cumulative mass indices of organic matter in the peats were used to determine their age. To calculate the cumulative mass of organic matter of peat for each of 10560 samples of sampling points, “Tables for determining the outputs of air-dry peat in tons at 40% relative humidity from 1000 cubic meters of raw peat” from [11] were used. According to these tables, taking into account the type, R and Hnat, the peat density, the layer-by-layer cumulative masses at a relative humidity of 40% were determined and calculated. Then the obtained values were recalculated for organic matter of an absolutely dry peat. The values of the cumulative mass and the rate of peat organic matter accumulation for the layers of different types of peat between the paleostratigraphic boundaries of the peat core-analogues were obtained. These values were used for the most reasonable determination of the age of the layers of the peat deposit at the sampling points.

Processing of the data on the dynamics of the Iksinskoe bog in a geoinformation system ArcGIS 10 was carried out. Interpolation of the paleophytocoenosis data for the creation of spatial-temporal model chrono-slices of the Iksinskoe bog paleosurfaces was performed.

4. Results and discussion
On the basis of a comparative analysis of data on the core-analogues (Figure 1) obtained for chrono-slices (Figure 2), reconstructions of the paleoclimate of the forest zone of Western Siberia [12] and global events of cooling [13], the following was established.

The first sporadic paludification hearths appeared about 8000 cal. yr BP (Figure 2a). This was the beginning of warming after a global cooling about 8200 cal. yr BP (Bond event 5) [11]. The degradation of permafrost was most likely favorable for paludification. Melt water accumulated in closed depressions of the slopes of the watershed plateau and of the channels of ancient streams. The type of paludification depends on the physical (melted/frozen) state of the soil. In place of sparse forests, eutrophic or mesotrophic grass communities were formed from sediments, horsetail, watch and reed. Sometimes small lakes were stuck by herbal-moss communities with *Sphagnum teres*. The peat accumulation was short-lived. After complete degradation of permafrost for a long time, up to 7400 and even 5900 cal. yr BP, it stopped.

About 7400–7200 cal. yr BP, in the wettest period of the Atlantic Holocene optimum, new hearths of eutrophic paludification appeared (Figure 2b). In the deepest depressions of the channels of ancient streams, the watershed plateau and its northern slope, shallow lakes appeared. These lakes started to overgrow with sedges, *Typha*, horsetails, and *Menyanthes trifoliata*, sometimes with an admixture of reed.

By 6400 cal. yr BP, in the warm humid climate, practically on the whole area of the future bog, the number of new hearths of paludification forests in deep closed depressions increased (Figure 2c). In some meridionally oriented channels of ancient streams, merging of isolated hearths occurred. Eutrophic weakly forested and open grass communities with dominant sedges prevailed. Hearths of mesotrophic paludification appeared. Most likely, it is the result of long seasonal thawing of soils during short-term cooling. At some sites peat accumulation has resumed. However, in the depressions of the highest flat part of the watershed, peat accumulation stopped. The total area of paludification was about 14% of the modern area of the peat deposit in boundary of the industrial depth.
By 5900 cal. yr BP, the number of hearths of mesotrophic, mostly afforested, herbal communities had significantly increased (Figure 2d). The main number of hearths appeared in depressions of the most elevated mesorelief elements. This was most likely facilitated by the widespread long-term thawing of seasonal frost here under the conditions of the beginning of global cooling about 5900 cal. years ago (Bond event 4). By this time, the hearths in many of the channels of ancient streams have merged. The total area of paludification has doubled and made up 26%.

By 4850–4700 cal. yr BP, under conditions of new cooling, the area of paludification has doubled and made up 53%. The hearths of mesotrophic paludification of forests in the depressions of sublatitudinal mineral ridges and their slopes, as well as on the periphery of the future bog massive appeared (Figure 2e). In general, mesotrophic communities prevailed (about 69%).

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**Figure 1.** Composition of macrofossil plant remains in core – analogues from Iksinskoe (a – ryam, b – hollow, c – ridge, d and e – pool) and Bakcharskoe (f – ryam) bogs

Plant remains: 1) *Sphagnum fuscum*, 2) *S. angustifolium*, 3) *S. magellanicum*, 4) *S. papillosum*, 5) *S. balticum*, 6) *S. majus*, 7) *S. jensenii*, 8) *S. fallax*, 9) *Hypnaceae*, 10) *Eriophorum vaginatum*, 11) *Scheuchzeria palustre*, 12) *Carex lasiocarpa*, 13) *C. rostrata*, 14) *C. limosa*, 15) *C. appropinquata*, 16) *C. cespitosa*, 17) *Phragmites sp.*, 18) *Menyanthes trifoliata*, 19) horsetail; 20) erica subshrub; 21) *Betula nana*, 22) wood, 23) water, 24) peat accumulation stopping.
Figure 2. Chrono-slices of Iksinskoe bog paleosurfaces of spatial-temporal model: a) 8000, b) 7400–7200, c) 6400, d) 5900, e) 4850–4700, f) 3950, g) 3200–2800, h) 2750, i) 2450, j) 1900, k) 0 cal. yr BP

1 – mineral bottom and dry land; modern and paleophytoceneses: eutrophic (2 – forested, 3 – herbal), mesotrophic (4 – forested, 5 – sedge–Sphagnum, 6 – Eryophorum vaginatum–Sphagnum, 7 – Scheuchzeria–Sphagnum swamp), oligotrophic (8 – tall ryam, 9 – Eryophorum vaginata –Sphagnum, 10 – ryam, 11 – mosaic Sphagnum swamp, 12 – Scheuchzeria–Sphagnum swamp); 13 – pool; 14 – termination of peat accumulation.
In many sites, eutrophic communities have changed into mesotrophic ones. *Eryophorum vaginatum* has appeared and even dominated in these hearths. This indicates that the surface has dried up locally. The transgressions of sphagnum mosses from long-term thawing seasonal frost and permafrost most likely contributed to the formation of waterproofing. In some areas, palsa were formed and peat accumulation stopped. $^{14}$C-dating of peat cores – analogs (Figure 1) and catastrophic oligotrophization of the vegetation at the sampling points in the subsequent warm period confirm this.

In the depressions at the foot of the watershed plateau about 4300 cal. yr BP, paludification of the hearths through oligotrophic *Eryophorum vaginatum–Sphagnum* communities took place (Figure 1b). In some of them, peat accumulation was short-lived. In the main area of the bogs, peat accumulation continued. In the subsequent period of some climate mitigation, paludification intensified.

By 3950 cal yr BP, by the Subboreal optimum the bog area reached 78% (Figure 2f). The mire water level increased. The area of mesotrophic sedge– and *Eryophorum vaginatum–Sphagnum* swamps, as well as the area of *Sheuchzeria–Sphagnum* swamps almost doubled. The hearths of oligotrophic *Eryophorum vaginatum–Sphagnum* communities, *Sheuchzeria–Sphagnum* swamps, tall and low ryams appeared (about 9%). New hearths of paludification appeared mainly in the eastern part of the mire on the highest elements of mesorelief. This effect of permafrost in mineral soils on their appearance is confirmed. The appearance of cotton-grass-*Sphagnum* communities also confirms the presence of permafrost hearths in the preceding cooling. At the foot and on the slopes of the watershed plateau, new hollows of runoff began to form. The mire water level increase with peat growth in conditions of a relatively humid climate, as well as water inflow from the degraded permafrost hearths, contributed to progressive paludification. During the formation of top water over these permafrost hearths, oligotrophic paludification took place.

By 3200–2800 cal yr BP the mire area increased to 90% (Figure 2g). Under the conditions of aridization of first warm and then cold climate, the area of mesotrophic and oligotrophic *Eryophorum vaginatum–Sphagnum* communities reached 21.5%. The number of hearths of tall ryams has increased. Some herbal communities have become afforested. Significant drying of the mire surface occurred. Global dry cooling about 2800 cal yr BP (Bond event 3) caused deep freezing of peat deposits and palsa formation. In a large area of the mire, peat accumulation stopped (Figure 1h) to 2450 or 1900 cal yr BP (Figures 2i, 2j). These cryogenic processes were most active in the areas with shallow peat deposits of the mire periphery. They also took place on high mesorelief elements, including the depressions of the central plateau. The $^{14}$C-data of peat core–analogue confirm the presence of these processes (Figure 1c–1f). Low values of the organic cumulative mass of the peat layer of the sampling points above the paleostratigraphic boundary corresponding to this age also confirmed this. Peat accumulation continued in the rest of the mire area. Especially active peat growth at the foothills of the central plateau and other highest mesorelief elements took place. Here, a continuous moss cover of *S. fuscum* was formed.

About 2750 cal yr BP, warming began. The mire area by oligotrophic and mesotrophic paludification of margins and mineral islands inside the mire massif reached up to 96% (Figure 2h). Oligotrophic ryams, *Eryophorum vaginatum–* and *Sheuchzeria–Sphagnum* communities occupied 34% of the area. The mire water levels in the central part of the mire increased. New hollows of runoff with oligotrophic mosaic swamps with *Sphagnum magellanicum* and *Sheuchzeria–Sphagnum* swamps began to form. The beginning of degradation of the permafrost hearths caused this. However, still a significant mire area in the permafrost state remained.

By 2450 cal yr BP, more than a half of the mire area (65%) was already occupied by oligotrophic communities (Figure 2i). The process of permafrost degradation continued in the
warm climate. The mire water levels rose. This was a period of maximum spread of the swamp communities. The main part of the bog was occupied by mosaic swamps with separate islands of low ryams. The main area of the mire was occupied by *Scheuchzeria*–*Sphagnum* swamps. The sublatitudinal mineral ridges were flooded, and hollow runoff formed on them. Primary lakes and secondary pools were formed as a result of flooding of mineral islands and depressions of the central plateau (Figure 1e).

By 1900 cal yr BP, oligotrophic communities already occupied almost the entire mire area (Figure 2j). This was promoted by active peat accumulation in the warm climate. On the periphery of the mire, some hearths of permafrost still preserved or new hearths were formed in dry cooling about 2000 cal yr BP. In the chrono-slice of this period, the area of the swamp communities decreased significantly due to an increase in the area of low ryam islands. This was a period of active formation of a surface hydrological system of runoff from the bog. The radial structure of slopes of the central plateau from alternating bands of ryams and heavily waterlogged swamps and ridge-hollow-lake complexes of hollow runoff in place of the ancient channels of water flow and submerged mineral ridges was formed at this time.

In the last two chrono-slices (Figure 2j, 2k), the *Scheuchzeria*–*Sphagnum* and mosaic swamps are well reflected. However, the areas of low ryam hearths are considerably overestimated in comparison with the data of space image interpretation and our field studies. This is due to the fact that during geological exploration in summer on the most watered areas, sampling of peat was possible only on high hummocks and ridges with *S. fuscum*.

5. Conclusions

Thus, it was found that the Iksinskoe bog dynamics has a high degree of consistency with extreme Holocene climate events. The appearance of the first paludification hearths is consistent with the onset of warming after a global cooling of about 8200 cal yr BP (Bond event 5). However, in the Atlantic period, under conditions of directional climate warming, due to the lack of connection with groundwater, the paludification had a focal character in the deepest depressions of the relief. There were no extreme conditions favorable for the development of a mire-forming process. An intensification of paludification and bog growth began during a period of directed climate cooling. During the period of global cooling of 5900 cal yr BP (Bond event 4), the number of hearths of mesotrophic paludification increased under the influence of a long-term thawing seasonal frost. The total area of paludification hearths was equal to 26% of the current area within the boundaries of the industrial depth of the deposit. Extreme events for the dynamics of the Iksinskoe bog were global cooling events of about 4850–4700 cal yr BP and 2800 cal yr BP (Bond event 3). The impact of these cold events was direct and negative, through the formation of permafrost, and indirect and positive, through degradation of permafrost during the periods of subsequent warming. By 3950 cal yr BP, under direct and indirect influences of a cold event of 4850–4700 cal yr BP the area of the bog increased first to 53%, and then to 78% of the modern area. The area of swamp paleophytocenoses has increased sharply. Hearths of oligotrophic paleophytocenoses appeared. The cooling of 2800 cal yr BP had the maximum impact on the functional state of the bog. It caused drying of the surface and a change in the paleophytocenoses, freezing of mineral and peat deposits, the palsa formation and the peat accumulation stopping of a large area of the mire. During the periods of subsequent warming, about 2450 and 1900 cal yr BP, as a result of the active influx of melt water from the degrading permafrost hearths, a gradual significant increase in the water content of the mire surface, an active formation of primary lakes, secondary pools, the modern hydrological runoff system, and phased oligotrophization took place. During this period, paludification covered almost the entire area of the mire, and a global transition to the oligotrophic stage of the development took place. Thus, for the dynamics of the southern taiga watershed bog Iksinskoe, as well as for the mires of the permafrost zone, the warm events of the subatlantic period were extreme. However, extremeness of these warmings
was caused not by their hydrothermal regime, but by an indirect influence of previous cold events.

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References
[1] Preis Yu I 2015 Proc. Int. Conf. Arctic, Subarctic: mosaic, contrast, variability of the Cryosphere (Tyumen Russia Yuli 2–5 2015) ed. V P Melnicov and D S Drozdov (Tyumen: Epoha publ. house) p 305
[2] Neischtadt M I 1977 Scientific Background of swamps development in Western Siberia (Moscow: Nauka) pp 39–48
[3] Lapshina E D Pologova N N and Mouldyarov E Ya 2000 Krylovia 2(1) 38–43
[4] Borren W and Bleuten W 2006 Water Resour. Res. 42 W12413 doi:10.1029/2006WR004885
[5] Preis Yu I and Karpenko L V 2005 Bulletin of the Tomsk Polytechnic University 308(1) 48–53
[6] Preis Yu I 2015 Bulletin of the Tomsk Polytechnic University, Geo Assets Engineering 326(2) 90–102
[7] Preis Yu I 2016 Geography and Natural Resources 2 94–103
[8] Bronzov A Ya 1930 Raised bogs of Narym territory (basin of the Vasyugan river) Proc. of Peat Research Institute 3 (Peat Research Institute Press) p 100
[9] Khotinsky N A 1977 Holocene of Northern Eurasia (Moscow Nauka) p 200
[10] Golovatskaya E A 2013 Carbon fluxes in bog ecosystems of the southern taiga of Western Siberia Synopsis dissertation for the degree of Doctor of Biological Sciences (Krasnoyarsk) p 33
[11] Methodological Guidelines for Office Processing of Materials for Exploration of Peat Deposits 1969 (Moscow: Ministry of Geology of the RSFSR) p 326
[12] Volkova V S Gnibidenko Z N and Goryacheva A A 2002 Basic laws of global and regional climate and natural environment changes in the late Cenozoic Siberia 48–57
[13] Bond G Kromer B and Beer J 2001 Science 294 2 130–36