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CONTENTS

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THE NATURE OF CYCLIC STRUCTURE OF THE ICE COMPLEX, EAST SIBERIA

ABSTRACT. The features of cyclic structure in the Karga-Sartan Ice Complex (IC) deposits in Northern Yakutia have been studied for the coastal lowlands. We have analyzed cycles of different genesis (cryolithological, structural, lithological, and soil-vegetation) and duration. Climate fluctuation was the major factor of cyclic structure in the IC deposits. Cyclic structure in the IC deposits develops in certain facial-genetic conditions characterized by cryogenic weathering and subsequent re-deposition of eroded soils in river valleys and alas depressions.

KEY WORDS: Ice Complex, cyclicity, content, mineralogy, weathering, soil, origin

INTRODUCTION

Over large areas of the plains and foothills of Eastern Siberia, are widespread deposits of the Ice Complex (IC) – a unique formation of ice-rich permafrost with polygonal-vein structure.

The IC of the Karga-Sartan period (50–40 to 11–12 thousand years ago) is particularly well-developed; it forms the surface of the so-called yedoma. The latter consist of isolated massifs and remnant hills separated by extensive erosion, thermokarst depressions, and river valleys.

In the early 1950s, the Institute of Permafrost of the USSR Academy of Science undertook a comprehensive study of these deposits in different regions of East Siberia, although quite a large volume of information had already existed in the XIXth and even the XVIIIth centuries. One of the first results of these studies was a conclusion on regular cyclic or rhythmic structure of the IC. A.I. Popov [1955, p.21] wrote: "The general pattern in the structure of all... the ice and organic-mineral complex, appears quite clearly and reflects certain cyclicity and interdependence of its formation (*underlined* by V.K.).

In other words, the most general conclusion has been made: transit, i.e., traced consistently throughout the IC deposits, ice wedges and separating them blocks of frozen organic mineral deposits with segregation ice and ice-cement, both these IC elements, accumulated not in continuous conditions, but intermittently, irregularly, i.e., cyclically; "...a typical unistratal section of a block between two veins always ends with peat" [Popov, 1955, p. 20].

Besides, the cyclic accumulation of the organic-mineral component of the IC and of ice veins is interdependent: "...Deposition of sediments lags behind the upward growth of ice veins. For continuous growth of veins, deposition has to be continuously "catching-up" with the veins" [Popov, 1955, p. 21].

A.I. Popov considered sediment deposition the leading factor in the formation of the polygonal-vein system of the IC "... ice accumulation is an indirect consequence of sediment deposition within the polygons; ...deposition, in the literal sense, defines the entire mode of ice accumulation, conditions of formation, and thickness (vertical) of interstitial ice" [Popov, 1955, pp. 22–23].

Practically at the same time, Ye.M. Katasonov [1954] in his Ph.D. thesis gave a detailed description of deposits, cropping out in the well-known outcrop Moose Khai (left bank of the River Yana in its lower reaches).

One of the main conclusions of this study was the detailed explanation of rhythmic, or cyclic, structure of the IC thickness, exposed in outcrop Moose-Khai. Ye.M. Katasonov wrote: "The structure of the valley deposits (in the opinion of Ye.M. Katasonov, V.K.) of Moose-Khai outcrop has two specific features: significant thickness (25–30 m) and, the most interestingly, the rhythmic nature."

"In the deposits, there are regular cycles (*underlined* by V.K.) formed by two or three lithological loose rocks (facies)" [Katasonov, 2009, p.79][1].

At the base of each cycle, there is dark gray greenish ice-rich loam. Up the profile, it transitions to dark-brown peaty loess loam, which is gleyic in some places and has a lighter color. The latter have lower ice content; ice-cement or thin hair layers of ice dominate. The upper horizons are penetrated by threadlike roots of grasses.

Using outcrop Moose-Khai as an the example, Ye.M. Katasonov investigated the relationship of cryogenic structure and lithological facies of sediments and proposed a concept of cryogenic-facies analysis, which allows identifying both the nature of deposits freezing and their facies-genetic origin.

Yu.A. Lavrushin [1963] described a number of sequences of the IC outcrop in the low reaches of the Indigirka River. His detailed descriptions indicate clearly that the IC of these deposits has cyclic structure, though the author does not use this term and talks about alternating "series" and "bands" of deposits.

The Lavrushin's work [1963] completes the important stage of research on the IC. This stage is associated with search of the IC facial-genetic analogies of modern alluvial deposits. To a large extent, the work of Ye.V. Shantser [1951] on the basic laws of the formation of thick alluvial formations provided the theoretical basis of the IC facial-genetic analysis.

THE ORIGIN OF THE IC DEPOSITS: CONSTRATAL-ALLUVIAL OR CLIMATIC?

The conclusion of the works of A.I. Popov [1953], Ye.A. Katasonov [1954], and Yu.A. Lavrushina [1963] was that the IC deposits are predominantly alluvial formations[2] formed by the constratal type and in predominantly negative tectonic movements. In the concepts of these authors, the cryogenic features of the IC, i.e., thick transit ice veins, segregation ice, deformation of layers, etc., represent some important features of the general process of sediments accumulation. Therefore, the concept of cyclic structure of the IC sediments means the alternation of different facies in the process of accumulation of thick alluvial strata and their syngenetic freezing.

Almost concurrently with the concept of the constratal mechanism of accumulation of the IC sediments due to the slow tectonic subsidence, there appeared another idea about formation of thick stratas of these deposits. N.A. Shilo [1964, 1971] pointed out contradiction that arises when attempting to apply the constratal mechanism for the entire vast geologically and tectonically diverse territory of the IC development. Indeed, it is difficult to assume unidirectional nature of synchronized tectonic movements in the territory from Alaska to Northern and Central Yakutia with the wide-spread IC deposits.

Thus, Ya.A. Lavrushin, contradicting to the constratal-tectonic concept that he shared, wrote: "Its extremely wide areal distribution (the IC of the Vorontsov suite, V.K.) indicates that its formation is attributed not only to such major rivers as the Yana, Indigirka, and Kolyma, but also to the network of small and

[1] This work was published as a monograph (Ye.M. Katasonov, 2009).

[2] These authors had different views on the facial conditions of the formation of the IC: according to A.I. Popov and Ye.M. Katasonov – floodplain facies; according to Yu.A. Lavrushin - near-channel and ice facies.

shallow rivers and streams … the climate of the formation of the Vorontsov suite was very sever. This has led to intense frost weathering of rocks and transport to the rivers of a large volume of crushed fine-earth material. As a result, the relation between water flow and sediment transport to the rivers appears to have been such that the rivers were overloaded with sediments and the rivers' channels were segmented into many small branches and channels whose beds were rising due to the accumulation of material". [Lavrushin, 1963, pp. 139].

Not only depressions of the erosion genesis were filled, i.e., practically all erosion network from the valleys of large rivers to small valleys of rivers and creeks, but alas depression, whose area was comparable with the area of the erosion network itself, was filled as well.

We can point to many studies that indicate that during the phase of cold climate, in periglacial lithogenesis, subaqueous accumulation was replace by subaerial (mainly slope). In the valleys of large rivers, thick strata of "periglacial" alluvium was forming [Ravsky, 1972]; in the valleys of small rivers and streams, alas valleys and depressions were being filled with slope and prolluvial sediments; terraces were transforming into terrace-ridges, in the foothills, thick benches of slope sediments were forming [Dedkov, 1975; Brinks 1975; Gravis, 1981].

This implies that the IC deposits are genetically heterogeneous entities and represent paragenesis of many genetic types, united by the fact that they were formed in the harsh climate [Zubakov, 1966; Konishchev, 1981].

In the relation between sedimentageneous and cryogenic factors, the latter play the leading role.

VARIETY IN THE IC CYCLIC STRUCTURE

Considering the overall climatic influence of the IC accumulation, it is feasible to assume that its cyclic structure is also climate-dependent. In the syngenetic IC sediments, two types of cycles can be distinguished, which either coincide or not. The nature of lithologic cyclicity, first described in detail by Ye.M. Katasonov [1954], is treated by the majority of authors as narrowly sedimentagenous [Popov, 1967, Lavrushin, 1963].

However, along with the lithologic cycles in the IC sediments, there may be isolated cycles and rhythms formed by cryogenic textures. Initially, the cryogenic rhythms were described by A.I. Popov[1967] who also suggested the mechanism of their formation.

Textural rhythms in syngenetic permafrost result from a certain ratio of sedimentation and cyclic changes in the depth of seasonal thawing.

The incremental increase of the permafrost thickness due to transition of the bottom seasonally thawed layer (STL) to the IC is not gradual but rapid and irregular, during the reduction of the depth of seasonal thawing. The latter is a function of the long-term climatic regime that determines the main factors affecting the depth of the STL (temperature, humidity).

The idea of textural cryogenic rhythmicity was developed by N.N. Romanovsky [1993] who stated that the STL depth depends mainly on changes of the amplitude of annual temperature variations on soil surface and the degree of hydration of this layer. Changes in the STL depth are due to fluctuations of average air temperature while soil plays a secondary role.

Facial-lithology cyclicity of the IC sediments is closely connected with the polygonal nature of the sedimentation surface, which in turn determines the water content of the surface and, therefore, the water content of the STL, its depth, and the differentiation of the vegetation cover. The nature of the polygonal relief is clearly reflected in the deformations of frozen deposits on contact with ice veins. The degree of deformation of deposits varies in the IC series; the thickness of these series is usually 0.3-0.5 m. The series unconformably overlie one above the other and cut each other. The grain size composition of the sediments that form different series is identical, but the ice content differs significantly. The greatest deformation on contact with ice veins occurs in ice-rich aleurites with thick-schlieren and ataxitic-schlieren cryotextures. The aleurites with massive-, micro-, and fine-schlieren cryotextures are practically undeformed and in the contact zone with ice veins, cut deformed layers of ice-rice aleurites (Fig. 1)

Cyclic or rhythmic structure changes consistently down the profile of IC. This is expressed most clearly in the lower part of the IC. As a rule, in outcrops (Vorontsov Yar, Chukochee Yar), this sequence is not fully exposed and its thickness is about 5-6 m, however, in some cases it crops out completely, for example in Moose-Khai outcrop (the Yana River) where its depths is 14.7 m. This sequence has a distinctive greenish color. It is characterized by alternation in the vertical profile of strongly deformed at contact with ice veins icy layers of aleurites with lenses of poorly decomposed peat that lies in the cores of ancient polygons, and of less icy and almost undeformed layers. Higher in the profile of the IC, the layer of greenish-gray aleurites, usually with clear contact, is covered by the layer of monotonous and very homogenous brown unclear laminated aulerite completely penetrated by vertically spaced roots of grasses. In general, the thickness has micro- and fine-schlieren crytextures. The most important feature of the brown aleurites is the absence of deformations at contacts with syngenetic ice veins independent of the depth of the latter. The cyclicality in this layer is not expressed as clearly as in the lower greenish-gray aleurites. However, it also exists and can be traced either in the form of humus interlayers of buried soils or as alternation of the layers with massive- and micro-schlieren cryotextures. The thickness of the brown aleurites varies in different outcrops of the IC from 5–10 m (a site of Duvanny Yar outcrop, upstream the Kolyma River) to 25 m (a site of Chukochee Yar outcrop, downstream the Kolyma River). As a rule, the thickness of this

Fig. 1. The cyclic structure of the IC deposits. New Siberian Islands (Bolshoi Lyakhovsky Island). Photo by V.Ye. Tumsky

layer is 10–12 m. The layers of the brown aulerites of small depth (less than 1 m) (in terminology of Ye.M. Katasonov [2009] – loess loams) are separate cycles in the underlying thick greenish-gray aleurites.

Analysis of the spore-pollen data of the major key sections of the IC (12 sections in total) performed by T.N. Kaplina [1979] showed that the coastal lowlands of the Yakutia IC have two types of spore-pollen spectra. The first of them is with a significant role of tree pollen and, especially, of shrub-pollen (from 10 to 40% and more).

These spectra have been named "shrub" and interpreted as forest-tundra and tundra. The "shrub" spectra are similar to the spectra of the modern southern margin of wet tundra, however on average, the ancient spectra yield to the subfossil spectra in relation to the pollen content of trees and shrubs, i.e., they reflect slightly cooler conditions than the present.

The second type does not have modern analogies; however it reflects treeless and shrubless landscapes with predominance of grasses (steppe- tundra). They were named "grassy" and they reflect very harsh climatic condition of the time of accumulation of the enclosing deposits. T.N. Kaplina [1979] has concluded that the spectra of these two types are distinctly confined to certain cryolithological layers of the IC. The "shrub" spectra are characteristic of the lower parts of the IC sections composed, as a rule, by yellow-green ice-rich aleurites with deformed layers at contacts with syngenetic ice veins. The "grass" spectra are characteristic of the horizon of the brown ice-poor aleurites with massive- or micro- schlieren cryogenic textures without deformations at contacts with ice veins that lie in the upper parts of the IC sections. It is important to note that in outcrop Duvanny Yar (the right bank of the Kolyma River), the "grass" spectra are found also in some layers (cycles) of the lower part of the IC section. The same pattern is characteristic of the bottom horizon of the IC of outcrop Moose-Khai, in the low reaches of the River Yana [Kondratyeva et al, 1976] where layers (cycles) with "grass" and "shrub" spectra alternate.

Thus, these data is a quite convincing argument in favor of the conclusion that the cyclic structure of the IC deposits is a result of climatic conditions, which in turn is determined by the cryogenic facial features of both isolated layers-cycles and their complexes – the layer of ice-poor brown and the layer of greenish-gray ice-rich aleurites.

The conclusion about the climatic origin of the IC cyclic structure is confirmed by the analysis of buried soils – a very characteristic component of these deposits [Gubin, Zanina, 2004]. On the territory of the Kolyma lowland, in the Karga period, there was repeated alternation of synlithogenic and epigenic pedogenesis [Zanina, 2006]. In complete sections of the IC, there have been found Early and Late Karga pedocomplexes. Epigenic peat and peat-gleyic soils formed in polygonal relief, when the flow of mineral deposit weakened, i.e., soils have recorded the final stages of the accumulation cycle. Hydromorphism of peaty soils indicates that the enclosing layers (cycles) have high ice content, and they are likely strongly deformed. The periods of synlithogenic pedogenisis, on the contrary, had intense sediment accumulation due to mineralization and humification of plant litter and dominance of detritus formation over peat accumulation. Synlithogenic pedogenisis, most likely, coincided with the accumulation of layers (cycles) of the brown aleurites with low ice content and the absence of deformation of the layers. The conclusion here is quite obvious: the cause of transition from syngenetic to epigenic formation was warming and not vice versa [Zanina, 2006]. Radiocarbon data indicate the following stages of the epigenic pedogenesis: 40, 37–35, 33–31, and 28 thousand years ago, which gives an idea of the duration of the individual cycles of the IC.

THE CYCLIC NATURE OF TRANSIT SYNGENETIC ICE VEINS OF THE IC

It was mentioned above that the first idea about the cyclic structure of vein polygons, i.e., both of rock blocks and enclosing syngenetic ice veins, was stated by A.I. Popov [1935]. As far as the cyclic structure of the latter is concerned, this issue has not been well studied. Recently, when isotope research on the composition of thick syngenetic ice veins became widely conducted, this problem practically dropped out of sight researchers. Meanwhile, in the literature there are enough specific data to understand the cyclic structure of syngenetic ice veins. B.I. Vtyurin [1975] based on the study of sections of vein polygons formed over thousands of years, has shown that, in the process of syngenetic growth, the veins not only slowed the upward growth and increased the growth sidewise, but periodically stopped growing. Discontinuity in the growth of syngenetic veins is a natural and common feature. The growth of veins, due to a combination of processes of cracks filling with water, its freezing, and squeezing up of ice [Leffingwell, 1915; Blaok, 1952; Konishchev, Maslov, 1968], outpaces sedimentation; ridges on the surface are formed. This, in turn, is the cause of interpolygonal small lakes and wetlands, which leads to destruction of ridges due to initial thermokarst and partial thawing of the upper parts of the ice veins. This process is manifested through the presence of lenses and interlayers of thermokarst-cave ice or soil at different depths of repeated wedge-ice.

Information about the structure of thermokarst-cave ice can be found in the works of P.A. Shumsky [1960], Sh.Sh. Gasanov [1969], B.I. Vtyurin [1975], G.E. Rosenbaum, et al [1978], and others. The participation of thermokarst-cave ice in the formation of powerful, transit, and syngenetic ice veins is not always easy to recognize, as this ice in the further growth of ice veins "is consumed" by ice of elementary frost cracks penetrating it from the top [Rosenbaum et al, 1978]. As a result, in the body of the veins there remain only fragments of termokarst-cave ice, which can be mistaken for ice of different genesis (Fig. 2).

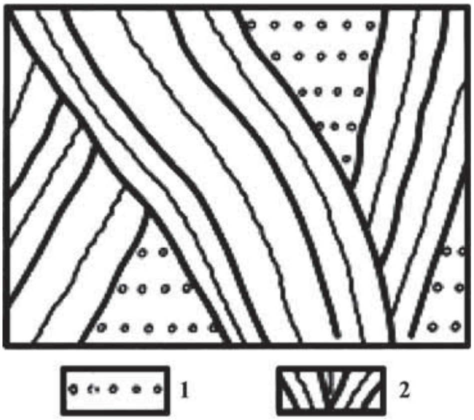

Fig. 2. Drawing of ice vein texture, Chukochee Yar (according to [Rosenbaum, et al, 1978]).

1 – thermokarst-cave ice; 2 – elementary veins

The interlayers and lenses of thermokarst-cave ice in ice veins represents undeniable evidence of change of thermal and moisture condition on the surface of forming polygonal-vein structure. At the present time, it is not quite clear what interlayers of thermokarst-cave ice in the body of ice veins correspond to what layers (cycles) of soil blocks. On the one hand, the interlayers should correspond to the icy and highly deformed layers of the greenish-gray aleurites that reflect the conditions of the polygonal-ridge micro-relief with interpolygonal lakes that are the cause of the destruction of ridges and of the embryonic local thermokars in ice veins. However on the other hand, the cause of the local thermokarst on the polygonal surface could be associated with deeper seasonal thawing that took place during the accumulation of layers (cycles) of the ice-poor undeformed brown aleurite. At that time, soil moisture was greatly reduced, vegetation transformed from shrub to grassy, and peat-gleyic soils were replaced by humified interlayers. As a result, seasonal thawing increased, which could have led to the local thermokarst in depressions (ditches) of the polygonal relief over ice veins and the bounding ridges.

This issue requires further study.

THE GENETIC ORIGIN OF THE MAIN HORIZONS OF THE IC – BROWN AND GREENISH-GRAY ALEURITES

Speaking again about the genetic origin of the two main horizons of the IC (the upper ice-poor brown and low ice-rich greenish-gray) it should be noted that initially they were viewed as different facies of the genetically homogeneous layer of the IC, i.e., deposits of the riverine and inner zones of floodplain [Popov, 1953; Katasonov, 1954]. Proponents of the concept of the alluvial origin of the IC still adhere to this position. However, even Ye.M. Katasonov [1954] pointed out that the brown aleurites have a very homogenous composition (70-90% of fraction 0.1–0.01 mm) and a very small amount of sand fractions, while the greenish-gray aleurites are characterized by considerably more diverse grain-size distribution and include much more of sand fractions compared with the brown aleurites (Fig. 3).

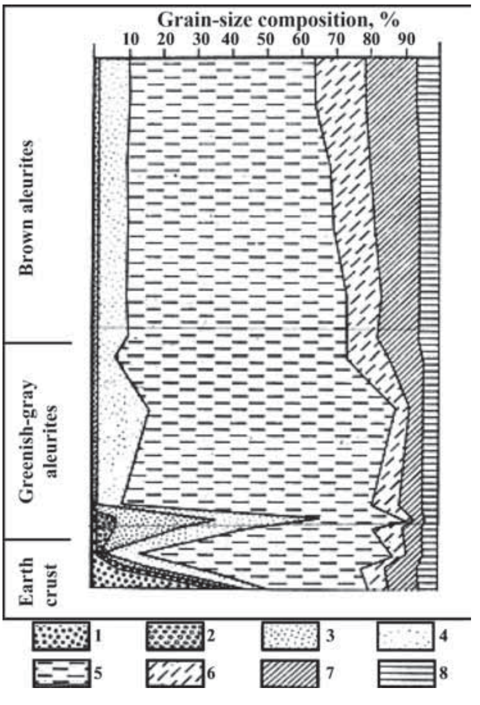

Fig. 3. The grain-size distribution of the IC sediments in the Yana-Omoloy interstream area.

Size fractions in mm: 1 – <0.5; 2 – 0.5–0.25; 3 – 0.25–0.1; 4 – 0.1–0.05; 5 – 0.05–0.01; 6 – 0,01–0, 005; 7 – 0,005–0,001; 8 – <0.001

Our research and data of other authors indicate that these differences are observed in other sections of the IC [Konishchev, 1981, Tomirdiaro, 1980]. Inconsistency in the grain-size distribution on the one hand and the nature of the cryogenic structure between the layers of the brown and greenish-gray aleurites of the IC on the other hand, are not related to differences in facial conditions of sedimentation on the floodplains of major rivers, but to other causes. Another explanation is the idea of the primary aeolian genesis of the brown aleurites with the micro- schlieren cryotexture, which has being developed by a number of researchers [Tomirdiaro, 1980, Gubin, 2002]. Recently, some researchers who adhere to the alluvial concept started to lean toward the aeolian genesis of these deposits [Kaplina, 2009] due to new data on entomofauna and seed and leaf flora that indicate sharply continental and dry climate with little snow in the Late Pleistocene. "It is more feasible to accept the aeolian processes in these conditions than the impact of large rivers and active slope discharge on vast territories" [Kaplina, 2009, p.170].

Let us consider in greater detail the arguments provided above and the features of the aeolian genesis of the brown aleurites.

Indeed, the brown aleurites, as in the form of the upper horizon of the IC and as isolated interlayers (rhythms) alternating with ice layers in the low horizons of the IC sections, appear by-sight to be very dry. Ye.M. Katasonov [2009, p.146] called these sediments "dry permafrost."

However, laboratory measurements of the moisture content of the brown aleurites have shown that its value in relation to the weight of dry soil reaches 80% and 40%-60% for micro- schlieren and massive cryotextures, respectively [Kondratyeva et al, 1976]. The results of an intriguing experiment are presented in the work of the authors who have being consistently developing the concept of the aeolian genesis of the aleurites with micro-schlieren cryotexture [Tomirdiaro, Chernenky, 1987]. A sample of such sediments with 40% moisture content collected in outcrop Oyagosky Yar was melted and then frozen as monolith in laboratory conditions. The freezing temperature is not specified. As a result, at the initial moisture content, there emerged "thick ice schlieres and laminated thick-schlieren texture formed" [Tomirdiaro, Chernenky, 1987].

The authors attributed this to a low speed of aeolian accumulation (1–1.5 mm per year), resulting in the same annual rise of the active layer - the upper limit of permafrost. Therefore, with such a small increase in the permafrost layer, the formation of thick ice schlieres was not possible and the developing deposits had strictly micro-schlieren cryotexture. Weakness of this explanation is obvious. A.I. Popov explained this phenomenon; he indicated that the increase of the syngenetic frozen layer is a result of mutual processes of sediment accumulation and dynamics of the STL (see above).

We have given a different explanation of cryogenic structure of the brown aleurites with micro- and massive schlieren cryotextures [Konischev, 2002]. Analysis of the brown aleurite microstructure showed that ice-cement there belongs to the basal type. Weak differentiation and the mineral component of this layer at the sufficient moisture content and a rather favorable, for ice formation, aleurite composition is due to a very high speed of freezing ($4.5–5.0 \cdot 10^6$ m/sec) at which fixation of water in place was occurring. Obviously, these conditions are very common in extremely continental climate, where due to strong cooling during the polar night, temperature drops to –70°C and below. However, soil moisture was sufficient for the development of highly productive and abundant vegetation, as evidenced by numerous thin roots of herbs that penetrate the thick brown aleurite.

The general perception of many researchers is that during the accumulation of the brown aleurite, a particular type of landscape – tundra, dominated; it had mixed flora and fauna of vertebrates and insects.

In contrast to the findings of most climate reconstructions of the time of accumulation of the brown aleurites and perceptions on steppe-tundras as cold landscapes with only tundra and even arctic deserts, the work of [Alfimov, Berman, 2004] has been developing a concept on conditions that provide for existence of the "steppe component." Based on the analysis of fossil insects, the authors concluded that in most of North Eeast Asia of the Sartan period, summer temperatures were higher than the modern temperatures in the tundra zone. According to [Alfimov Berman], 17–18 thousand years ago in the lower reaches of the Kolyma River, summer temperatures were 12–14°C, which is higher than the present that vary from 6–7°C in the mouth to up to 11–12°C in 100 m upstream.

Judging from the descriptions of various sections of the IC, the brown aleurites are characterized by abundance of plant residues in the form of thin fibrous roots of plants and presence of humus spots, sinters, and interlayers. This indicates a significant impact of soil processes on the brown aleurites. The carbon content there reaches 1.5% [Zanina, 2006].

As mentioned above, the contact between the layers of the ice-poor brown and the ice-rich greenish-gray aleurites is usually very contrast. Moreover, in some outcrops, it has typical characteristics of erosive nature (Fig. 4). Recently, there have been descriptions of deep, up to 20-30 m, gullies filled with the brown aleurites of the Sartan period in the low reaches of the Yana River and the southern bank of Bolshoi Lyakhovsky Island [Tumsky, 2012]. Thus, this phenomenon is regional.

The reason for this phenomenon is lowering of the sea level at the beginning of the Sartan period and, as a consequence, change of the basis of erosion [Tumsky, 2012]. Agreeing with this explanation, we should provide some clarification. Since the thickness

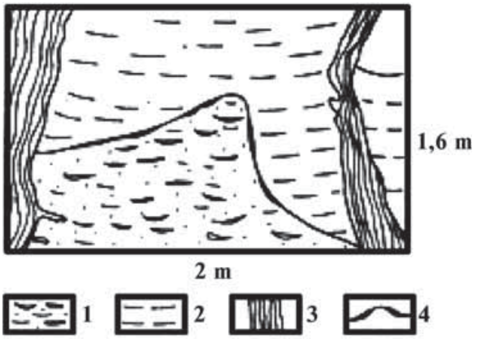

Fig. 4. The contact between the brown and greenish-gray aleurites in outcrop Duvanny Yar (the Kolyma River downstream):

1 – greenish-gray aleurites, icy, with lenticular cryotexture; 2 – brown aleurites, with micro-schlieren cryotexture; 3 – ice vein; 4 – contact between brown and greenish-gray aleurites, fixed by the interlayers and pockets of white porous firn

of the underlying Karga IC, similar to the horizon of the brown aleurites was formed in conditions of sea regression, the regression rate had surged prior to the formation of the brown aleurites and, most likely, was because of accumulation due to the glacial-ecstatic factor. Therefore, the cause of the erosion contact between the brown and greenish-gray aleurite is climatic. Besides, the landscape conditions changed dramatically and, in particular, the nature of the land cover. In the steppe-tundra landscapes characteristic of the time of accumulation of the brown aleurites, thermo-erosional processes were probably manifested more intensely than in shrub-tundra.

Many researchers, and especially soil scientists, isolate a special type of synlithogeic soils – cryopedoliths (Zanina). In the Sartan brown aleurite layers (outcrop Duvanny Yar, the Kolyma River), a small buried burrow, was found, which belonged to small rodents; it was filled with well-preserved bedding consisting of herbs. In the layers of the brown aleurites (cryopedoliths) in the underlying Karga layer of the IC, several buried rodent burrows were found [Gubin et al., 2001].

All this is undisputable evidence of the fact that summer temperatures did not prevent but contributed to the spread of thermophilic steppe-tundra ecosystems and vegetation on the shelf during sea regression beyond the boundaries of the modern terrain; the temperature supported living conditions (food) not only for small rodents, but for larger representatives of the mammoth fauna. During the regression of the Arctic seas, the effect of the polar day significantly increased: thawing index (the sum of summer air temperatures) increased with strongly reduced cloudiness (now, in coastal areas, it is 65–70%) and the temperature effect of direct solar radiation increased as well.

Thus, hygrothermal conditions of the summer period provided for the formation of a continuous grass cover and a rather powerful soil horizon.

Compared to the current conditions, the prevalence of open landscapes of steppe-tundras with a large role of grasses caused the increase in the depth of seasonal thawing of not less than 1 m (now, 40–50 cm). Similar values of the STL are also obtained from analysis of the depth of locations of fossil rodent burrows [Gubin et al., 2001].

The data presented contradict in general to the aeolian genesis of the brown aleurites layer from the point of view of a local source of aeolian material, because solid and sufficiently dense and productive land cover prevented wind erosion. Nevertheless, this does not contradict the fact that the source of aeolian dust was not associated with local wind erosion, but with some fairly remote areas. In this case, aeolian dust is a product of distant transfer, perhaps the result of global transport of material, which, in the opinion of some scholars, was very characteristic of the cold Pleistocene.

According to some researchers, specifically the deposition of atmospheric dust is the source of formation of loess deposits over large areas, including the IC deposits in Eastern Siberia. In the XIXth century already, it has been shown [Udden, 1898] that a transport system ability of sorting material is inversely proportional to its carrying capacity and, thus, the density. Therefore, wind transport is the most effective means of sorting. These considerations represent one of the reasons for the use of the aeolian theory to explain the genesis of the IC that differs from other types of deposits in terms of high grain-size differentiation.

The grain-size distribution of sediments is very sensitive to wind impact; directional changes in mineralogical composition occur along with mechanical differentiation. This has been shown in numerous publications on aeolian sediments of different facies [Buchanan, 1947; Sidorenko, 1956; Romanov, 1968; etc.].

Aeolian differentiation of particles by size and mineralogical composition leads to a certain relationship between the grain-size distribution and mineralogical composition of aeolian deposits. According to L.B. Rukhin [1961], the content of heavy minerals (specific gravity more than 2.9) in the size fractions of aeolian deposits consistently decreases with increase in grain size (Fig. 5). The maximal content of the heavy mineral

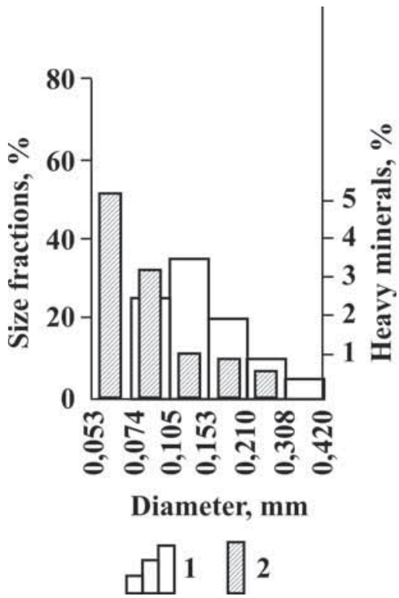

Fig. 5. Percentage of heavy fraction in relation to the grain-size of aeolian sands.

1 – size fractions (histogram); 2 – heavy minerals

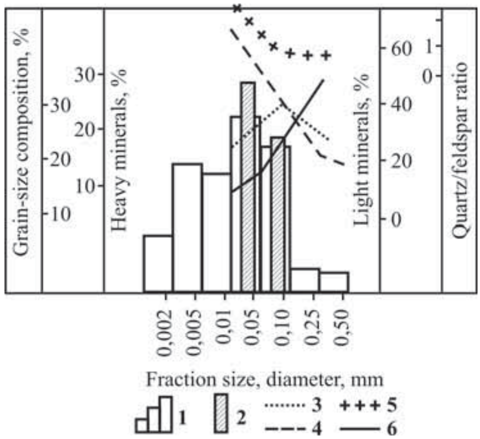

Fig. 6. Grain-size and mineralogical composition of aeolian fine earth on the right branch of Shokalskiy glacier (Zailiyskiy Alatau, Tien Shan, H = 3950 m, rocky setting is located at 800–900 m from the sampling site).

1 – grain-size composition; 2 – percentage of heavy fraction; 3 – quartz content by size fractions (%); 4 – feldspar content by size fractions (%); 5 – quartz/feldspar ratio by size fractions; 6 – rock fragments distribution by size fractions (%)

fraction is in a fraction similar in size to coarse aleurite (0.05–0.01 mm). A similar, but slightly subdued situation is associated with deposits of water genesis. Fig. 6 shows the results of our research of the accumulation of aeolian dust on the Tien Shan Mountains, in which different mineralogical parameters were studied in several size fractions. These deposits - typical products of differentiation of mineral matter in the atmosphere, have a clear sedimentagenous distribution of the total content of heavy minerals by particle size: the maximal content of heavy minerals is in the coarse fraction of aelorite (0.05–0.01 mm).

The studied sediments of the brown aleurite from several sections of the IC have a fundamentally different pattern (Fig. 7).

Despite a high degree of granulometric sorting (the content of coarse aleurite particles reaches 50–60) there is non-sedimentagenous distribution of the heavy mineral fraction% in all samples; its maximum is localized in the fine sand fraction (0.1–0.05 mm) and not in the fraction of 0.05–0.01 mm, as it should have been in the case of the aeolian

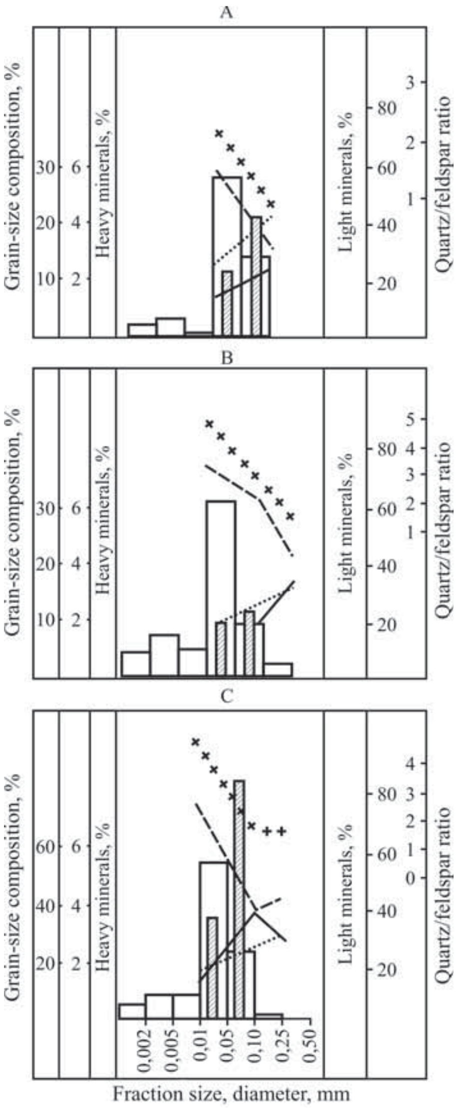

Fig. 7. Relationship between grain-size and mineralogical parameters in the sections of brown aleurites:

A – foothills of the Kular Ridge (Northern Yakutia); B – outcrop Moose Khai, depth 4.4 m (low reaches of the Yana River); C – outcrop Chukochee Yar (the Chukochee River), depth 4.0 m. For symbols, see Fig. 6

fine earth sediments on the glaciers. From the position of aeolian or water genesis of these sediments, the disagreement between granulometric and mineralogical sorting is unexplainable. Such non- sedimentagenous distribution of the heavy fraction within the granulometric range is associated with eluvium of bedrock and slope sediments [Konishchev, 1981]. This suggests that the brown aleurites of the IC is a product of the nearest re-deposition of elluvial formations or, more simply, of slope deposits. Here, we mean not the eluvium of bedrock, but cryogenic eluvium – the product of cryogenic impact (multiple cycles of freezing and thawing) on any original dispersed rocks. Numerous experimental data have shown that exposure to repeated cycles of freezing – thawing of various fine-grained soils (sand, loamy sand, sandstone, and other rocks) leads to significant changes in the size distribution, the result of which is the accumulation of 0.05–0.01 mm fraction due to destruction of larger particles and aggregation of fine clay particles [Konishchev, Rogov, 1976; Minervin, 1982].

Experimental and theoretical studies of the process of destruction of various minerals in alternate freezing and thawing have led to a conclusion that there is a specific stability sequence of minerals [Konishchev, 1981].

A fundamental feature of this sequence compared with other known sequences of mineral stability is a lower stability of quartz grains in relation to fresh and unchanged, by preceding processes of weathering or hydrothermal effects, feldspar grains - the most common rock-forming minerals. The limits of cryogenic disintegration of quartz grains are 0.05–0.01 mm, for feldspar – 0,1–0.05 mm, for biotite – 0.25–0.1 mm, for muscovite – 0.5–0.25 mm. Cryogenic organization of matter is expressed, thus, in a certain distribution of minerals within the granulometric range.

The main feature of this approach is not the absolute concentration of minerals, but the distribution of minerals between the particle size ranges of the granulometric fractions.

In all samples of the brown aleurite, the distribution of particle size fractions of the major minerals (quartz, feldspar, and quartz/feldspar ratio) was typical cryogenic. The deposits of warm and temperate climate zones have the opposite, mirror character (Fig. 8, A). This refers to the well-known scheme of N.M. Strakhov [1962].

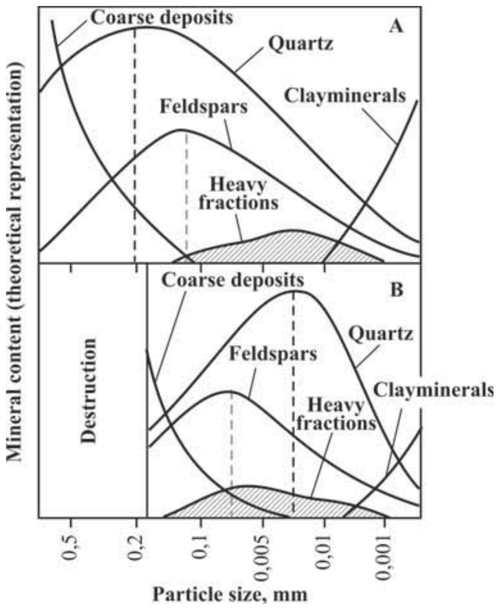

Fig. 8. Mineral content by the grain-size range in fine sediments formed:

A – under warm climate (according to N.M.Strakhov [1962]);
B – within the cryolithozone (according to the author)

The data of the immersion method analysis of minerals, which was used in the study of the sediments of the IC, is also supported by the results of the total chemical analysis for different fractions (Fig. 9). It is clear that the maximum SiO_2 content is typical of a 0.05–0.01 mm fraction, whereas in sediments and soils of temperate and warm climates, the maximal SiO_2 is observed in larger-size fractions.

The particle size distribution histograms of the brown aleurite, to some extent, correlates with the mineral composition: the predominant size fractions: 0.05–0.01 mm – up to 60%, and 0.1–0,05 mm – up to 25%, reflect the ratio of quartz and feldspars. This indicates, in addition to the above discussion, the leading role of cryogenesis in the formation of the composition of the brown aleurite. Fig. 8, B shows schematical representation of transformation of the original deposits in the course of their cryogenic weathering, whose basic content is associated with a prevailing destruction of quartz grains larger than 00.1 mm and concentration of this mineral in a 0.05-0.01 mm fraction – the limits of size for this mineral.

In general, the maximal content of light minerals (quartz and feldspar) is typical to smaller size fractions. The maximal content of heavy minerals hardly changes its position in the range of particle size and, therefore, relatively light minerals are shifted to larger-size fractions. The maximal contents of quartz and feldspar are reversed in accordance with their cryogenic stability.

The facies of the greenish-gray aleurites in the low part of the IC sections are characterized by different cryogenic sedimentation distribution of mineralogical parameters within the granulometric range. The distribution of the heavy fraction is typical sedimentageneous, i.e., the maximum content is in the fraction of 0.05–0.01 mm. At the same time, quartz, feldspar, and their ratio have the cryogenic type of distribution (Fig. 10). Exactly the same distribution of mineralogical indicators is characteristic of the underlying subaqueous (lacustrine or floodplain) deposits. Thus, while the lower horizons of the IC, not to mention the underlying sediments, were formed under the impact of sorting aquatic environment, the upper layers of the brown aleurite represent typical cryogenic fine earth.

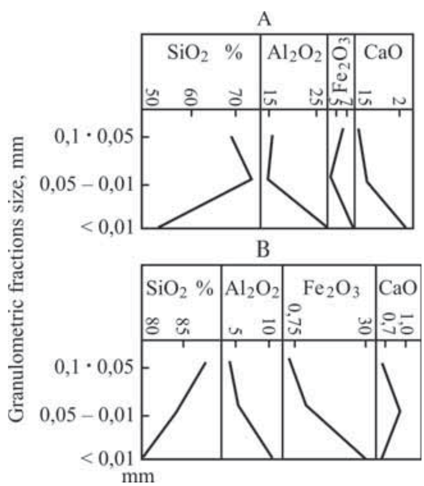

Fig. 9.

A. Distribution of chemical components within the particle size fractions of soils of temperate and warm climates [Kovda, 1973]

B. The gross chemical composition of different size fractions in the cryolithogenic sediments of the Kolyma lowland

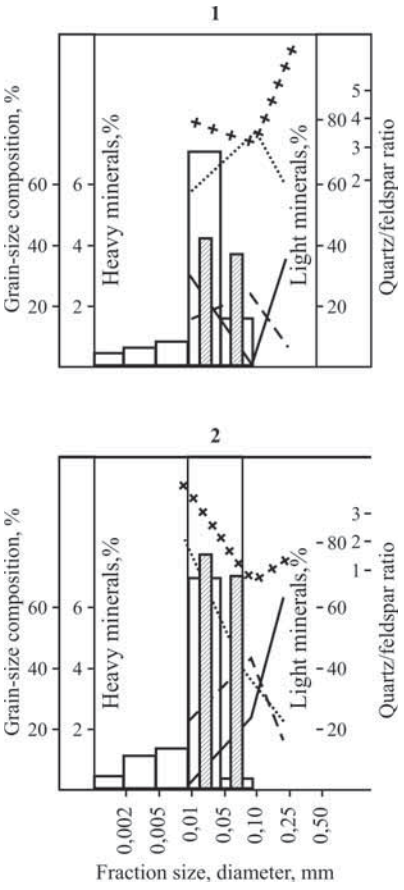

Fig. 10. Relationship between grain-size and mineralogical parameters of the greenish-gray aleurites of the IC

1 – outcrop Moose Khai (the low reaches of the Yana River), depth 19–20 m; 2 – outcrop Oyagossky Yar (the Laptev Sea coastal area), depth 15.5–16.0 m. For symbols, see Fig. 6

PALEOGEOGRAPHIC FACIAL CONDITIONS OF SEDIMENT ACCUMULATION OF THE IC

The Karga-Sartan interval of the Late Pleistocene was an extremely favorable time for the accumulation of products of cryogenic weathering – the basis of thick layers of different facies of the IC. In the phase of sufficiently cold (the Karga period) and, then, in the phase of very cold and relatively dry climate (the Sartan period), large masses of particulate material, mostly of aleurite composition, the result of cryogenic weathering, entered valleys of different orders – from large to very small, and alas basins also.

The erosional activity of streams and magnitude of the subaqueous accumulation were significantly decreasing. Thick alluvium was forming in the valleys of large rivers; the valleys of small rivers and creeks and alas depressions were filling with slope and prolluvial sediments; terraces were transforming into terrace-ridges [Gravis, 1981 Konishchev, 1981]. Depending on the geomorphological conditions, at least three types of environment of the IC accumulation can be identified. The first corresponds to the terrace-ridges conditions. Terrace-ridges have accumulated the mantle of aleurite material; it formed as a result of cryogenic processing of alluvial deposits on the slopes and the formation of thick (up to 20 m) fans of loess slope deposits intersected by the polygonal grid of repeated vein ice sometimes deformed in the direction of sloping e surface [Gravis 1969] and filling small valleys in the foothills and lowlands. The IC of this type is usually underlain by coarse alluvial deposits. Its mineralogical parameters are typical cryogenic [Konishchev, 1981]. The second situation corresponds to the valleys of rather large stable watercourses and their deltas. There, alluvial deposits, quite diverse in composition, have accumulated: sandy aleurites, medium- and fine-grained sand, and sometimes silty and interbedded with gravel. In these deposits, thick syngenetic ice wedges, sometimes as several horizons, were also forming. Deposits of this type are also the IC facies and are characterized by the cryogenic-sedimentageneous type of differentiation of mineralogical parameters within the granulometric range [Konishchev, 1981].

The third and the most typical and common situation was occurring in the alas valleys, alases themselves, and small valleys and streams on the coastal plain. There, the IC is often underlain by lacustrine loam, peat, or alluvial sand deposits, whose age dates to the beginning of the Karga period (40 thousand years or more) that had relatively warm climate with development of taiga vegetation [Zanina, 2006]. These deposits were overlain by quite a diverse range of facies. Climatic fluctuations of the period are manifested in their alternation – from water-rich ridge to flat ridge-free polygons. The average annual ground temperature during the accumulation of the horizon of icy and highly deformed yellow-green aleurites, separated by layers of brownish-gray non-icy and undeformed aleurites, ranged from –10°C to –2 ÷ –3 ° C [Konishchev, 2002], and this specifically was the reason for the cyclic structure of this section. The products of cryogenic weathering that filled alas basins and small valleys and that moved from the slopes with melt water and by solifluction processes, even at this stage, have been already subjected to sorting impact of the aquatic environment.

This is manifested in the cryogenic sedimentation type of the distribution of the mineralogical parameters within the size fractions (Fig. 10).

The brown aleuties with fine schlieren and massive cryotextures and undeformed layers at contact with ice veins were accumulating at the final stage of filling of the alas depressions and valleys under very harsh and relatively dry climate of the Sartan period when the average annual soil temperature reached 28÷ –30°C [Konischev, 2002]. This IC type has thick (up to 8 m wide) transit syngenetic ice veins that intersect, as solid wedges, all facies and horizons of the IC.

CONCLUSION

Thus, at all levels of structure of the IC deposits – from the most general (lower Karga and upper Karga - Sartan horizons) to different types of cycles - the determining factor of the accumulation of deposits was multi-scale fluctuations of cryogenic-climatic conditions. The facies and genetic structure of different types of the IC is a derivative of the permafrost-climatic characteristics. Cryogenic weathering, the character of slope processes, and frost cracking were most responsive to climate change. Climate impact on other processes of morpholithogenesis in the cryolithozone (erosion, thermokarst) was more complex and indirect. Precisely this has determined the accumulation of the IC deposits. ■

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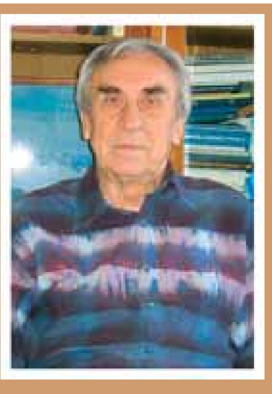

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ICE EFFECT ON COAST AND SEABED IN BAYDARATSKAYA BAY, KARA SEA

ABSTRACT. For the engineering design of underwater pipelines and communication cables in freezing seas, reliable estimates of the frequency and penetration depth of ice-keel scour on the seabed and shoreface are required. Underestimation of ice gouging intensity on the seabed can lead to the infrastructure damage, while overestimation leading to excessive burial depth raises the cost of construction. Here we present results from recent studies of ice gouge morphology in Baydaratskaya Bay, Kara Sea. The direct impact of ice gouging by floes on the seabed and shores is described, generalized and systematized: the depth of the gouges varies from the first centimeters up to 2 m; the most intensive ice gouging is observed near the fast ice rim, due to the maximum impact executed by ice ridges frozen into large floe. We propose a zonation of Baydaratskaya Bay based on the types of ice formation and the intensity of ice impacts on the coasts and sea floor.

KEY WORDS: Kara Sea, arctic coastal dynamics, geotechnical safety, sea ice, ice ridges, ice gouging, bottom topography, the intensity of ice influence, zoning.

INTRODUCTION

Sea ice, as a zonal factor associated with the high latitudes of Arctic seas, plays an important role in the evolution of northern coasts. The ongoing development of oil and gas fields and the construction of relevant engineering facilities in the coastal and shelf areas (including navigation channels, coastal terminals, drilling platforms, submarine pipelines, and artificial islands) require new information on the effects of sea ice on coastal and seabed dynamics [Løset et al., 2006: Lanan et al., 2011]. This is one of the most important factors determining the selection of pipeline landfall sites, shore-crossing design, and required depths of burial.

Until recently, little work has been done in Russia on the interaction between sea ice and the sea floor in coastal regions, whereas abroad, especially in Canada and the USA, there is a long history of research on this topic. American and Canadian researchers have documented the occurrence and processes of bottom scour and related seabed forms associated with pressure ridges and grounded ridges (stamukhi).

Pioneering studies were undertaken on the Alaska shelf [e.g. Carsola, 1954; Rex, 1955; Reimnitz and Barnes, 1974; Barnes, 1982; Reimnitz and Kempema, 1984; Barnes et al., 1984]. With the help of echo sounders and diving surveys, later augmented by sidescan sonar, ice gouges were found on the sea floor at depths of 0-65 m (a few deeper), with the highest density in depths of 20–40 m. They were up to 2 km long, incised as deep as 2,5 m into the sea floor, and were up to 67 m wide [Barnes et al., 1984]. In the Canadian Beaufort Sea, seminal work by Shearer and Blasco [1975], Lewis [1977], Hnatiuk and Brown [1977] established that ice scour occurred out to about 55 m depth, was most intense if the depth range of 15–40 m, and that depths of scour penetration were typically <1 m but as deep as 7,6 m. Later syntheses of results were provided by Rearic et al. [1990] for the Alaska shelf and Hill et al. [1991] for the Canadian Beaufort Sea. Barrette [2011] provides a recent review of issues related to pipeline protection from ice gouging and Wadhams [2012] provides new estimates of extreme depths and scour frequencies in the Beaufort Sea, recognizing the evidence for a reduction in gouging rates [Blasco et al., 2004], possibly related to a reduction in the frequency of multiyear ice incursion.

Ice gouging is a destructive mechanical impact of ice on the underlying ground surface. This impact on the shore and the floor of the Arctic seas is driven by the ice cover dynamics and mobility, hummocking (ridging), and formation of grounded hummocks (pressure ridges) controlled by hydrometeorological factors and coastal topography [Ogorodov, 2003]. Ice scour and push can extend onto and across the beach as ice pile-up and ice ride-up [Kovacs and Sodhi, 1980; Shapiro et al., 1984; Reimnitz et al., 1990; Forbes and Taylor, 1994], while underwater ice gouging is observed in the coastal zone out to depths of 55 m or more below the sea level (much deeper in regions of iceberg grounding). In direct observations from submarines, keels of large hummock formations reaching 50 m depth have been recorded [Lisitsyn, 1994].

In Russia, special studies of the sea ice impacts (first of all, the effect of ice gouging) started significantly later and were carried out in the areas of submarine pipeline construction (Baydaratskaya Bay of the Kara Sea, the Pechora Sea, and the Sakhalin Island shelf [Environmental conditions..., 1997; Vershinin, 2005; Zubakin, 2006].

In 2011, the so-called "Nord-Stream Gas Pipeline" directly connected Russia and Germany through the seabed of the Baltic Sea. In 2013 this pipeline will reach full capacity. To provide gas for this pipeline, in 2005, the "Yamal-Europe" pipeline project [Environmental conditions..., 1997], the lines of which would cross Baydaratskaya Bay, was revived and by August 2007, the construction of the underwater crossing of the main gas pipeline across the Baydaratskaya Bay was underway. This was to connect gas fields of the Yamal Peninsula with the pipeline network in the European part of Russia by the shortest route (Fig.1). The length of the underwater part of the pipeline is approximately 65 km, the maximum bottom depth in the crossing area is 22–23 m. In connection with the renewing of the project, investigations of coastal zone dynamics and sea ice effects continued in 2005 after a 10-year hiatus. In order to assess the impact of the ice on the

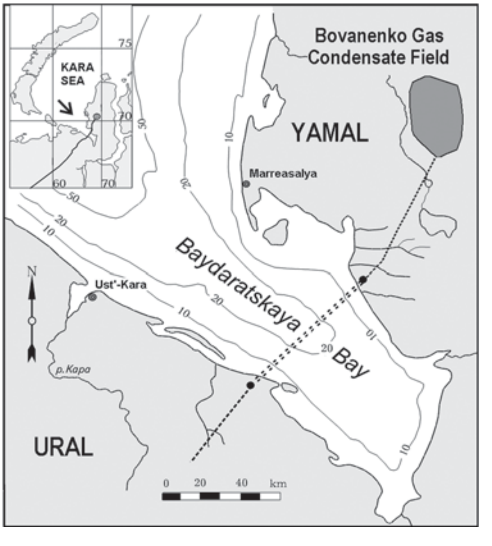


Fig. 1. "Yamal-Europe" gas pipelines crossing Baydaratskaya Bay in the Kara Sea

sea bottom, a wide range of investigations has been carried out, including field studies as well as mathematical modeling. Some of the results and scientific conclusions of the work in which the authors participated directly are presented in this paper.

ICE CONDITIONS

The autumn ice formation in Baydaratskaya Bay usually occurs in the absence of residual ice, i.e. in open water. At the beginning of October, as the radiation balance and surface water temperature descend to negative values, the first, usually unstable ice appears. The climatic mean freeze-up date for the formation of stable ice is about 15–20 October. Year-to-year variations in the hydro-meteorological conditions determine the temporal range of freeze-up. In seasons when cold air masses from the Arctic Ocean or the cooled continent prevail, ice formation starts early (the first 10 days of October); in contrast, when warm air from the Atlantic dominates the autumn season, ice formation occurs late (end of November or even into December). In more seaward parts of the bay remote from the shore, freeze-up occurs 10–15 days later the ice formation close to shore.

After the ice cover reaches the grey-white stage, the rate of further growth in ice thickness is directly proportional to the intensity of the underlying surface cooling and poorly correlated to the date of stable ice formation. Ice thickness typically increases every 10 days by 8–10 cm from November to February and then declines to 5–6 cm per 10 days in March, 2–4 cm in April, and 1–2 cm in May. It is important to note that the mean ice thickness along the shallow Yamal coast is generally greater than along the steep Ural coast. By the end of the cold season, the ice thickness along the Yamal coast reaches 140 cm on average, i.e. the ice cover in general fits into the category of thick first-year ice. Across the bay along the Ural coast, the annual maximum ice thickness is typically only 120 cm. The ice cover in that area often does not qualify as thick first-year ice and is categorized as medium first-year ice.

The sea ice of Baydaratskaya Bay consists of drift ice and fast ice (Fig. 2*a*). Close to the open parts of the Yamal and Ural coasts, fast ice forms 20–30 days after the initial freeze-up, with a thickness of approximately 30 cm. This young, relatively thin, fast ice is very unstable in the initial stages and therefore it can be easily broken strong wind shear or sea-level rise. However, with the growth of sea ice thickness (up to 0.5 m) and the formation of ice hummocks and stamukhas, stabilizing ice conditions, the fast ice resistance increases considerably. Stable fast ice forms near the Yamal coast and in the inner part of the bay only. Next to the Ural coast, fast ice is less stable and in the last several years, cases of its break-away have been observed. In the early part of the season, the fast ice spreads seaward quickly, its outer border reaching the 5–7 m isobath in November and the 8–10 m isobath in December. In February-March the seaward border of fast ice corresponds to the isobath of 15 m at the Yamal coast, where its width is 7–9 km, and to the isobaths of 10–12 m off the Ural coast, where its width is approximately 5–7 km.

Outside the fast ice limits, the central part of Baydaratskaya Bay, in depths of more than 10–15 m, is the area of mobile pack ice. Compared with the immobile fast ice, in the same equal conditions, the thickness of drifting ice is generally less. Along the interface between fast ice and pack ice, as well as on the borders of drifting ice fields, ice hummocks (pressure ridges) form. Ice hummocks freeze into ice fields, building up complex ice formations, which drift together.

Drift ice consists of ice fields of different sizes. Analysis of ice field size for April 2006 based on satellite imagery has shown that most of the ice fields (floes) are less than 2 km in diameter (Fig. 2a), though several reach sizes of 6-10 km. The maximum vertical dimension of pressure ridges observed in Baydaratskaya Bay, including both the sail and the keel, reaches 30 m, while the length can be up to 300 m. The mass of a 1 km diameter ice field with ice thickness of 1 m is approximately 10^6 tons. The mass of the largest pressure

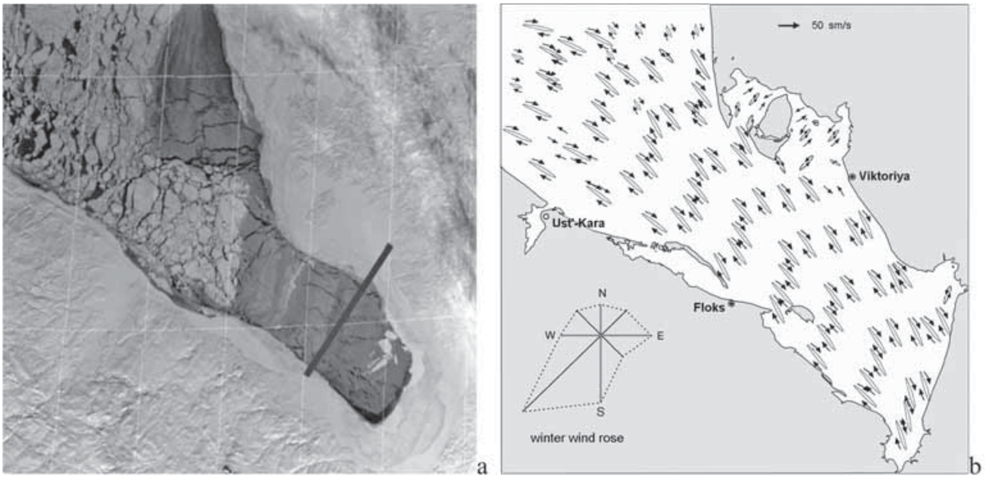


Fig. 2. Baydaratskaya Bay, Kara Sea:

a – ice conditions on 06.03.1999: TERRA satellite image; b – tidal currents [Environmental conditions..., 2007]

ridge 30 m × 30 m × 300 m is therefore about $2.7 \cdot 10^5$ tons, far less than the mass of the 1 km ice field [Marchenko et al, 2007]. Consequently, the ice scour process in Baydarakskaya Bay is dominated by the mass of ice fields with pressure ridges (ice hummocks and their associated keels) frozen in and incorporated within them, rather than by individual ridges.

The driving forces of ice-field drift are the wind and currents and the shear stress they exert on the upper and lower surfaces of the ice field. Currents measured in the ice-free period are practically reversive and aligned long the axis of the bay. Currents are driven by the semidiurnal tide (Fig. 2*b*). The maximum speed of the tidal current during the tidal cycle is 0,5, while the measured maximum current speed is 1,0 m per second. The maximum tidal range (spring tides) is 1.1 m, but including storm surges, the water levels have a range of up to 2 m. During the winter season, southwesterly and southerly winds prevail. In the absence of counteracting currents, these winds create conditions for ice drift from the Ural to the Yamal coast of the bay.

METHODS

The most commonly used approach to the assessment of sea-ice impacts on the coast and seabed is statistic analysis of data on the distribution and parameters of the ice scour features and the variability of this parameter over time. Acquiring a wide knowledge of the distribution and penetration depth of ice gouges on an extensive area of seabed is possible only with the use of specialized geophysical equipment – side-scan sonar, multibeam sounding, interferometric sidescan, acoustic sub-bottom profilers and GPS/GLONASS positioning systems. Investigations of the bottom ice gouging are conducted from a specialized research vessel equipped with these devices (Fig. 3*a*). For field surveys of the ice gouging microrelief and determining the morphology and morphometric parameters of ice gouging forms on the sea bottom, we use a complex approach, which allows us to combine the results of several complementary methods. Side-scan sonar and echo-sounding surveys are executed at the same time from the same vessel.

The position of the sounding tracks is determined with high precision using modern GPS and GLONASS receivers, accepting WAAS error corrections. The speed of the vessel during the tracks should not exceed 4 knots. All the information coming from the side-scan sonar, echo sounder, and GPS/GLONASS goes to the computer module and is observed at the monitor in real time.

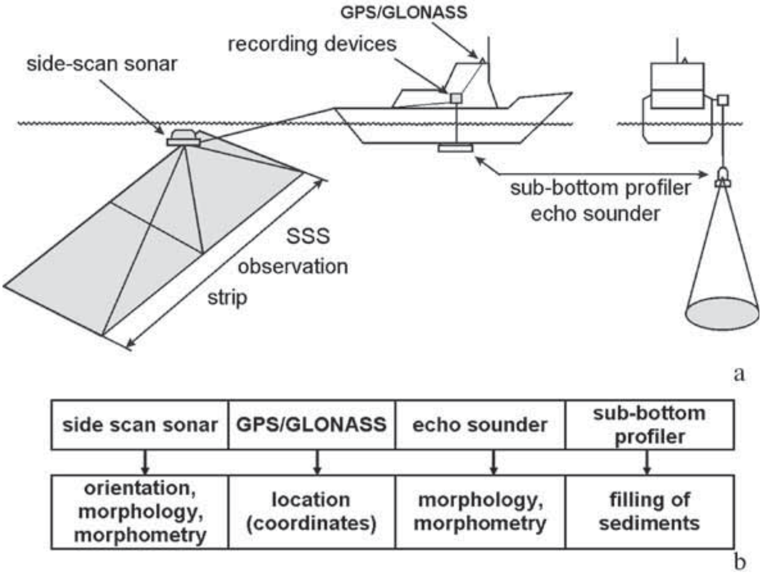


Fig. 3. Geophysical survey technology for mapping seabed features including ice-gouging features:
a – research vessel with geophysical survey devices;
b – selection of geophysical devices to determine the relevant parameters of ice forms

It is registered on the hard drive with the help of the licensed software provided by the sonar equipment suppliers. An echo-sounding profile shows the morphology and morphometry of the forms (depth, width, etc.), as well as whether they are filled with bottom sediments; the side-scan sonar gives the idea of spatial distribution and orientation of the ice gouging forms (Fig. 3*b*). Inertial motion units tracking the 3D motion of the survey vessel improve quality by reducing the noise arising from pitch, roll, yaw, or (more commonly) combinations of all three.

As a rule, such investigations are conducted with the aim of assessing ice gouging impacts on the seafloor and oil and gas transportation infrastructure (trenches, pipelines) on the bottom. The spatial resolution of the soundings is determined by proximity to the projected objects and the necessity of repeating previous sounding tracks. To assess the intensity of the ice scour at the present time, it is necessary to conduct repeated soundings and to distinguish forms which appeared between the two measurements. In the context of climate change, identification of "fresh" gouges is especially important in light of the climate warming of the last few years causing changes in the ice regime and displacing the maximum impact zone towards shallower water.

In this study, the position of the pipeline and the number, depth, width, orientation and bottom sediment fill of the ice scour troughs which have appeared between investigations conducted in different years are documented. For this purpose, the tracks of new surveys should coincide with the previous ones, and the same type of equipment should be used. The field stage is only the first step in the complex geophysical survey processing stream. This work enables statistical processing of morphometric data on the ice gouging forms, distribution, and parameters.

Accounting for very recent climate changes, the best time for conducting geophysical surveys in the coastal and shelf zone of the Russian Arctic is from the second half of July to the beginning of August, when the water areas are ice-free and storms are least frequent.

In areas of shallow water, where ice gouging microforms do not remain stable due to high hydrodynamic activity, preliminary reconnaissance investigations of the fast ice cover are conducted, with the aim of determining the position of stamukhi and hummock ridges, which are fixed with GPS/GLONASS. Shallow water sounding using side-scan sonar and an echo sounder are performed from smaller vessels immediately after fast ice melting, in order to identify new ice scour features formed by stamukhi before they are obscured by wave and current action.

Diving is a complementary activity which is conducted mostly for the confirmation of geophysical interpretation of the ice gouging forms. Divers acquire underwater photo and video imagery, take samples, and perform experiments for determining the speed of sedimentation in the ice gouging forms.

Besides ice gouging relief sounding on the sea bottom, coastal investigations are performed. As a rule, observations are made directly before the water area becomes ice-free. Using GPS/GLONASS and laser total stations, morphological and morphometric parameters of ice formations (ice piles, stamukhi, hummock ridges) and ice microforms created by them (gouges, pits, ridges) are measured.

RESULTS AND DISCUSSION

The first subdivision of the coastal zone of Baydaratskaya Bay by the types of ice formation and their effect on the sea coasts and floor was by V.A. Sovershaev [Environmental conditions..., 1997], who has made a huge contribution to studies of Arctic coastal dynamics. Detailed investigations performed in recent years under the guidance of the lead author, have made it possible to refine Sovershaev's model regarding the characteristics of ice formation as well as understanding of the mechanisms of ice scour (Fig. 4). Moving offshore down the underwater slope, we can observe the mechanisms and features of the coastal zone of Baydaratskaya Bay and the general types of ice formations and bottom topography changes caused by them.

Sea coasts are affected by ice during the periods of ice formation in autumn and fast-ice destruction and break-up in spring. On shoreline composed of sand-pebble material, the imprint of ice push is clearly defined. Our surveys reveal the widespread occurrence of ridges formed by ice-push (Fig. 5*a*). In autumn and early winter, young sea ice (20–40 cm thick) can be pushed onshore through wind-driven ice ride-up (unbroken floe) or pile-up (equivalent to pressure-ridge formation). During an ice-push event, the solid ice cover trims off the beach sediments and forms ridges of

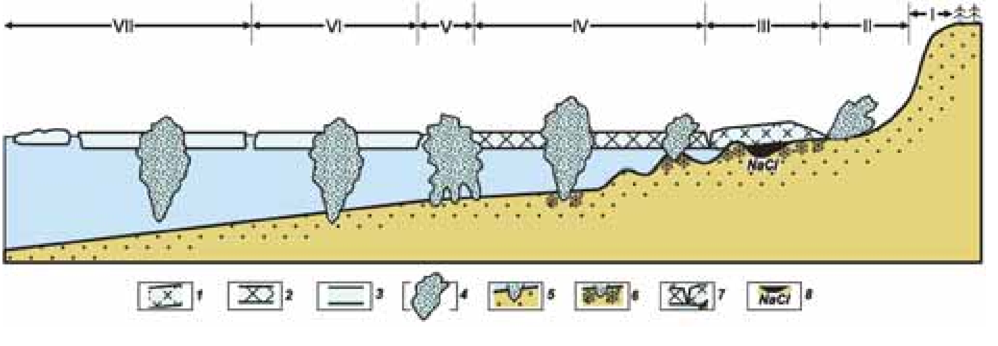


Fig. 4. Subdivision of coastal zone by types of ice formations and their effects on coasts and seabed:

1 – fast ice frozen to the bed; 2 – floating fast ice; 3 – drift ice floes; 4 – hummocks ice formations (ice ridges, grounded hummocks and ice dam), ice piles and overthrusts; 5 – hummock keel penetration into the ground; 6 – seasonally frozen ice forming at contact between ice and bed; 7 – tidal crack; 8 – high-salinity water in longshore troughs, cryopegs

Fig. 5.

a – ice-pushed ridge (photo by N.V.Kopa-Ovdienko),
b – coastal dynamics monitoring network bench mark damaged by sea ice overthrust

unsorted material [Barnes, 1982]. In spring the ice also produces small-scale forms, such as furrows, striations, wallow depressions and also various ice-pushed ridges, all of which appear on sandy beaches [Forbes and Taylor, 1994]. The depth of these forms does not usually exceed 0,5–1,0 m, and the length is typically <50 m. Most ice gouges are oriented transverse to the coastline. These forms, along with most of the ice squeezing forms, are usually preserved until the first considerable storm.

On maritime lowlands that can be flooded during high storm surges, sea ice can be brought inland as far as tens and even hundreds of meters, which causes surface scouring and infrastructure damage. In Baydaratskaya Bay, geodetic benchmarks give evidence of these processes. Most of the benchmarks lower than 2,5 m a.s.l. are bent near the base (Fig. 5*b*).

The thermal effects of sea ice are also important where the ice becomes bottomfast, allowing the formation of seasonally frozen ground and the preservation of relict permafrost beneath the seabed. These phenomena are widely recognized in the shallow areas of Baydaratskaya Bay [Sovershaev et al., 1988]. The presence of bottomfast ice in the nearshore and in open shallow areas induces the freezing of bottom sediment and the development of new permafrost areas. The development of bottomfast ice is preceded by the freeze-up of beaches and tide flats and the formation of an ice protective cover. In autumn, developing fast ice freezes to bottom sediments, starting just from the water edge and going on until the sea depth becomes equal to or greater than the ice thickness. This process results in the formation of subaqueous frozen grounds in the areas of freezing. These grounds often alternate with unfrozen grounds cooled below 0°C to –2°C. The permafrost underlying the sea floor gradually acquires specific subaqueous features, which are expressed through increased temperature, a higher proportion of unfrozen water, and increased salinity of this water. The nearshore profile reveals a "cap" from frozen-ground forms in the landfast ice contact zone and protruding into the sea (Fig. 6).

The chemical effect of sea ice on sea floor can be seen in near-coastal shallows and lagoons in the form of salt depletion in the fast ice during its formation. By the end of winter, when the ice reaches its maximum thickness, these areas become almost completely isolated from the sea and acquire their own salt and temperature regimes different from those in the open sea [cf. Grasby et al., 2013]. The salinity of water in these closed areas exceeds average values; therefore, the water temperature can fall below the freezing point of sea water, leading to the formation of the so-called cryopeg. Similar conditions favoring the cryopeg formation occur in the longshore troughs, when the thickening ice reaches

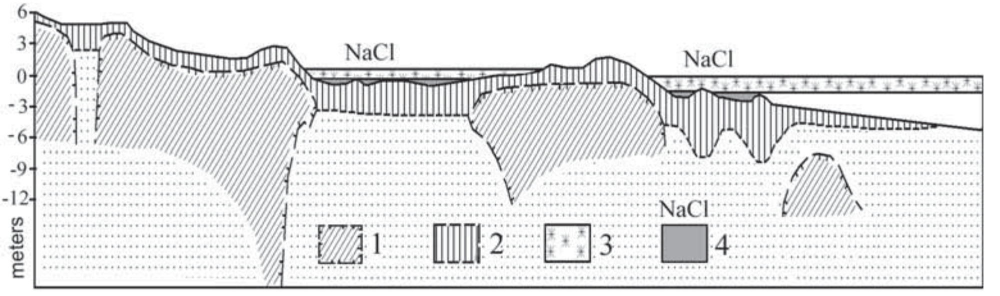


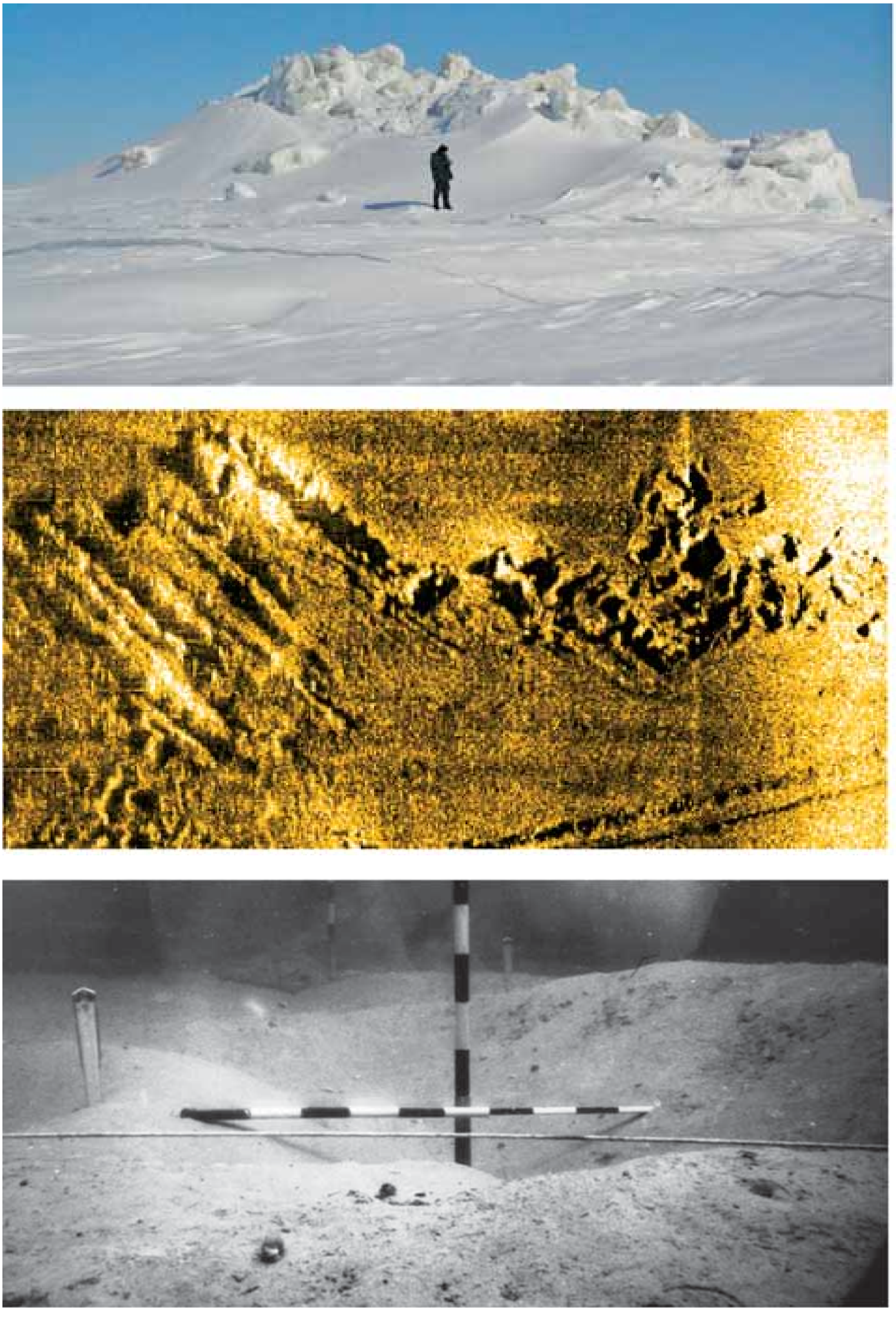
Fig. 6. Geocryological section of the Yamal coast of Baydaratskaya Bay, Kara Sea:
1 – permafrost, 2 – seasonally frozen layer, 3 – sea ice, 4 – cryopegs

the sea floor and freezes to longshore bars [Grigoriev, 1987]. In this case, the longshore troughs also become isolated from the sea. They get filled with high-salinity water which protects bottom ground from freezing.

The mechanical action of the ice on the sea bottom lasts from the onset of ice formation until the sea is completely free of ice. After young ice freezes to the seafloor in the nearshore zone, this new strip of ice serves as a protective buffer. The ridges of hummocks closest to the coast develop above submarine bars [cf. Forbes et al., 2002]. Because of a decreased sea depth above these bars, they become the focus of ridging and, thus the number of hummock ridges commonly corresponds to the number of submarine bars. Due to the onshore pushing impact of sea ice, ice gouges in this zone are mostly oriented normal to the coastline. The effect of the coastal hummock ridges and barriers on beaches and in shallow areas (down to a depth of 7–10 m) can be traced only immediately after fast ice is destroyed. The life expectancy of ice-gouged forms developed on sand beaches and shallow areas is very short, until the first summer storm. These forms, the depth of which is mainly <0.5 m, commonly disappear with the first strong waves in summer and autumn.

Further out in the bay, the pattern of hummocky pressure ridges is irregular and controlled by hydrodynamic factors, particularly the location of the fast ice edge during storms. Storm winds can destroy the fast ice edge and form a new ridge of hummocks or single grounded hummocks (Fig. 7*a*). The pattern of ice plowing in this case is either chaotic or parallel to the coastline. This is due to the prevailing along-shore drift of hummock formations. After the final onset of the fast ice the stamukhi remain non-mobile, often frozen down to the bottom. After their melting and wave destruction, small (up to 1 m deep) holes and shallow, relatively short ice gouges remain (Fig. 7*b, c*). Ice gouges in this area are oriented mostly either chaotically or normally to the coastline, which is enhanced by the pressure of ice from the seaward side. Due to high hydrodynamic activity here, the gouges are quickly smoothed, and the gouge density in shallow areas is lower than in the zone of the fast ice edge.

The fast ice edge (within Baydaratskaya Bay near the 10–15 m isobaths) is the zone where the ice impact on the sea floor is the strongest. Here, pressure ridges reaching the floor ("ice dam") develop throughout the winter (Fig. 8*a*). In this case, ice gouges form a so-called "comb", usually oriented normal to the coastline due to the pressure of ice from the open sea. In 2007, during sonar tracking from the research vessel *Ivan Petrov*, such a "comb" was observed with dimensions of approximately 70 m wide and 400 m long; it consisted of a system of parallel ice gouges up to 1,5 m deep (Fig. 8*b*). Ice gouges are well preserved at this depth. They can be partly smoothed during extreme storms only. At depths of 14–16 m (within Baydaratskaya Bay), the occurrence and density of ice gouges turns out to be lower than at greater depths, though ice gouging is the most intense (most of the mobile systems of hummocks and grounded hummocks are formed here). The above situation is due to more active hydrodynamics at shallow depths, where the wave effect still influences the bottom and the velocities of tidal currents are higher. Due to this, the gouges at depth can exist over several years – first decade years here (as distinct from their short existence in



a

b

c

Fig. 7. Grounded hummock (stamukhi) (photo by A.A.Ermolov) and its effect on the seabed

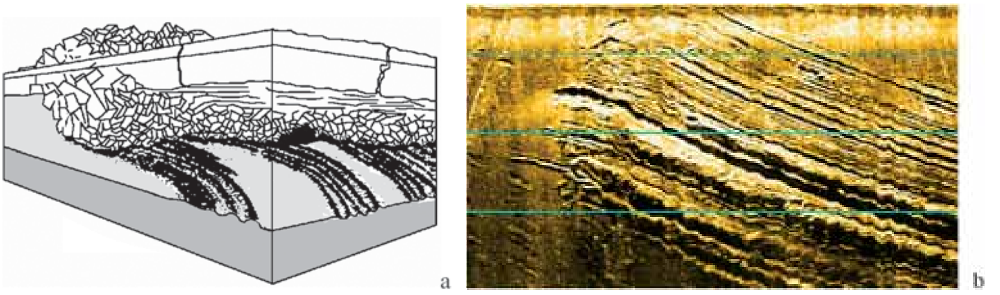


Fig. 8. Ice dam and its effect on the seabed

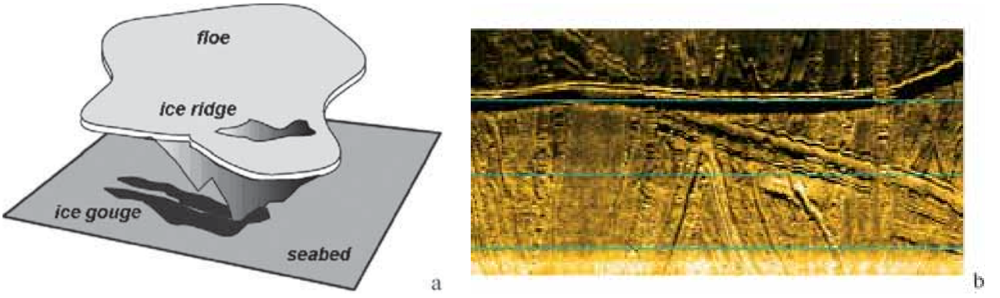


Fig. 9. Ice gouging by hummock frozen into the floe

shallow areas), gradually smoothing over and vanishing.

The most intensive and deep ice gouges occur in the area of drift ice at the range of depths from 16 to 19 m, next to the Yamal coast fast-ice rim, where ice hummocks is going on during the whole cold season and along which ice fields and hummocks, reaching the bottom frozen into them drift (Fig. 9a). Given the fact that the mass of the whole ice formation (floe and hummock) participates in the ice gouging, the deepest (up to 2 m), the widest (up to 50 m) and the longest (up to several km) ice gouges have been observed in this area (Fig. 9*b*). They are oriented conformably with tidal currents directions – lengthwise the Baydaratskaya Bay [Marchenko et al., 2007]. Due to the low hydrodynamic activity at these depths, unaffected by wave action, the rates of sedimentation are very low. As a result, ice gouges are well preserved on the sea bottom and are mostly superimposed. Sometimes they cover up to 100% of the sea bottom [Ogorodov, 2003]. Deeper than 19

Fig. 10. Iceberg at the pipeline route "Yamal–Europe", May 2007 (photo by A.M. Kamalov)

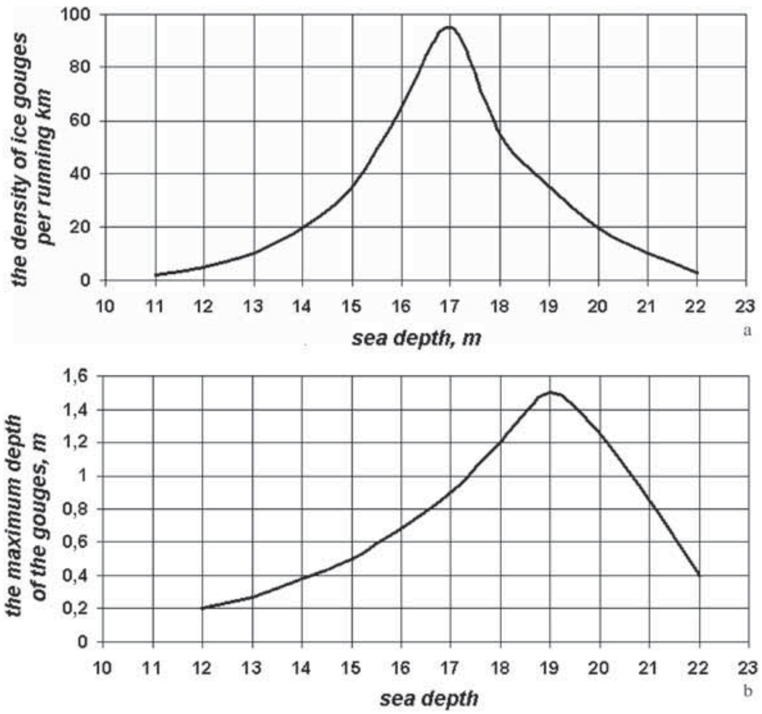


Fig. 11. The distribution of the density (*a*) and depth (*b*) of the ice gouges with sea depth

m, ice gouges occur rather frequently. However, ice formations rarely occur at these depths. This situation is caused by a low hydrodynamic activity and low sedimentation rates. Under such conditions, the gouges, especially large ones, can exist on the bottom surface for decades. Thus, a low intensity of ice gouging is compensated by the long life of gouge forms. This "accumulation" effect gives a false impression of a high intensity of ice gouging here.

At depths exceeding the maximum possible hummock thickness, 23–26 m in this area, bottom ice gouging stops. Ice gouges are rarely observed here. The hypothesis is that ice gouges at these depths are left by icebergs. Icebergs have been documented in Baydaratskaya Bay documented very rarely, including in 1932 and 2007 (Fig. 10). It is possible that the appearance of icebergs is connected to warm periods and occurs during the time of minimum ice cover of the water area.

Investigations on the Baydaratskaya Bay, Kara Sea show that the depth of ice gouges and the density of ice gouging forms reach their highest values at depths of 17–19 m (Fig. 11*a*, *b*). However, this does not denote that the intensity of ice gouging is lower in shallow depths with rarer occurrence and smaller depth of ice gouges. The main method of indirect estimation of ice gouging intensity is the estimation of ice gouges' density and depth. Meanwhile, the lifetime of such forms can essentially vary according to sea depth, type of the sediments and the duration of dynamically active period, so the question about sea ice gouging intensity of the coasts and bottom is directly connected with the problem of ice gouging forms' preservation [Ogorodov, 2011].

The depth of ice gouging forms depends not only on sea depth, ice thickness and intensity of sheer stress, but also on the composition and state of bottom deposits. The shape of ice gouging forms probably depends on plasticity, mobility and granulometric composition of the sediments as well. However, no simple correspondence was found between field data on the occurrence and density of gouges and the type of sediments, except in a very few cases. Observations shows that ice gouges, especially large ones, have considerable lengths, sometimes up to several kilometers, i.e. hummocks can constantly gouge the bottom for a long time due to their large kinetic energy. Therefore hummock can gouge bottom sections with rather different characteristics of the sediments.

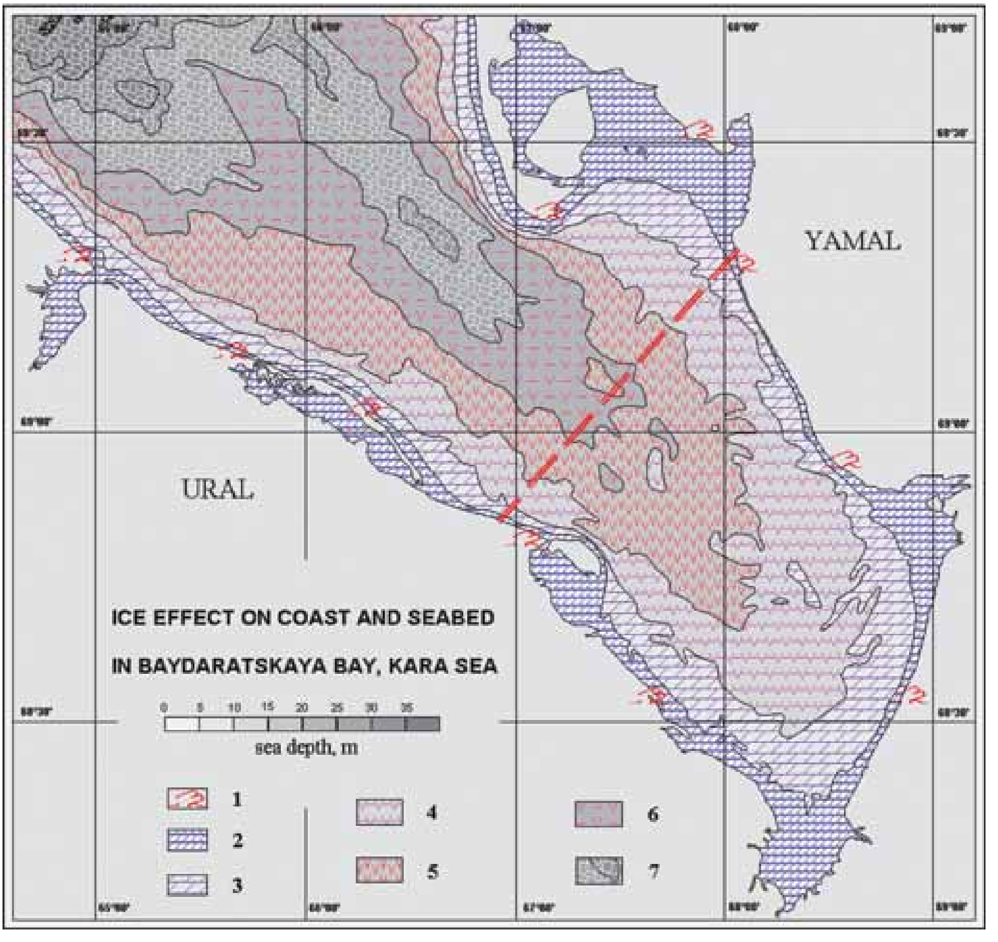


Fig. 12. Map of the arias with different intensity of the sea ice impact on the coasts and bottom of Baydaratskaya Bay, Kara Sea. Legend:

1 – sea ice overthrust on low coasts, beaches and foreshores area; 2 – area of development of stable fast ice "on the bottom" with sites where the ices freezes to the ground near the water edge, on underwater bars and shallow gulfs. Sea ice formations: hummocks ridges and stamukhi are situated on underwater coastal bars. The ice gouging is limited by the stableness and immobility of the fast ice; 3 – area of unstable "floating" fast ice. Ice hummocks ridges developed along the coast, "ice barriers" and separate stamukhi correspond to the periods of contraction due to pressure at the forming fast ice rim, reflecting the stages of its prorogation. Ice gouging intensity is medium; 4 – area of ice hummocks at the fast ice rim. High intensity of bottom ice gouging as a result of pressure-forced movements of the ice cover towards the land and the action of ice hummocks drifting along the fast ice rim; 5 – drifting ice area. The most intensive ice gouging is caused by the keels of the ice hummocks, frozen into the ice floe drifting with the tidal currents; 6 – drifting ice area. Formation of big ice gouges by the keels of heavy low-sitting hummocky formations frozen into the ice fields and remnants of icebergs drifting with tidal currents; 7 – area of drifting ice out of the zone of ice gouging impact. Keels of the ice formations mostly don't reach the bottom. The probability of ice gouging is low

Based on an integrated analysis of ice conditions, bathymetry and results of statistical processing of the ice gouges' frequency obtained as a result of expeditions in 2005–2012, a map-scheme "Sea ice impact on the coasts and bottom of the Baydaratskaya Bay, Kara Sea" has been developed (Fig. 12). Several zones, in which the mechanisms and the intensity of the ice impacts vary considerably, have been selected within the bay. The sea bottom experiences the strongest impacts at 15-20 m depth – the area of ice floes with hummock formations frozen into them, which drift with the help of tidal currents along the fast ice rim. Most parts of the underwater pipeline crossing "Yamal-Europe" are situated in this zone. Therefore it will be necessary to consider the ice factor while laying the 3rd and the 4th pipeline runs as well as to conduct constant monitoring of the already laid pipeline runs to establish the frequency and depth of bottom disturbance over them by ice formations. The buried pipeline and the covered trench where the pipelines have already been built are literally a "blank sheet of paper" and an ideal polygon for sea bottom ice scour monitoring.

CONCLUSIONS

Based on a detailed analysis of the sea ice impacts on the coasts and bottom of Baydaratskaya Bay, Kara Sea, and on the zoning of the pipeline crossing area, the following conclusions can be drawn:

- Coasts between 2 m above sea level and 26 m below sea level experience the influence of sea ice scour or gouging;
- For Baydaratskaya Bay ice gouges can be up to 2 m deep, 50 m wide, and several kilometers long;
- At the depths of more than 14 m for the Ural section and more than 12 m for the Yamal section, ice gouges are the most frequent bottom features, which infer that at these depths gouging is the main controlling factor of the bottom relief formation. For shallower depths, ice gouging relief is re-worked by wave processes;
- 80% of the observed gouges have a north-west – south-east orientation (or close to it), consistent with the general shape and alignment of Baydaratskaya Bay and the pattern of tidal currents;
- With increasing depth, the "life span" of the ice gouges also grows, such that they can be preserved for tens to hundreds of years; and for some of the areas 100% of the seabed is covered by these gouging artefacts;
- Taking into consideration the varying hydrodynamic activity and different "age" of the ice gouging forms, the intensity of the ice impacts can not be determined solely from the density or frequency of the ice gouges;
- The highest ice gouging intensity occurs along the winter rim of the landfast ice off the Yamal coast and in the adjacent drift-ice area;
- The underwater pipeline "Yamal-Europe" crossing is situated in the most dangerous area; this should be considered when projecting the burial depths for the pipes. Constant monitoring of the ice impacts on the bottom is also necessary.

ACKNOWLEDGEMENTS

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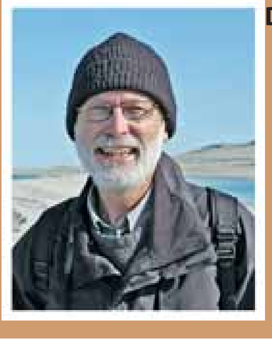

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RADIOCARBON CHRONOLOGY OF HOLOCENE PALSA OF BOL'SHEZEMEL'SKAYA TUNDRA IN RUSSIAN NORTH

ABSTRACT. Six palsa mire in Usa River valley and in Vorkuta area in North-eastern part of European Russia were studied in detail. In total 75 new ^{14}C dates from different palsa sections were obtained. In palsa mire near Bugry Settlement 3.2 m high palsa dated from 8.6 to 2.1 ka BP. The permafrost and palsa began 2.1 ka BP. In palsa mire near Usa Settlement low moor peat in 2 m high palsa dated 3690 BP, palsa began to heave at least 3700 BP. A low-moor peat of 2.5 m high palsa indicates the change in the hydrological-mineral regime during 7.1 to 6.3 ka BP, heaving commenced 6 ka BP. A number of 8 ^{14}C dates from 5.6 to 2.7 ka BP obtained from peat of 3 m high palsa. Near Abez' Settlement palsa development began about 2.8 ka BP. There are both large and smaller palsas. Low-moor peat of 3.5 m high palsa is dated between 9180 BP to 6730 BP near Nikita Settlement. In Vorkuta area near Khanovey Settlement the northern most palsa is found. The ^{14}C age of peat at slope of the palsa is much younger, than in an axial part, there is inversion of the dates: the date 3.5 ka BP is between dates 2.9 and 2.8 ka BP. It is probably caused by creep of peat downwards from a summit. This evidenced this frozen mound is real palsa, but not a residual form as a result of erosion.

KEY WORDS: palsa; permafrost; mires; North-Eastern Europe; radiocarbon.

INTRODUCTION

Palsas represent one of the most widespread forms of permafrost terrain. They are abundant in areas of discontinuous permafrost with mean annual temperatures close to the freezing point, although they are also sufficiently common in the zone of low-temperature continuous permafrost [Åhman, 1976; Seppälä, 1986; Pissart, 1983; Washburn, 1983; Vasil'chuk, 1983; Vasil'chuk, Vasil'chuk, 1998; Allard, Rousseau, 1999; Westin, Zuidhoff, 2001; Cyr, Payette, 2010; Seppälä, 2011; Christensen et al., 2012; Magnan et al., 2012; Farbrot et al., 2013]. It is normally assumed that palsas are relatively old (older than 4–5 ka BP), and are today generally subjected to degradation [Popov, 1967; Yevseev, 1976]. The aim of this paper is to determine the time of formation of palsa in different geocryologic environments in North-Eastern European

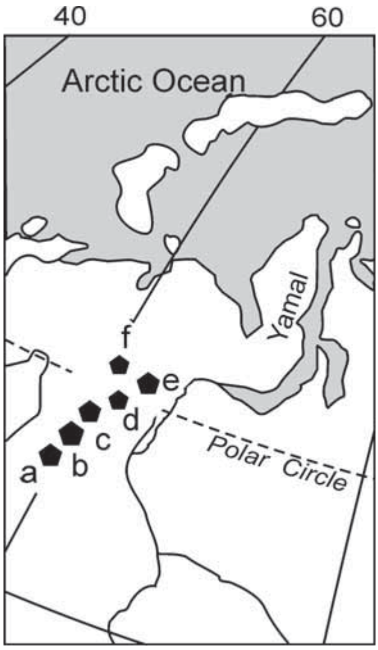

Fig. 1. Map of palsa localities mentioned in text:

Usa River valley: near Bugry (a), Usa (b), Abez' (c) Nikita (d), Eletskaya (e) Khanovey (f) settlements

part of Russia, north Usa River valley and in Vorkuta area (Fig. 1).

In these areas palsas of different configuration, height and age are widespread. Detailed dating of the peat covering the frost mound and plant macrofossil analysis allow to determine the initial stage of palsa growth and to separate the palsa peat on its low-moor (eutrophic) and high-moor-transitional (oligotrophic-mesotrophic) types. Hummocky peat bogs represent one of the most appropriate objects for radiocarbon dating. Autochthonous organic material is usually prevalent in such peat. There are virtually no age inversions in the radiocarbon dates obtained from the examined palsa shown in cross-sections excepting special case of Khanovey palsa.

METHODS

Taking into account that commonly palsa growth begin after accumulation of peat cover, we have concentrated the attention on detailed radiocarbon dating and detailed botanical and palynological study of the peat overlapping palsa. The whole palsa history such as its growth, stabilization and degradation, is recorded in the peat.

The radiocarbon dates were obtained in the Radiocarbon Laboratory of the Geological Institute (GIN) of the Russian Academy of Sciences and the Radiocarbon Laboratory at the University of Helsinki (Hel). Both dating laboratories have long experience in dating peat samples and are well aware of the problems involved.

In Dating Laboratory of Geological Institute RAS the alkaline extract from the peat was dated. ^{14}C is measured by the liquid scintillation counting technique using 8 two-channel beta-counting spectrophotometers. The benzene-production process, worked out by L.Sulezhitsky, differs from the more conventional method in that lithium carbide is produced by reacting the pretreated samples directly with lithium, rather than combusting the samples to CO_2 and reacting the CO_2 with lithium.

In the Helsinki Laboratory rootlets were first removed and the samples treated by a standard acid-alkali-acid. The fulvic and humus fractions are thus removed and the innermost part of the peat is dated.

For all samples measured in Helsinki $\delta^{13}C$ values were measured and the dates corrected accordingly. For the peat samples the mean $\delta^{13}C$ value is – 29.0 ‰ and the standard deviation 0.7‰. If this value can be applied also to the results from the Moscow laboratory the age correction for them would be about 30 years. The samples from the most representative cross-sections of palsa were dated in both laboratories simultaneously and independently. The scheme of dating was as follow: dates from one laboratory were located between the dates from the other laboratory. This provided high precision of the ^{14}C dates obtained and a test on the different methods used in the two laboratories.

RESULTS

Six palsa mires were studied in detail in Usa River valley and in Vorkuta area in North-eastern part of European Russia. In total 75 radiocarbon dates from different palsa sections were obtained (Table 1).

Palsa mires near Bugry Station. The southernmost large palsa mire (300 × 500 m) is located near Bugry Station (66°23´N, 61°24´E), 27 km S of the Abez' Settlement and 72 km N of Inta town at the 2070 km point of the railway line Moscow – Vorkuta. About 15 dome shaped palsas are found at the mire. The dimensions of the palsas range from 15 × 30 to 40 × 80 m, their height is 3 m or more (Fig. 2, *a*).

The cross-section of a 3.2 m high palsa was investigated (Fig. 3, *a*). The palsa has begun to destroy, two large present day deflation depressions are located on its periphery. Dwarf birch of 1 m height grow on its slopes, and *Spagnum* and *Ledum palustre* cover the central part. There are some grasses and sedges in inter mound depressions.

The sediment sequence is as follows from the top to the bottom of the palsa pit (Fig. 3, *a*):

0.0–0.05 m – Lichens cover
0.05–0.17 m – Brown, dense peat
0.17–0.35 m – Peat with leaves
0.35–0.45 m – Peat
0.45–0.5m – Frozen peat from the bottom of active layer
0.5–0.7 m – Frozen peat with loam and bark, with ice lenses.

Seven samples from the central part of the palsa were ^{14}C dated (Table 1). The results show that peat began to accumulate about 8.6 ka BP. Peat accumulation was continuous about 6.5 ka in non permafrost conditions because the peat consists of low moor, well decomposed wooden-sedge peat. Freezing and palsa growth began about 2.3–2.1 ka BP, the evidence is appearance of dwarf birch and *Sphagnum* mosses in the peat. Subsequently peat accumulation ceased at this palsa.

Palsa mire near Usa Settlement. In the lake-bog area in the vicinity of the Usa Settlement (66°31´N, 61°40´E) both high (up to 4 m high – Fig. 4, a) and small (less than 1 m – Fig. 4, b) palsas can be found. The larch-birch open woodland is located in the periphery of this area. Only in the central part of the lake-bog depression there are two palsas more then 1 m high. Two birches were growing at the slope of one of the palsas. In the 0.4 m thick peat section (Fig. 5, a) overlying a relatively young, 0.8 m high palsa the grass-hypnum low-moor peat occurring at a depth of 0.35-0.4 m can be referred to a subaqueous stage. This peat is dated to 2090 ± 40 BP (Table 2). The heaving process initiated probably at the time when accumulation of this basal peat layer already occurred. A second palsa studied is about 2 m high and 5 × 13 m in size (Fig. 5, *a*). Its peat section encloses a layer of grass low-moor peat with a fine-

Table 1. Radiocarbon dates of peat in palsa near Bugry Station, North-eastern part of European Russia, Usa River valley

Radiocarbon dates (BP)	Laboratory number	Field number	Depth, m	Material	Decom-position degree, %
2150 ± 30	GIN–11968	386-YuV/1	0.05–0.17	Peat dense brown, grass-wood	65
2310 ± 30	GIN–11969	386-YuV/2	0.2–0.3	Peat with leaves, wood (birch)	55
3460 ± 30	GIN–11970	386-YuV/3	0.3–0.35	Peat hypnum, low moor	60–65
4240 ± 30	GIN–11971	386-YuV/4	0.35–0.45	Peat, sedge-wood low moor	60
5040 ± 30	GIN–11972	386-YuV/5	0.45–0.5	Peat sedge-wood	50
6250 ± 30	GIN–11973	386-YuV/6	0.6–0.7	Peat frozen, grass-wood with loam and bark	55
8690 ± 50	GIN–11974	386-YuV/7	0.7–0.8	Peat, grass low moor	45

Fig. 2. Palsa mire near (A) Bugry and (B) Abez' settlements, Usa River valley

grained sand admixture located at a depth of 0.4 m. The peat includes remains of birch (bark of *Betula*, 5%), cotton grass (*Eriophorum)*, horsetail (*Equisetum*, 10%), sedge (*Carex rostrata*, 1%), buckbean (*Menyanthes trifoliata*, 50%), grasses and hypnaceous mosses. This peat layer is dated to 3690 ± ± 50 BP, which corresponds most likely to the subaqueous stage. Consequently the palsa began to heave around 3700 BP.

The third palsa studied in this area is 2.5 m high and 8 × 8 m in size (Fig. 5, *a*). The palsa section demonstrates upward replacement of a sedge peat composed of *Menyanthes trifoliata, Carex chordarrhiza, C. caespitosa,* and hypnaceous moss *Polytrichum strictum* by a peat largely consisting of buckbean (*Menyanthes trifoliata)* accompanied by *Carex chordarrhiza* and *Equisetum*.

Although both these peat layers are referred to as low-moor type, the replacement of sedge peat by buckbean peat indicates initiation of the change in the hydrological-mineral regime during the time interval 7.1 to 6.3 ka BP

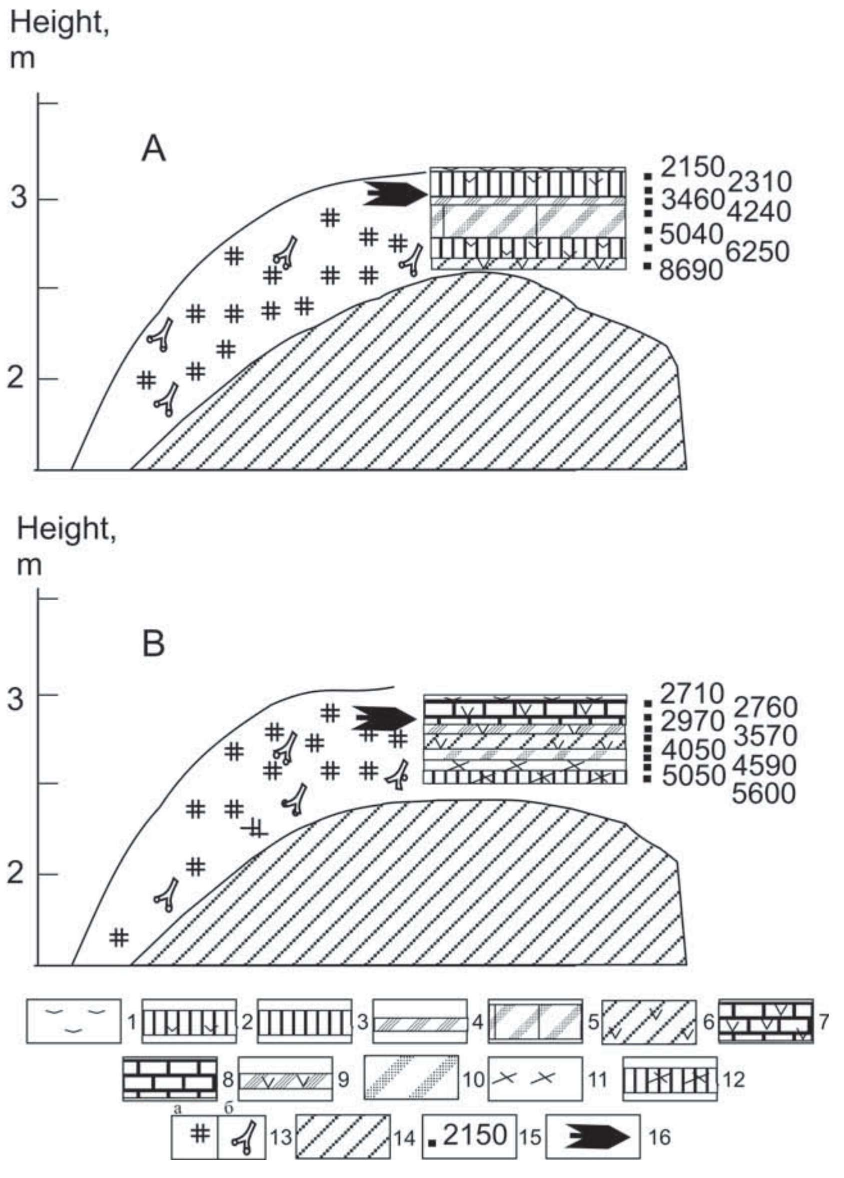

Fig. 3. Radiocarbon dated palsas near (A) Bugry and (B) Abez' settlements, in Usa River valley:

1 – moss, lichen cover; 2 – peat, grass-wood; 3 – peat wood; 4 – peat, hypnum low moor; 5 – peat sedge-wood; 6 – peat, grass low moor; 7 – peat, grass-moss; 8 – peat moss; 9 – peat grass-hypnum, low moor; 10 – peat, sedge low moor; 11 – peat, Equisetum; 12 – peat, wood-equisetum; 13 – peat (a) and wood remains (b); 14 – loam; 15 – ^{14}C dates (years); 16 – assumed starting point of palsa formation

(the dates 7140 ± 40 BP, 6320 ± 40 BP) and suggests that freezing and heaving commenced 6 ka BP or later. The fourth palsa studied is about 4 m high and 7 × 8 m in size (Fig. 5, *a*).

Transition from a subaqueous to a subaerial stage is distinguishable at a depth of 0.8 m. This stratum is marked by the replacement of predominant *Equisetum* and *Menyanthes trifoliata* remains by wood remains of birch and frutescent forms (*Vaccinium*) characterizing oligotrophic environments and dating back to 650 ± 50 BP. The palsa surface commenced to heave in the period bet-

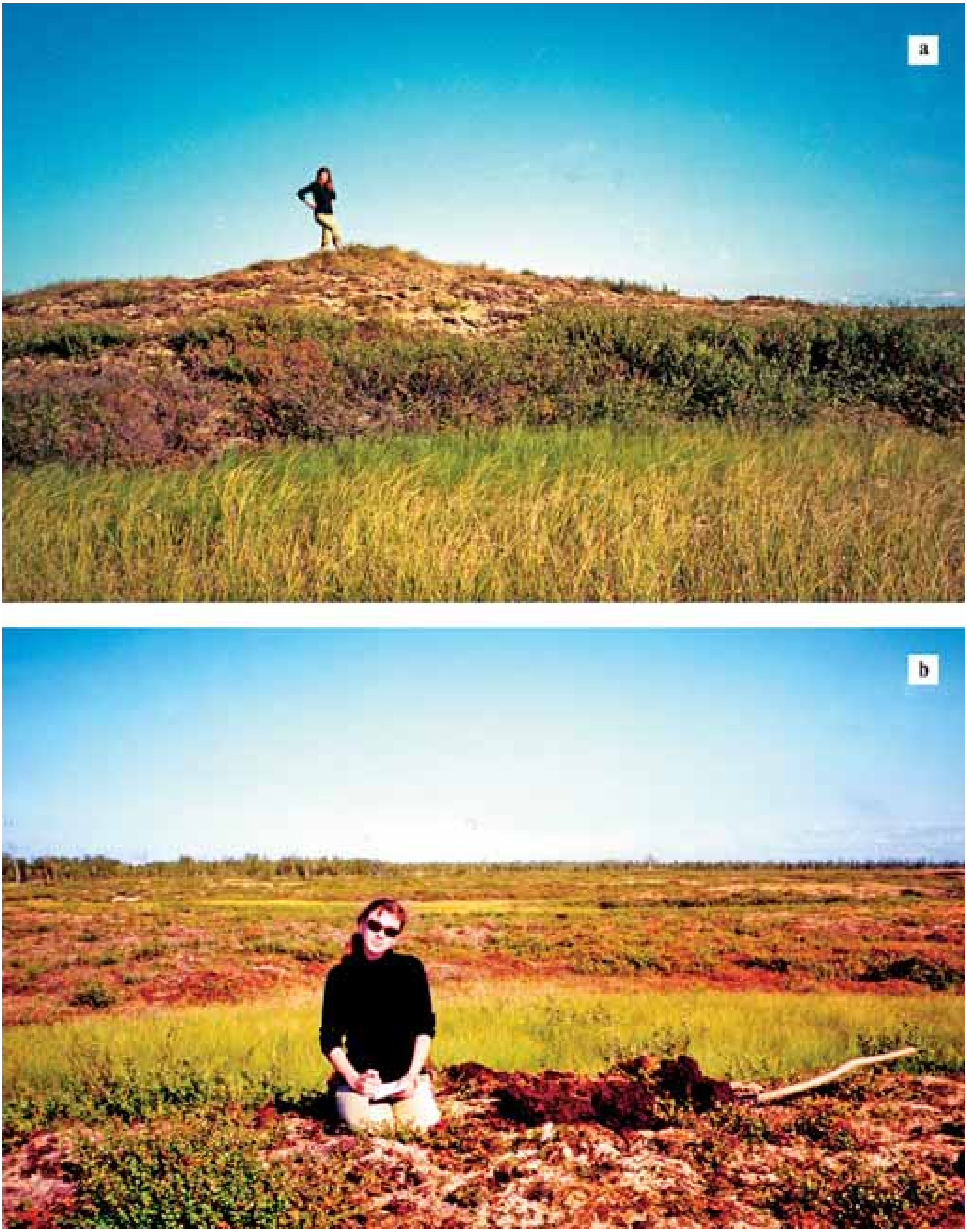

Fig. 4. Palsa mire near Usa settlement:

high (a) and small (b) palsa, Usa River valley

ween 6.5 and 6.0 ka BP. This process was accompanied by the change of buckbean low-moor peat to peat containing woody remains of pine, willow and birch. The accumulation rate of the peat during the subaqueous stage was high, averaging 0.6 m/ka, whereas that in the subaerial stage was less than 0.1 m/ka.

Palsa mire near Abez' Settlement. The site is situated 1.2 km N of the Abez' Settlement (66°31´N, 61°46´E), 100 m N of railway line, at 2098 km point of railway line Moscow – Vorkuta. A large palsa mire with separate trees is located in the wood. Both high (up to 4 m – Fig. 2, b) and small (less than 1 m) palsas of different age can be found here.

Table 2. Radiocarbon dates of peat in palsas near Usa Settlement, North-eastern part of European Russia, Usa River valley

Radiocarbon dates (BP)	Laboratory number	Field number	Depth, m	Material	Decomposition degree, %	$\delta^{13}C$, ‰
Palsa, height 0.8 m						
140 ± 40	GIN-10976	383-YuV/2	0.1	Hypnum peat,	5	
780 ± 40	GIN-10977	383-YuV/3	0.25	Wooden-sedge peat	75	
1890 ± 80	Hel-4499	383-YuV/4	0.3–0.35	Grass-hypnum brown peat with wood remains	60	–28.9
2090 ± 40	GIN-10978	383-YuV/5	0.4	Grass-hypnum peat	50–55	
Palsa, height 2.0 m						
3690 ± 50	GIN-10979	383-YuV/11	0.4	Grass low moor peat	65	
Palsa, height 2.5 m						
6320 ± 40	GIN-10981	383-YuV/14	0.25	Buckbean low moor peat	55	
7140 ± 40	GIN-10980	383-YuV/13	0.5	Sedge low moor peat	85	
Palsa, height 4 m						
5230 ± 40	GIN-10982	383-YuV/15	0.3	Wooden peat	75	
6490 ± 110	Hel-4507	383-YuV/16	0.6–0.7	Wooden peat	55	–29.5
6650 ± 50	GIN-10983	383-YuV/18	0.8	Buckbean, low moor peat	60	

Spots of naked peat are found on the surface of large palsas. Initial palsas are also found on inundated bog surface (Fig. 3, b). Their size is from 1 × 1 m to 3 × 5 m, their height is not more than 0.5 m. These palsas are often surrounded by a ring-like depression and platen. The pit of a large 3.0 m high palsa was investigated (Fig. 2, b). Its size is 20 × 40 m. There is no vegetation on the palsa surface. Lateral erosion destroyed the palsa. The following sediment sequence was observed from the top to the bottom of the palsa pit:

0.0–0.3 m – Dry brownish-red peat
0.3–0.5 m – Wooden peat with twigs
0.5–0.6 m – Dense peat with black vegetation remains
0.6–0.75 m – Dark brown peat with dark spots, pine and birch bark and shrub twigs
0.75–0.85 m – Loamy peat with wood
0.85–0.95 m–Frozen gray sandy loam.

Eight samples from the central part of the palsa have been ^{14}C dated (Table 3). From the results it can be established that the peat began to accumulate about 8.6 ka BP. Peat accumulation was continuous about 5.6 ka during eutrophic conditions. Low moor horse tail peat changed to low moor sedge peat and further to grass peat with sequence remains of wood. Freezing and palsa growth began about 2.8 ka BP. This is fixed in the pit with slightly decomposed moss and grass-moss peat with remains of grasses, *Comarum palustre* and *Scheuchzeria palustris*. Earlier two ^{14}C dates have been obtained from the bottom of the palsas in vicinity of Abez' (5600 ± 70 and 6250 ± 70 BP, MSU-429) [Evseev, 1986].

Comparison of pollen diagrams from palsa and the inter mound depression demonstrate that there are similarities in the pollen spectra from the lower part of depression and from the palsa. The pollen spectra from the palsa reflects that forest tundra was replaced with birch-spruce open woodland. Pollen spectra of spruce wood are found only in the upper part of the pollen diagram from the depression. This indicate that heaving began at the spruce wood stage.

Palsa mire near Nikita Settlement. In the Nikita Settlement area (67°02´N, 63°48´E) there are

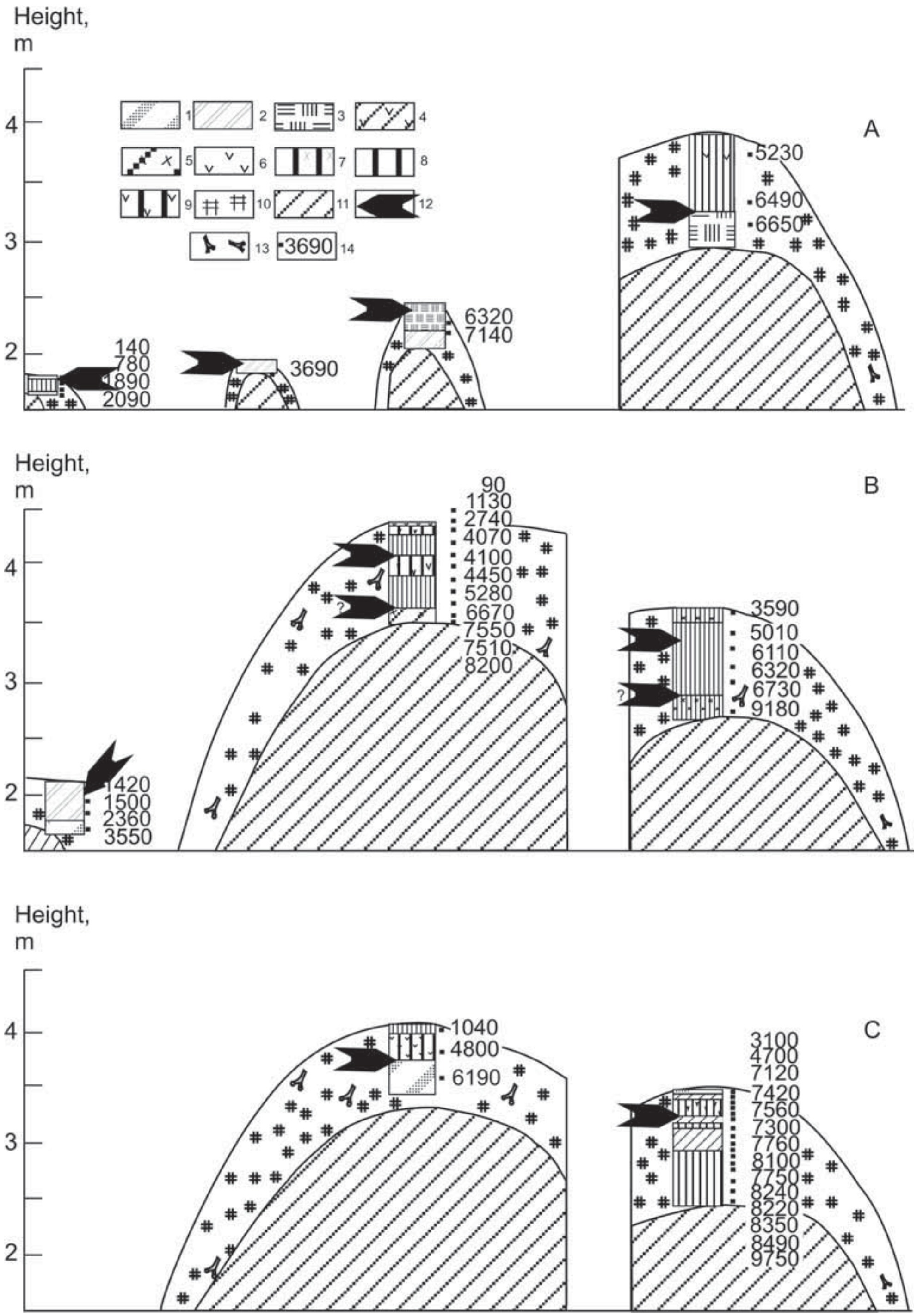

Fig. 5. Radiocarbon dated palsas near (A) Usa, (B) Nikita and (C) Eletskaya settlements, in Usa River valley:

1 – peat, sedge, low-moor; 2 – peat, sedge-hypnum; 3 – peat, buckbean, low-moor; 4 – peat, grass, low-moor; 5 – peat, equisetum, low-moor; 6 – peat, high-moor; 7 – peat, wood–equisetum; 8 – peat wood; 9 – peat, grass-wood; 10 – peat; 11 – loam; 12 – assumed starting point of palsa formation; 13 – wood; 14 – ^{14}C dates (years)

Table 3. Radiocarbon dates of peat in palsa near Abez' Settlement, North-eastern part of European Russia, Usa River valley

Radio-carbon dates (BP)	Laboratory number	Field number	Depth, m	Material	Decom-position degree, %
2710 ± 40	GIN-11960	385-YuV/17	0.0–0.1	Peat, moss-grass	10
2760 ± 40	GIN-11961	385-YuV/18	0.1–0.2	Peat, moss	15
2970 ± 30	GIN-11962	385-YuV/19	0.2–0.3	Peat, hypnum-grass, low moor	30
3570 ± 30	GIN-11963	385-YuV/20	0.3–0.35	Peat, grass-wood, with leaves, twig and bark of birch, pine and willow	25
4050 ± 30	GIN-11964	385-YuV/21	0.45–0.5	Peat, grass with twigs and bark of birch, pine and spruce	20
4590 ± 30	GIN-11965	385-YuV/22	0.55–0.6	Peat, sedge, low moor	25
5050 ± 40	GIN-11966	385-YuV/23	0.65–0.75	Peat, horstail low moor peat, with twig and bark of birch, pine	35
5600 ± 40	GIN-11967	385-YuV/24	0.75–0.85	Peat, horstail-wood with loam and bark of birch, pine, at 0.85 m – loam	45

Fig. 6. Palsa mire near (*a*) Nikita and (*b*) Eletskaya settlements, Usa River valley

both large (up to 5 and, even 8 m high) and smaller (up to 1.5–2.0 m high) palsas. The first palsa (4.7 m high) studied in this area is situated north of the Nikita railway station (Fig. 6, *a*). The total thickness of the peat overlying this palsa is 0.8 m. Its section demonstrates transition from peat that formed in an environment of a bog covered by arboreal-horstail vegetation (depth interval of 0.8–0.65 m, dated at 8.2–6.7 ka BP – Fig. 5, b) to peat with high content of wood remains at a depth of 0.65 m. At the beginning of the heaving process, the palsa surface was populated, along with arboreal forms, by sedges (*Carex caespitosa, C. chordorrhiza, and C. diandra)* and horsetails; the latter occur currently here in depressions located between palsas and resembling eutrophic swamps.

Consequently, 0.65 m of mainly woody peat accumulated during the subaerial stage. The rate of the palsa growth during the initial phase was sufficiently high and could reach the value of approximately 0.4 m/kyr. Subsequently, it decreased to about less than 0.1 m/kyr. The peat located at a depth of 0.25–0.35 m contains remains of buckbean (*Menyanthes trifoliata)*, sedges (*Carex chordorrhiza, C. diandra*), and horsetail

Table 4. Radiocarbon dates of peat in palsas near Nikita Settlement, North-eastern part of European Russia, Usa River valley

Radio-carbon dates (BP)	Laboratory number	Field number	Depth, m	Material	Decom-position degree, %	$\delta^{13}C$, ‰
Palsa, height 4.7 m						
90 ± 70	Hel-4500	380-YuV/1	0–0.03	Peat with lichens	<5	–28.0
1130 ± 40	GIN-10621	380-YuV/2	0.03–0.1	Wood –hypnacum peat	80	
2740 ± 40	GIN-10622	380-YuV/3	0.1–0.15	Wooden peat	65–70	
4070 ± 90	Hel-4501	380-YuV/4	0.15--0.2	Wooden peat	55	–29.4
4100 ± 40	GIN-10623	380-YuV/5	0.2–0.25	Wood-grass peat	60	
4450 ± 40	GIN-10624	380-YuV/6	0.25–0.35	Wood-grass peat with birch remains	70	
5280 ± 100	Hel-4502	380-YuV/7	0.35–0.45	Wooden peat	60	–29.4
4890 ± 40	GIN-10628	380-YuV/11	0.5	Birch		
6670 ± 40	GIN-10625	380-YuV/8	0.45–0.55	Wooden peat, 65%		
7550 ± 50	GIN-10626	380-YuV/9	0.55–0.65	Wooden peat -sedge	75	
7510 ± 60	GIN-10627	380-YuV/10	0.65–0.75	Horstail low moor peat	65–70	
8200 ± 130	Hel-4512	380-YuV/21	0.75	Horstail low moor peat, with ice lenses	55	–29.0
Palsa, height 3.5 m						
3590 ± 90	Hel-4503	380-YuV/12	0.12–0.2	Brown peat with frutescent remains	60	–28.6
5010 ± 90	Hel-4508	380-YuV/13	0.2–0.3	Wood-horstail peat	45–50	–27.9
6110 ± 110	Hel-4509	380-YuV/14	0.4	Wood		–25.5
6320 ± 90	Hel-4511	380-YuV/20	0.4-–0.5	Remains of large shrubs		–25.4
6730 ± 100	Hel-4510	380-YuV/15	0.55–0.6	Wooden peat	45–50	–29.9
9180 ± 100	Hel-4504	380-YuV/16	0.8	Wood-horstail peat	40–45	–28.6
Palsa, height 0.7 m						
1420 ± 120	GIN-10629	380-YuV/22	0.1–0.15	Hypnum-sedge peat	5–10	
1500 ± 40	GIN-10630	380-YuV/23	0.2–0.25	Hypnum-sedge peat	60–65	
2360 ± 90	Hel-4513	380-YuV/24	0.3–0.35	Brown hypnum-sedge peat	35	–28.9
3550 ± 40	GIN-10631	380-YuV/25	0.5–0.55	Sedge low moor peat	35	

(*Equisetum*), which suggests partial thawing and subsidence of the palsa that occurred about 4.5 ka BP. Later, the palsa was restored and grew to its modern height. The second 3.5 m high palsa is situated approximately 1.5 km south of the Nikita Settlement.

The black-coloured wood-equisetum at the near-bottom peat with *Betula* remains at the base of section corresponds to a subaqueous stage of peat growth. This stage is dated to between 9180 ± 100 BP to 6730 ± 100 BP (Fig. 5, *b*) and is marked by accumulation of low-moor peat and disappearance of arboreal vegetation due to swamping of this previously dry area. The palsa formation took place about 6.7 ka BP. Judging from the occurrence of horsetail remains in the peat, the partial thawing of the palsa took place approximately 5 ka BP. The third palsa is small, 0.7 m high (Fig. 5, b). The botanical composition of the peat cover allows recognition of the layer that corresponds to the stage of palsa surface oscillation relative to the bog surface and is marked by the replacement of low-moor sedge peat by the sedge-hypnum variety with occurrence of buckbean and grass in the depth interval 0.55–0.35 m and dated to 2.36–3.35 ka BP (Table 4). This palsa was quite unstable also during the period 2.3 to 1.4 ka BP (according to dates 2360 ± 90 BP and 1420 ± 120 BP).

Palsa mire near Eletskaya Settlement. A palsa mire is located 1.5 km to the north-east of the Eletskaya Settlement (67°16′N, 63°39′E). The first palsa, 4 m high and 6 × 7 m in size (Fig. 6, *b*), is overlain by a 1.15 m thick layer of peat. The commencement of heaving and termination of the subaqueous stage is observed at a depth of 0.3 m. This level is dated to 4.8 ka BP (Fig. 5, c; Table 5). The subsequent

Table 5. Radiocarbon dates of peat in palsas near Yeletskaya Settlement, North-eastern part of European Russia, Usa River valley

Radiocarbon dates (BP)	Laboratory number	Field number	Depth, m	Material	Decomposition degree, %	$\delta^{13}C$, ‰
Palsa, height 4 m						
1040 ± 50	GIN-10968	382-YuV/17	0.15	Peat with frutescent remains	20	
4800 ± 50	GIN-10969	382-YuV/18	0.3	Wood-sedge peat	60	
6190 ± 40	GIN-10970	382-YuV/19	0.6	Sedge peat	25–30	
Palsa, height 3.5 m						
3100 ± 40	GIN-10971	382-YuV/1	0.05	Sedge peat	80	
4700 ± 50	GIN-10972	382-YuV/2	0.1	Grass-sedge peat	65	
7120 ± 100	Hel-4518	382-YuV/3	0.1–0.15	Brown wood-grass peat with twigs	65	–28.9
7420 ± 110	Hel-4519	382-YuV/4	0.15–0.2	Wood-sphagnum peat	65–70	–28.1
7560 ± 90	Hel-4520	382-YuV/5	0.2–0.25	Grass-hypnum peat with wood remains	30–35	–28.4
7300 ± 40	GIN-10973	382-YuV/6	0.3	Grass-hypnum peat	60	
7760 ± 110	Hel-4527	382-YuV/7	0.35–0.45	Hypnum peat	30	–29.3
8100 ± 90	Hel-4528	382-YuV/8	0.45–0.5	Wooden peat	30	–29.5
7750 ± 40	GIN-10974	382-YuV/9	0.6	Grass, low moor peat	45	
8240 ± 90	Hel-4529	382-YuV/10	0.65–0.75	Wooden peat	40	–30.2
8220 ± 110	Hel-4521	382-YuV/11	0.75–0.8	Wooden peat	60–65	–29.6
8350 ± 110	Hel-4505	382-YuV/12	0.8–0.82	Frozen peat		–27.9
8490 ± 70	GIN-10975	382-YuV/13	0.9	Wooden peat with sand	75	
9750 ± 160	Hel-4506	382-YuV/14	1.15	Peat with ice lens		–29.3

subaerial stage lasted less than 5000 yrs and peat with *Vaccinium sp*., *Chamaedaphne calyculata* and *Carex vesicaria* accumulated with the average rate of 0.06 m/kyr. The botanical composition of a 0.9 m thick peat layer overlying a 3.5 m high palsa indicates that its surface was first covered by arboreal vegetation (*Betula sect. Albae*) and was then flooded. In the interval 0.25 to 1.15 m peat of the subaqueous stage is marking the stage of low-moor bog. As a result of subaqueous development, arboreal vegetation was replaced by a low-moor herbaceous one dominated by *Menyanthes trifoliata, Carex diandra, C. chordorrhiza*. This stage is dated to 9.7 to 7.56 ka BP (Fig. 5, c). The palsa summit shows also the presence of low-moor sedge peat, which might suggest partial thawing during the period of about 4.7 to 3.1 ka BP (according to dates 3100 ± 40 BP and 4700 ± 50 BP from low moor peat).

Palsa near Khanovey Settlement. A single palsa 20 × 40 m and 3 m high (Fig. 7) was found in 2 km S of the Khanovey Settlement, 25 km S-W of the Vorkuta town, at the 2233 km point of railway line Moscow – Vorkuta. There is naked peat on it summit, as indicator of initial destruction. Typical high moor vegetation covers the palsa (*Ledum palustre, Oxycoccus* sp., et al.)

The following sediment sequence was observed from the top to the bottom of the palsa:

0.0–0.03 m – Dry moss cover
0.03–0.08 m – Dark brown peat with rootlets
0.08–0.2 m – Dark brown wet peat
0.2–0.3 m – Brown peat
0.3–0.7 m – Dark brown frozen peat
0.75–0.8 m – Light brown peat with remains of aquatic plants
0.8–0.85 m – Brown icy peat.
The pit on the palsa slope has following sequence of sediments:
0.0–0.07 m – Dry moss cover
0.07–0.2 m – Dark brown peat with rootlets
0.2 m–0.3 m – Frozen dark brown peat with rootlets
From 0.3 m – Frozen grayish loam.
The pit at the basis of palsa has following sequence of sediments:
0.0–0.15 m – Black peat with rootlets from 0.15 m – Frozen grayish-brown loam.

Six samples from the center of the palsa were ^{14}C dated (Fig. 8). The results indicate that the peat began to accumulate about 8.8 ka BP (Table 6).

Fig. 7. Palsa mire near Khanovey settlement, Vorkuta area

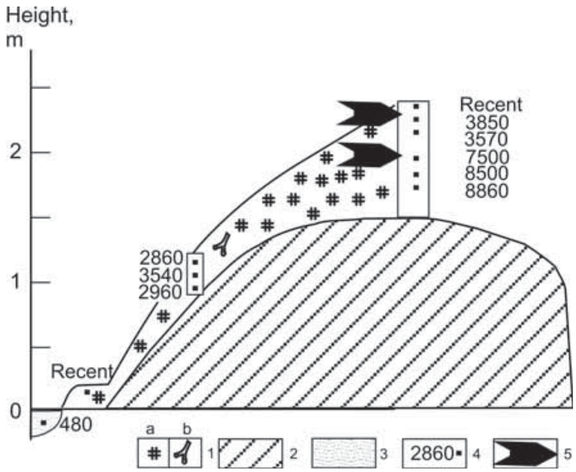

Fig. 8. Radiocarbon dated palsa of Northeast Europe, Vorkuta area, near Khanovey settlement:

1 – peat (a) and wood remains (b); 2 – loam; 3 – pond near palsa, water; 4 – ^{14}C dates (years); 5 – assumed starting point of palsa formation

Peat accumulation was continuous about 1.3 ka at eutrophic conditions. Low moor light brown peat with remains of aquatic plants accumulated at that time. Then from 7.5 to 3.5 ka BP peat accumulation ceased because the mire was frozen and palsa formed. A short resumption of peat accumulation took place about 3.5 ka BP. ^{14}C dating of 3 samples from a pit at the slope of the palsa show that the peat at that point is younger than peat in the central part of the palsa. The thickness of the peat layer is not more than 0.25 m and the dates are about 2.9–2.8 ka BP. There is also an inversion of dates such that a

Table 6. Radiocarbon dates of peat in palsa near Khanovey Settlement, North-eastern part of European Russia, Vorkuta area

Radiocarbon dates (BP)	Laboratory number	Field number	Depth, m	Material
Pit at the top of the palsa, height 2.5 m				
Recent	GIN-12072	393-YuV/1	0.0–0.05	Peat
3850 ± 40	GIN-12073	393-YuV/3	0.1–0.2	Peat
3570 ± 40	GIN-12074	393-YuV/4	0.2–0.3	Peat
7500 ± 40	GIN-12075	393-YuV/7	0.4–0.5	Peat, frozen
8500 ± 60	GIN-12076	393-YuV/10	0.6–0.65	Peat, frozen, dark brown
8860 ± 40	GIN-12077	393-YuV/20	0.65–0.7	Peat, frozen, light brown with aquatic plants remains
Pit at the slope of the palsa				
2860 ± 30	GIN-12078	393-YuV/11	0.07–0.15	Peat dark brown with rootlets
3540 ± 40	GIN-12079	393-YuV/12	0.15–0.2	Peat dark brown
2960 ± 40	GIN-12080	393-YuV/13	0.2–0.25	Peat frozen brown at the contact of loam
Pit at the basement of the palsa				
Recent	GIN-12081	393-YuV/14	0.05–0.15	Peat, black with rootlets
Pit in inundated depression near the palsa basement				
480 ± 50	GIN-12082	393-YuV/17	0.2	Hummock

date of 3.5 ka BP is located between the two dates of 2.9 and 2.8 ka BP. Date inversions are rare for the palsas in this area. This inversion is caused by peat moving down the slope. The youngest dates, 480 BP and a recent one, were obtained from peat at the basement of the palsa and in an inundated depression around the palsa. This is the first case with such a distribution of ^{14}C dates. The old ^{14}C dates are obtained from peat in the central part of the palsa and younger dates are from peat at the slope. This evidences that this palsa is a result of frost heaving but has not been flattened by erosion [e.g. P'yavchenko, 1955].

The initial heaving took place around 7.5 ka BP and a secondary heaving from 3.5 to 2.8 ka BP. In the surrounding depression peat accumulated up to 2.8 ka BP. As a result a 3 m high palsa more than 45 m in diameter had been formed.

DISCUSSION

Initial point of palsa formation. The initiation of palsa formation as a topographical structure can best be evaluated from the radiocarbon age of peat formed at the period when the palsa surface appears above the water table of a surrounding bog (more exactly, the surface of seasonal thawed layer at the top of a palsa). In different zones the starting point of palsa formation appears to be very similar. The rate of palsa growth during the initial phase is sufficiently high, but after heaving peat accumulation slows down and finally ceases.

Dynamics of palsa development in the Holocene. It is assumed that the Holocene optimum covering about two thirds of the first half of Holocene was period of general permafrost degradation and the decay of most of palsa. But the research of the authors of this article showed that it is not absolutely true.

H. Seppa with colleagues [Välliranta et al., 2010, Salonen et al., 2011] studied the changes in the wood vegetation during Holocene at palsa massifs in Bolshezemelskaya tundra, Pechora River basin. They assume that the expansion of the natural areas of wood vegetation (spruce, birch) occurred at this region (currently located at the timberline and outside it) during the Holocene optimum. The vegetation grew here as isolated rare forests since the beginning of the Holocene [Välliranta et al. 2010]. During the Holocene optimum which was defined here between 8.0 and 3.5 ka BP the summer mean temperature in tundra was 3°C higher than the nowadays [Salonen et al., 2011]. Spruce forests were growing at that time around the Khariney Lake located 150 km to the north from the modern timberline. The temperature decreased about 3.5–2.5 ka BP that led to an active aggradation of permafrost and intensive palsa growth as well as wood vegetation extinction. The most ancient remains of the vegetation dated about 2.5 ka [Salonen et al., 2011].

T. Jaworski and W. Niewiarowski [2012] studied late Holocene palsa formed within a network of ice-wedge polygons on Hermansenøya, NW Svalbard. They occur in the part of the peat bog that is always better drained than other parts of the bog. The height of palsa vary from 0.2 to 1.3 m, the thickness of the peat cover reaches 32–37 cm, but the total thickness of the peat in the examined mound reaches about 50 cm, while on the peat bog it is 25–40 cm. The radiocarbon dates of the peat suggested that a low (0.4–0.5 m) frost peat mound was formed during the considerable climate cooling in the period around 3.0–2.5 ka BP. Its formation and survival until today correspond to the formation and survival of pingos and ice wedges in Adventdalen (central Spitsbergen) and of the oldest palsas in northern Finland and on the Kola Peninsula [Jaworski, Niewiarowski, 2012].

According to J. McLaughlin and K. Webster [2013] palsa of Hudson Bay Lowlands – the largest peatland complex with the southernmost distribution of non-alpine permafrost in North America – started to grow primarily during the Little Ice Age when permafrost aggradation occurred in this region. Peat accumulation began much ealier: the 14C dates of bottom peat of palsa vary from 6.9 to 4.6 ka yr [McLaughlin, Webster, 2013].

The radiocarbon dating carried out by the authors allowed to define the beginning of heaving and the dynamics of palsa in the Holocene at the areas near the Bugry Station and Usa, Abez, Nikita, Eletskiy and Khanovey settlements. Calculations show that the heave processes within the areas are caused both by general climatic changes and local factors. Peat accumulation rate, periods of heaving and the duration of the subaerial and the subaquatic phases can be different within the same massif. Nonetheless, the stages of the intensification and relative fading of heave processes can be identified based on a large data. Permafrost did not degrade and, on contrary, the formation of new palsa could begin during the Holocene optimum even within the southern part of the permafrost area. Intensive peat accumulation as a result of high summer temperatures and the same winter severity (locally more severe than present) during the Holocene optimum was the main factor of this phenomenon that at first glance can seem a geocryological antinomy. Let us describe the dynamics of the studied palsa in more detail.

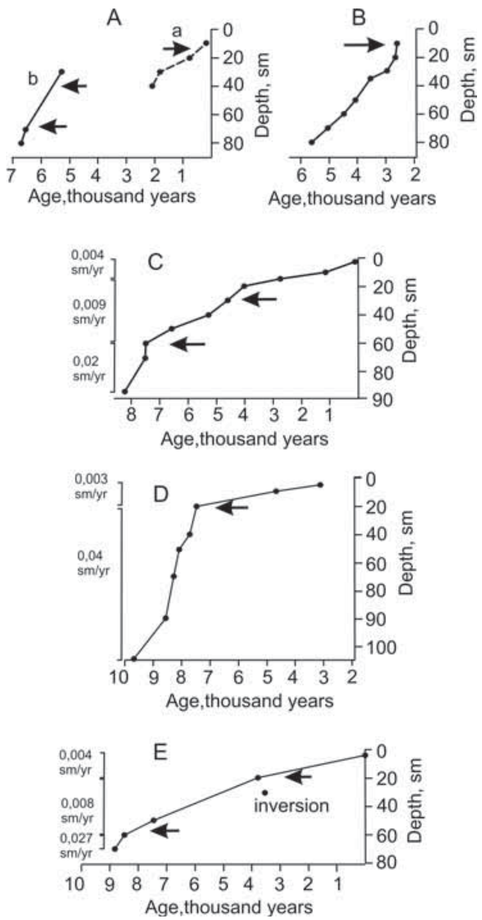

Fig. 9. Assumed heave events (shown with arrows) and the rate of peat accumulation in palsa of Bolshezemelskaya tundra:

A – Usa settlement, B – Abez settlement, C – Nikita settlement, D – Eletskiy settlement, E – Khanovey settlement

Bugry Station. It was found that at the initial stage the growth of a minor palsa 0.8 m high near the Bugry station repeatedly ceased. It was evidently formed during the recent century, since the age of the sample from 0.1 m depth and that of the sedge-hypnum peat from the surface is approximately 140 years (Fig. 9A). The formation of another palsa about 2 m high started not earlier than 3.7 ka BP. Since sedge-hypnum peat beds at the surface, it can be assumed that the heaving process was quite fast. This is associated with the fact that the high-bog peat did not have enough time to form. Since there is no lichenous cover on palsa, it can be assumed that heaving occurred not long ago (within the recent 100 years).

Change of sedge lowland peat 7.10 ka BP (at 0.5 m depth) to lowland buck-bean peat 6.32 ka BP is found in the section of palsa 2.5 m high. This indicates the activated process of the change of the water-mineral supply regime between 7.1 and 6.3 ka BP. According to radiocarbon dates and peat composition, heaving occurred here not earlier than 6 ka BP. The formation of palsa about 4 m high began not earlier than 6.5-6.0 ka BP. At the same time the buck-bean lowland peat was replaced by the wood peat with residuals of pine, willow and birch. The peat accumulation rate during the subaquatic phase was quite high – 0.06 cm/yr. According to the correlation of dates and the peat layer thickness, the transition to the subaquatic phase finished about 5 ka BP. At that time peat accumulation and palsa growth ceased completely.

Usa Settlement. The heaving process near Usa settlement was most intensive after 6.5-6.0 ka BP. The palsa rose above the surface by 2–3 m. Some of palsa formed at that time now begin to decay. However, the active heaving process started again 3.7–2.1 ka BP and is still going on. The uplift of the younger palsa surface consists of 0.35-1.60 m (Fig. 9A).

Abez' Settlement. The formation of palsa near Abez' settlement started about 2.7 ka BP. This is identified by transition to the young, i.e. quickly freezing, transient moss and moss-grass peat with the remains of scheuchzeria, herbs and cowberry (Fig. 9B).

Nikita Settlement. The formation of palsa 4.7 m high near Nikita settlement started about 7.5 ka BP, according to replacement of the lowland bog peat by peat with high content of wood remains (which probably indicates partial site drying, Fig. 9C). Heaving took a long time according to peat accumulation rate. The transient phase finished about 2.7 ka BP. Buck-bean (Menyanthes trifoliata), sedge (Carex chordorrhiza, C. diandra) and horsetail (Equisetum) remains are found at the depth of 0.25–0.35 m. This can evidently indicate the partial thawing and subsidence of the palsa about 4.5 ka BP. Later it recovered again and grew till the current size. Palsa 3.5 m high started forming about 6.7 ka BP. This is identified by replacement of black wood-horstail near-bottom peat by with remains of wood and large bushes. Partial thawing of palsa probably occurred approximately 5 ka BP, according to horsetail remains in the peat at the depth of 0.2–0.3 m. Then palsa recovered again (not earlier than 3.6 ka BP). A minor palsa 0.7 m high composed of peat accumulated in conditions of intensive flooding of the site began growing about 2.3 ka BP. This was defined by replacement of sedge lowland peat with sedge-hypnum peat containing buck-bean and herbs. The heave was extremely unstable: it evidently thawed and subsided repeatedly (it is most probable that only a low hillock or a hummock remained after the subsidence). Then it froze and heaved again. But after 1.5–1.4 ka BP this pulsating state was transformed to a more stable one.

Eletskiy Settlement. The beginning of heaving and termination of the subaquatic phase of palsa development was identified in the section of the 4 m high palsa near Eletskiy settlement at 0.3 m depth, and it was dated as 4.8 ka BP. The next subaerial phase lasted for about 5 ka. The formation of palsa 3.5 m high evidently occurred 7.5 ka BP. The rate of peat accumulation during subaquatic phase was 0.27 m/ka (Fig. 9D). The peat accumulation rate during the subsequent subaerial phase was 0.08 m/ka. Sedge lowland-type peat is found on the palsa top. This can indicate a partial thawing of palsa 4.7–3.1 ka BP. It can be assumed that the heave process near Eletskiy settlement occurred most intensively about 7.7 ka BP when palsa grew by 3.0–3.4 m.

Khanovey Settlement. The dating of the peat from palsa near Khanovey settlement showed a long gap in peat accumulation or steep slowing down of the peat formation process 7.5-3.5 ka BP. This testifies to the massif's freezing and the formation of a comparatively low palsa. Peat accumulation resumed for a short period about 3.5 ka BP. Since a recent date was received for the palsa top (the peat accumulation is still going on), it is evident that palsa uplifted above the surface not long ago (Fig. 9E). The distribution of radiocarbon dates in palsa section (more ancient in the axial part and younger on the slope) demonstrated two important points. Firstly, this land form is properly palsa, it is not a residual form occurred as a result of the erosion of an initially flat peatland. Not only the followers of the hypothesis of the erosional origin of palsa at this area thought so. It was also acknowledged by the researchers who principally recognized heaving as the main mechanism of palsa like forms, but thought that in the Bolshezemelskaya tundra this process take place in more southern areas, while the heave terrain forms that occurred in the north, near Vorkuta, in the conditions of lower ground temperatures were referred to residual large-block forms generated as a result of erosion in frost cracks. Secondly, both the initial moment of heaving 7.5 ka BP and the moment of secondary additional heaving approximately 3.5–2.8 ka BP are clearly observed here. At the moment of initial heaving a minor palsa several meters in diameter and probably no more than 1.0–1.5 m high was formed. At the moment of secondary heaving a palsa more than 3 m high and more than 45 m in diameter was formed from the initially small one. It covered the surrounding flooded depression where peat accumulation occured 2.8 ka BP but then stopped after heaving.

Usa River Valley. Palsa mires in Usa River valley developed in several stages. Palsa 3.5-5.0 m high were formed 7–6 ka BP. The height of the peatlands' surfaces at that time reached 2.25–4.0 m. Smaller palsa were formed 3.5–2.0 ka BP. Their height was 0.35 m.

In Northern Finland Seppälä [1971, 2011] has found similar appreciable difference between radiocarbon dates of peat from palsa and its immediate vicinity as we obtained for palsas in Usa River valley. In a cross-sections of a peat plateau at the Rogovaya River (about 62 km to the north from Abez', 50 km southwest from Khanovey), the transition from sedge peat to Sphagnum peat is dated to about 3 ka BP (3120 ± 100, Hel-3796) [Oksanen et al., 1998]. The transition probably marks the beginning of freezing and elevation of surface. Ortino peat plateau near Pechora delta began to develope after 4800 BP [Väliranta et al., 2003, 2010] when Sphagnum fuscum peat changed by Sphagnum rossowii peat.

In the Bygristoe bog in central part of Western Siberia palsa formed in Holocene according to pollen data and botanical composition of peat [Blyakharchuk, Sulerzhitsky, 1999]. The wet-plant mire communities with *Menyanthes trifoliate,* which grows only in wet unfrozen mire, were replaced by vegetation of relatively dry mire conditions; *Pinus sibirica* forest with dwarf mire shrubs and moss (*Chamaedaphne caliculata, Ledum palustre, Vaccinium vitis-idaea, Vaccinium myrtillus*) as a result of freezing and heaving of peat. The transition is dated to 4740 ± ± 100 BP (GIN-5517). The increase of seasonality about 4300 BP caused Bugristoe bog to freeze, the accumulation of peat slowed down and ceased. This event coincided with the end of *Abies* forests and spread of pure *Pinus sibirica* forests in the taiga of Western Siberia.

Age of palsa growth and collapse. The radiocarbon dates shown in Table 1, and also dates from other areas in the permafrost zone of Russia suggests that the age of palsas is almost independent of latitude and temperatures of the permafrost. It seems that heaving processes are controlled by both general climatic changes and local factors even within a small area. The heaving process in the Usa River Valley was most intense in the period from 7.5 to 6.2 ka BP. Substantial activation of the heaving process occurred 3.7–1.4 ka BP and resulted in intense formation of younger palsas, which continue to grow rapidly until today. At present, new palsas are observed in some draining areas.

In Laivadalen (Sweden) most of the palsas started to grow in the period 1520 to 1730 AD (390 ± 70 BP, Ua-13229; 95 ± 65 BP, Ua-13228; and 105 ± 65 BP, Ua-13230). However, oligotrophic peat with *Sphagnum* remains dated to 8150 ± 85 BP (Ua-13227) has been found, which indicates that the palsa is older than 8000 yr. The dating from Laivadalen in combination with the climate records suggest a very young age, possibly as late as the cold period around 1860-1890; the longest cold period since 1721 in the Uppsala, southern Sweden, temperature record [Zuidhoff, Kolstrup, 2000]. New ^{14}C-datings of peat of interfluve areas and joint analysis of the dynamics of the mire systems and permafrost conditions of Bolshezemel'skaya tundra in Holocene [Maksimova, Ospennikov, 2012] demonstrated close matching with our results. They have shown that active growth of palsa in this region was preceded process of mire evolution about 8.5–4.5 ka BP as a result of permafrost degradation. About 4.5 ka BP a climate cooling has begun as well as process of change fen bogs by high bogs. Permafrost aggradation in bogs was accompanied by palsa formation. High bogs were wide spread at this stage and their cooling effect protected permafrost from long-term thawing during the warming periods [Maksimova, Ospennikov, 2012].

Heaving caused both global climatic changes and local factors. It has different appearance even within single palsa array due to differentiation of the moment of initial heaving, accumulation rate of the peat, duration of subaqueous and subaerial stages. Certain of the palsa grow and collapsed cyclically. Surface thermokarst leds to erosion, flash of palsas, but and subsequent drainage leds to young palsa formation. Similar palsa often observes in the north of Canada [Lewkowicz, Coultish, 2004] and in Scandinavia [Seppälä, 2011].

V. Barcan studied palsa near their southern boundary in the Cola Peninsula [Barcan, 2010] (up to 67°55′ N in Nyudo Lake and 67°57′ N in Monche Lake, Lumbolka Lake, Imandra Lake). It was found that most part of palsa did not thawed during last 80 years in spite of annual temperature variation from –3.0°C to +2.8°C. Relief features favor to conservation and modern growth of the palsa in Nyudo Lake area located between Nyud and Sopchel Mountains. Strong winter wings blow off the snow cover from mire surface. The same situation is observed in the other palsa mires which are located along to main direction of the winter wings [Barcan, 2010]. Near Umbozero Lake (Kola Peninsula) palsas started to grow about 4.5 ka yr BP and now they are in the stable state even in the "warm" permafrost [Romanenko, Garankina, 2012]

The wooded palsas at the treeline of the Rivière Boniface, Canada, were formed during two different periods of the last millennium between 750 and 1000 AD and during the 1500s. The maintenance of a permafrost mound under forest cover is a rare situation in northern environments, and wooded palsas in eastern Canada form peculiar ecosystems where forest and permafrost coexist; these have survived over the last 500 to 1000 years. According to S. Cyr and S. Payette [2012] the inception of wooded palsas was facilitated during a prolonged period of snow-poor winter conditions. Tree establishment was possible due to well-drained soil conditions associated with palsa upthrusting. Although thicker snowpack preventing deeper frost penetration into the soil is maintained by the development of a forest/krummholz cover, wooded palsas at the treeline can survive because of low annual temperatures, reduced solar radiation beneath the tree canopy, variable accumulation and duration of annual snowpack [Cyr, Payette, 2012].

Palsas in Usa River valley and in Northwest Siberia are of different age and represent all varieties of Seppala-type palsa stages such as embryo-mature-degraded ones. Palsa formation took place in different time periods both in different geocryologic zones and within separate palsa massifs. The transition from low-moor peat to that accumulated during a subaerial stage and, consequently, heaving of the palsas occurred in the periods lasting from 7.5 to 6.7 ka BP and from 3.3 to 1.4 ka BP. Later, this process stabilised, and palsas grew slowly. The slow heaving of the young palsas commenced 3.3-1.4 ka BP and still continues. In northern areas with continuous permafrost palsas are stable and can grow even in case of global climate warming. In discontinuous permafrost conditions most part of palsas can thaw very fast.

CONCLUSIONS

1. Convex peat mounds (palsa) are found in Northern Europe both in the areas of continuous permafrost and in the discontinuous and sporadic permafrost.

2. The southern limit of palsa in the North-East of Europe coincides with southern

border of permafrost ground: in the Kola Peninsula it is about 67°50' N, in the Kanin Peninsula about 67° N, in the Nenets Autonomous District to the South of 67°10' N, in Bolshezemel'skaya Tundra to the South of 66°20' N.

3. The palsa area in the North-East of the Europe located in the low-temperature continuous permafrost and it enters up to 68°10' N in the Nenets Autonomous District and to 67°30'–68° N in Bolshezemel'skaya Tundra.

4. Palsas are not always degraded in the Holocene Optimum, even in the southern part of the permafrost area, but on the contrary, new palsas started to form. An intense accumulation of peat (due to high summer temperatures), and its good preservation (due to severe winters) in the Holocene Optimum are main factors of such geocryological paradox.

5. Some of the mounds develop cyclically: surface thermokarst processing of previously formed palsa leads to abrasion and subsidence part of them, and the subsequent draining ends with the formation of new palsa.

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PLEISTOCENE-HOLOCENE PALAEOENVIRONMENTAL RECORDS FROM PERMAFROST SEQUENCES AT THE KARA SEA COAST (NW SIBERIA, RUSSIA)

ABSTRACT. The Kara Sea coasts were studied using comprehensive stratigraphic and geocryological methods. The paper presents the new analytical studies of ground ice and Quaternary deposits of Western Taymyr and presents the results of spore and pollen, foraminifera, grain-size, mineralogical, geochemical, oxygen isotopic, and other analyses. Several stratigraphic-geocryological transects from Yenisey and Gydan Bays enable us to refine the stratigraphy and palaeogeographical reconstruction of the environments and freezing of Late Pleistocene-Holocene sediments. Marine sedimentation conditions during the late Kargino time (MIS3) changed to continental conditions in MIS2 and MIS1. Marine sediments were frozen syn- and epigenetically with cryotexture and ground ice formation. Ice wedges formation corresponds to the end of the Pleistocene (MIS2) and during cooler periods of the Holocene.

KEY WORDS: Arctic coasts; permafrost; tabular massive ground ice; stable isotopes; syngenetic polygonal ice wedges; palaeoclimate.

INTRODUCTION

Accumulation of Late Pleistocene sediments in climatic conditions similar or colder than present ones, and wide distribution of polygonal ground ice exclude the presence of large ice sheet in the north of West Siberia [Svendsen at al., 2004]. There is evidence of marine conditions in the lower Yenisey River during the entire MIS5, which excludes the glaciation around 90 kBP [Gusev and Molodkov, 2012]. Such contradictions in currently existing models of development of northern West Siberia in the Middle-Late Pleistocene indicate the need for a more detailed comprehensive study of Quaternary deposits and ground ice sediments of the North.

The Yenisey Gulf and Gydan Peninsula regions are characterized by severe climatic conditions, continuous permafrost, and low ground temperatures. The coasts are composed of fine grained sediments with high ice content and are constantly modified by thermodenudation, thermoabrasion, and slope processes. Geological sections on slopes and surfaces of watersheds are completed by a layer of continental sediments with syngenetic polygonal ice wedges (SPIW). Thick SPIW is part of the section of the second alluvial terrace of the Yenisey River. Parental bedrocks are subjected to intense cryogenic weathering and are composed mostly of fine-grain saline marine Quaternary sediments with a thickness of more than 100 m [Matyukhin and Streletskaya, 2012]. Saline marine sediments contain ground ice: tabular massive ground ice bodies (TMGI) (large tabular ice bodies with volumetric ice content around 100%) and segregation ice. The genesis of the TMGI and the enclosing clay deposits is a subject of the debate [Danilov, 1969, 1978; Kaplyanskaya and Tarnogradsky, 1986; Solomatin, 1982; Streletskaya at al., 2009]. TMGI are classified as buried or intrasedimental in origin.

SPIW and TMGI have unique natural features. They provide important paleogeographic information and are used in paleoclimatic reconstructions.

The main objective of the work presented herein was reconstruction of the paleogeographic conditions and sedimentation environment in the Late Pleistocene-Holocene based on comprehensive research of permafrost exposures along the Kara Sea coasts [Danilov, 1969; Oblogov et al., 2012; Romanenko et al., 2001; Streletskaya et al., 2007; Streletskaya and Vasiliev, 2009; Streletskaya et al., 2011; Streletskaya et al., 2012]. Generalization of analytical studies of ground ice and the sediments with application of new techniques supported by dating of Quaternary sediments allows revising the Quaternary stratigraphy and paleogeographic reconstruction of the conditions on the Yenisey North in the Pleistocene and Holocene.

MATERIAL AND METHODS

The scope of work included investigation of sections of coastal cliffs with a total length of more than 30 km at five sites which allowed detail characterization of permafrost features in the main geologic and genetic Quaternary complexes. The distance between the northern (village Dikson) and southern points (Cape Sopochnaya Karga) is about 150 km, and the distance between the western (Ery-Maretayakha River mounth) and eastern points (Cape Sopochnaya Karga) is about 250 km (Fig. 1).

Complex field and analytical investigation included dating of sediments, determination of ice content, particle size and mineralogical composition, total salinity and composition of water-soluble salts, organic carbon content, and palynological analyses of micro and macro faunas in the sediments. The sediments from the sections were sampled at intervals of 30 cm – 1 m for grain-size and for the investigation of organic matter and biostratigraphic indicators – foraminifers, ostracodes, spores and pollen, diatoms. Peat, wood fragments, and bones were picked for ^{14}C age determination.

Along with recording sediment descriptions, the gravimetric ice content was estimated immediately after thawing by relating the weight of the frozen sample to the weight of the dry sample, expressed as weight percentage (wt%).

Grain size was determined by sieving and pipette analysis. The chemistry: aqueous migrate (Makarov: water extract) analyses were conducted using standard methods in the Laboratory of Lithology and Geochemistry of All-Russian Research Institute for Geology and Mineral Resources of the World Ocean (VNIIOceangeologiya) in St. Petersburg, Russia.

The determination of organic carbon contents (OCC) were carried out using the laboratory mill "Retsch" (Germany) sample preparation.

Radiocarbon dating using the accelerator mass spectrometry (AMS) was determined at the laboratories of the Sobolev Institute of Geology and Mineralogy of the Russian Academy of Sciences and Saint Petersburg State University. All radiocarbon

Fig. 1. Location of the study area in Northern Siberia in the Yenisey Gulf and Gydan Bay. The sites are described in the text

dates through this paper are reported as uncalibrated ages.

The chemical and isotope compositions of ground ice ($\delta\ ^{18}O$ and δ D) were determined in samples of melted water from the ice-wedges and intrasedimental ice. The stable isotope composition of ground ice was determined at the Isotope Laboratory of the Alfred Wegener Institute for Polar and Marine Research, Research Unit Potsdam. δD and $\delta^{18}O$ values give the respective permil-difference relative to the international standard Vienna Standard Mean Ocean Water (V-SMOW). The internal 1s errors are <0.8% for δD and <0.1% for $\delta^{18}O$ for all measurements (Meyer et al., 2000). Stable isotope data of ice and water are generally displayed relative to the Global Meteoric Water Line (GMWL) [Craig, 1961]. The deuterium excess ($d = \delta D - 8\delta^{18}O$) introduced by Dansgaard [1964] is an indicator for non-equilibrium fractionation processes.

THE STUDY SITES AND RESULTS

The exposure near Sopochnaya Karga Cape

Pleistocene and Holocene sediments containing large inclusions of ground ice as well as sediments with no visible ice inclusions were previously studied in several exposures along 6 km segment of the Yenisey Gulf coast on Cape Sopochnaya Karga (Fig. 2 and Fig. 3) [Streletskaya at al., 2007, 2009, 2011, Streletskaya and Vasiliev, 2009].

Sands from the northern part of the cliff (Fig. 3A) were analyzed by infrared optically

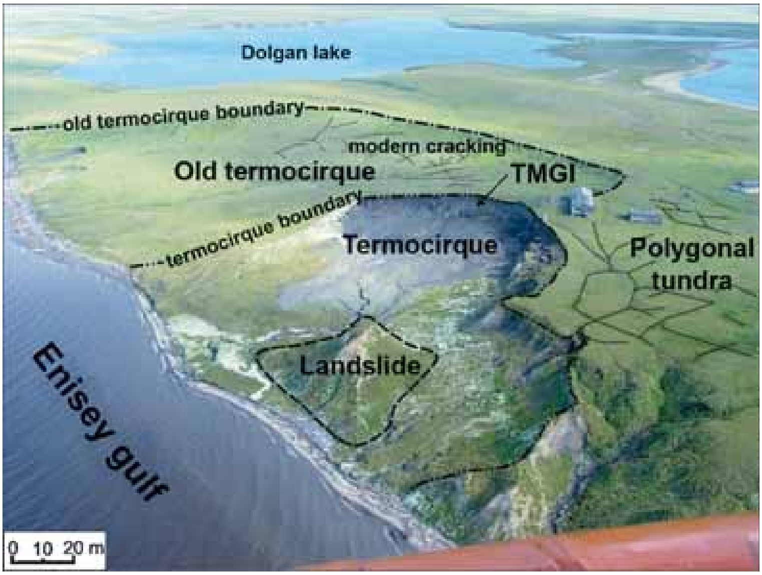

Fig. 2. Location of the Sopochnaya Karga study site. August 2004. (Photo taken from helicopter by E. Gusev)

stimulated luminescence method (IR-OSL). The results allowed us to determine the age of two samples from this section in 112,5±9,6 KA (RLQG 1769-107) and 117,7±10,0 KA (RLQG 1770-107) [Streletskaya et al., 2009; Gusev et al., 2011].

Radiocarbon dating of two peat samples showed that the age of the organic horizons is 7320±130 yrs (GIN 13056) and 8050±60 yrs (GIN 13055), which corresponds to the climatic optimum [Streletskaya et al., 2009] (Fig. 3C).

The range of $\delta^{18}O$ in SPIW is –20.3‰ to –19.0‰, and the range of δD is –150.4‰ to –140.6‰. The deuterium excess is near 13.0‰ [Streletskaya at al., 2011].

The stable isotope content in TMGI is rather constant and is -23‰ for oxygen and -177‰ for deuterium. The deuterium excess is from 4.5‰ to 5.8‰.

The scale of the processes can be inferred from the landslide of 22 m height and 200 m wide, which covers the fragment of the second alluvial terrace of the Yenisei River (Figure 3D).

The landslide body represents partially thawed and later refrozen sandy-clay sediments moved down the slope. The radiocarbon age of the sediments is older than 43,700 yrs. Pollen complex extracted from clay sediments is characteristic of forest-tundra vegetation of the Kargino time of the Late Pleistocene (MIS3).

To the north from the Sopochnaya Karga settlement, the coastal exposure of the Yenisey Gulf is 15–20 m high, the level of the second terrace of the Yenisey River (Fig. 3B).

From the surface of the terrace down to 1 m, there is peat; according to the radiocarbon dating, the formation of the peat layer started 9–10,000 years ago.

Under the peat, layered silty loams and sands 4–15 m thick are found. The horizon is underlined by peat older than 37,200 yrs. A caribou bone was found at the base of the exposure, which was dated 13,770 ± 480 yrs (LU-6998).

At the contact with the underlined clays, the sands have gravel inclusions (Fig. 3B). Sandy-loams and sands have inclusions of SPIW up to 10 m thick and 2–3 m wide in the upper parts of the wedges. Lower parts

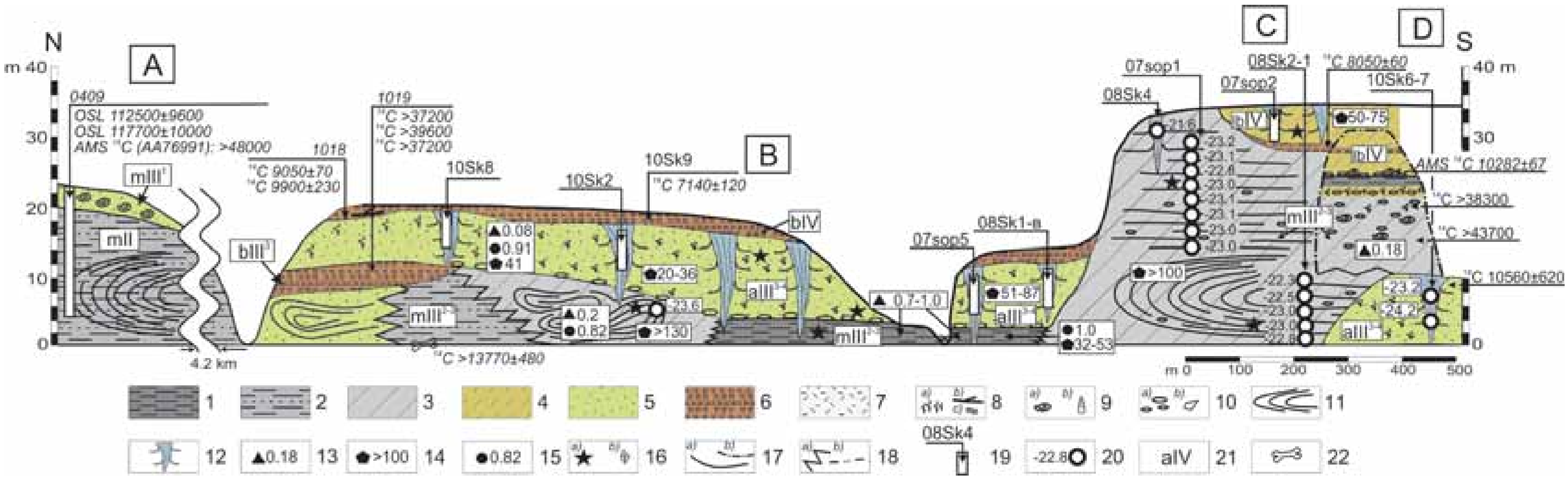

Fig. 3. Schematic representation of the studied Sopochnaya Karga permafrost sequence with ground ice; sample positions, some analyses results and radiocarbon ages:

1 – clays; 2 – clays with sandy silts and sands interlayers; 3 – clay loam; 4 – sandy loam; 5 – sands; 6 – peat; 7 – talus; 8 – inclusions a) detritus, b) wood debris, c) peat debris; 9 – a) sea mollusks, b) fresh-water lacustrine shells; 10 –inclusions a) rounded pebble, b) coarse gravel; 11 –cryoturbations; 12 – polygonal wedge ice (shown outside of scale); 13 – degree of salinization of sediments, %; 14 – gravimetric water content, %; 15 – organic carbon content, %; 16 – sampling for a) granulometric and mineralogical analysis, b) palynological analyses; 17 –boundaries: a) lithological, b) landslides; 18 – boundaries of granulometric facies, 19 – location and number sites of exposed SPWI where isotopic composition was studied; 20 – composition of oxygen ($\delta^{18}O$) stable isotopes of ice, ‰; 21 – genesis and age deposits; 22 – bone

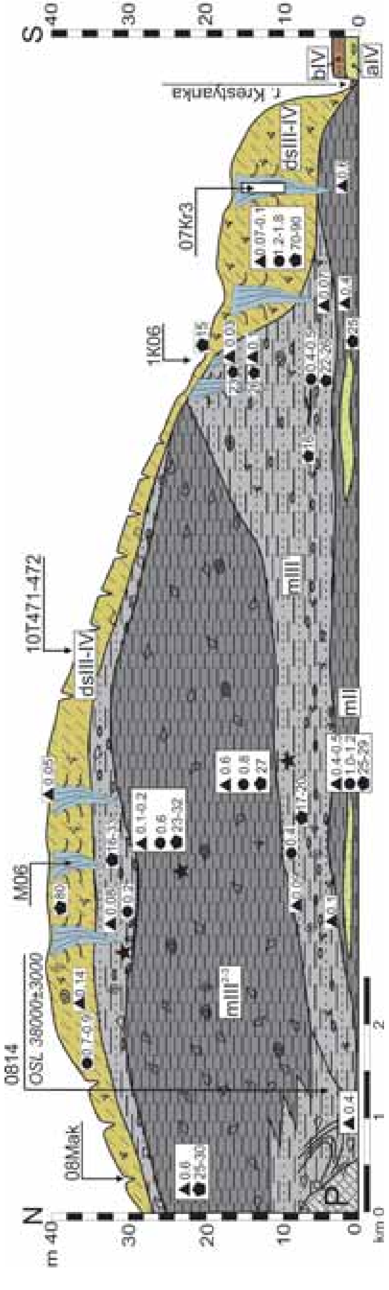

Fig. 4. Schematic representation of the studied Krestianka permafrost sequence with ground ice, sample positions, some analyses results, and radiocarbon data (see legend for Fig. 3)

of the wedges intrude the clays or TMGI up to 0.5 – 1.0 m deep.

The $\delta^{18}O$ content of SPIW is from –24.8 to –24.5 ‰. The deuterium excess is from 6.8‰ to 10.2‰. The same isotope composition is found in SPIW in sands buried by the landslide (Fig. 3D).

The clays below the sands and sandy-loams are saline (salinity up to 1.5%) and characterized as marine (chlorine content is 70–85 mmol/1 %, sodium 97 mmol/1 %). The total gravimetric moisture content of clays is 32–53% and sometimes higher than 130% (TMGI). The organic carbon content in clay sediments is independent of pure ice content and is 0.8–1.0%. Salinity in the icy sediments layer is less (0.2%), but among the ions, the chlorine and sodium dominate.

The stable oxygen isotope content in TMGI is –23.6‰ which is similar to the composition of TMGI in the southern part of the exposure (Fig. 3C). The stable oxygen isotope content from ice of reticulate cryostructure in the clay is relatively heavy (–18.4 ‰).

The profile near the Khrestianka River mouth

Near the Khrestianka River mouth, the Quaternary deposits are overlying the Permian bedrocks, the top of which is located at 5–10 m asl (Fig. 4).

The particle-mineralogical analysis of the sand fraction from the clay showed the distribution of minerals characteristic of marine beaches.

The OSL dating of the sand lens at the bottom of the profile indicated the age of 38.0 ± 3.0 thousand yrs [Gusev et al., 2011].

4. Under the clay horizon, there are yellowish-grey well sorted sub-horizontally layered sands 5.5–10 m thick. The layering is visibly supported by iron oxidation. The granulometric and mineralogical analysis showed that the sediments were

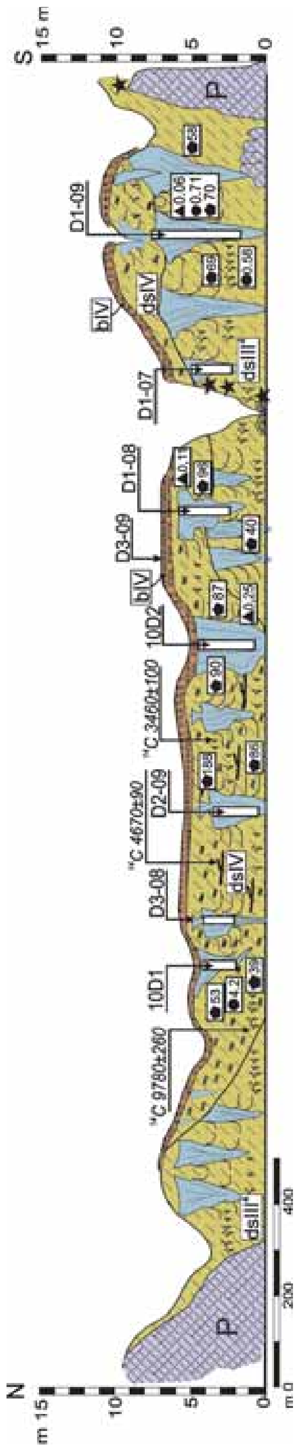

Fig. 5. Schematic representation of the studied Dikson permafrost sequence with ground ice, sample positions, some analyses results, and radiocarbon data (see legend Fig. 3)

accumulating in the underwater part of the delta under wave action at the bottom. The sorting of the sediments by size and density and absence of silt and fine-grained sands show possibility of formation of gravelly sands in the underwater zone of the beach near the mouth of the river.

The pollen spectra from the sands indicated the taiga vegetation type of the Kazantsevo age with extensive meadows.

5. At the base of the exposure (1–2 m above the gulf level), sands transition to dense lumpy loams and clays.

The SPIW on the slopes of the interfluves near the Krestyanka River mouth have a lighter isotope composition compared to the Holocene wedges of Cape Sopochnaya Karga. The values of $\delta^{18}O$ and δD range from –23.7 to –21.3‰ and from –180.0 to –165.0‰, respectively. Deuterium excess is less than 10 ‰ (from 5.2 to 9.9‰).

The exposure near the Dikson village

The most complete section of the Quaternary sediments was studied in the Dikson area where two layers of SPIW penetrate the coastal scarp (Fig. 5).

The deposits are ice-rich (the total moisture content is over 86%) and have a rhythmically-layered structure typical of syngenetic deposits. The cryostructure between the layers is reticulate, ataxitic, and massive, while near the layers, it is micro-lenticular-layered. The apparent thickness of the deposits is about 10 meters, but SPIW continues below the sea level, suggesting that the deposits are very thick.

In the deposits, including the SPIW of the lower layer, organic matter is spread regularly in the section. There are no large inclusions or plant debris.

The results of the analysis of the oxygen ($\delta^{18}O$) and hydrogen (δD) isotopic composition of SPWI showed changes of

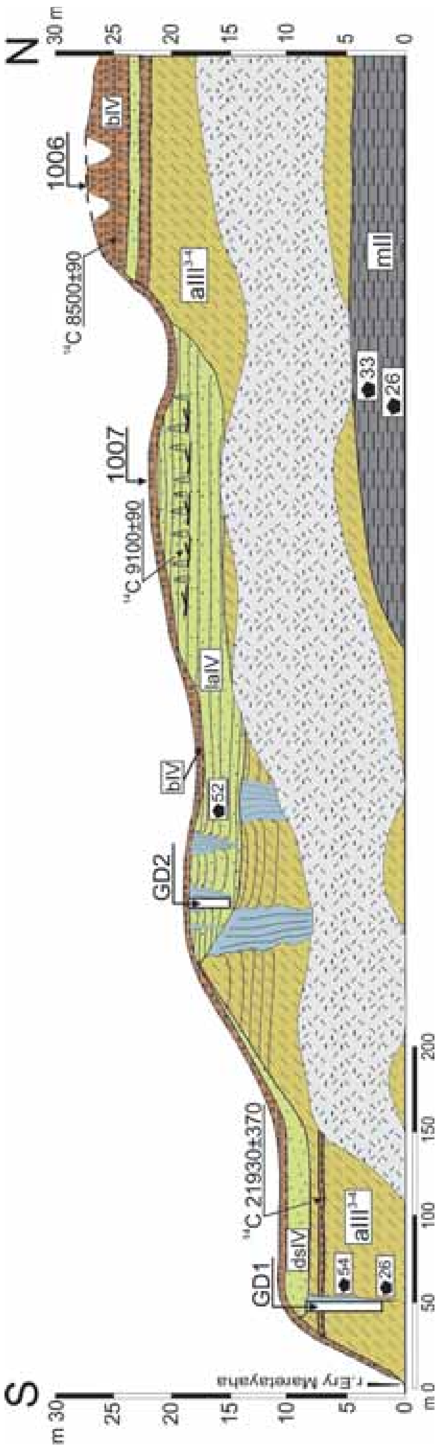

Fig. 6. Schematic representation of the structure of the coastal outcrops of the Ery-Maretayakha River mouth, the Gydan Bay (see legend Fig. 3)

values from –26.8 ‰ to –20.1‰ ($\delta^{18}O$) and from -205.0 ‰ to –150.4 ‰ (δD). The isotopic composition of the upper layer PWI is from –21.7‰ to –19.5‰ ($\delta^{18}O$) and from –161‰ to -147‰ (δD). The isotopic composition of the lower layer SPIW is 6‰ lighter: it changes from -24.3‰ to -26.8‰ for $\delta^{18}O$ and from –205‰ to –184‰ for δD. Currently, the growing ice branches of wedges have a heavier isotopic composition from –17.1 ‰ to –16.2 ‰ for $\delta^{18}O$ and from –124 ‰ to –118 ‰ for δD in the Dikson area [Streletskaya et al., 2011].

The western coast of the Gydan Bay

The coastal cliff structure near the Ery-Maretayakha River mouth was studied. The structure consists of thermodenudational surfaces with the elevations of 10–25 m and a thermoabrasive cliff descending to the modern beach (Fig. 6).

The upper part of the section is represented by frozen lacustrine (lacustrine-boggy) deposits that are characterized by a substantial ice content. Radiocarbon dating by a peat sample showed the age of 8,500 ± 90 yr BP (LU-6535). Radiocarbon dating by plant roots from the depth of 4 m showed the age of 9,100 ± 90 yr BP (LU-6534)

Closer to the Ery-Maretayakha River mouth, in the section of a surface about 10 m high, sandy silts are interbedded with fine sands and peat interlayers. The peat interlayer in sandy deposits at the elevations above the sea level 7.8 m has the radiocarbon age of 21,930±370 yr BP (LU-6542). Yu.K. Vasilchuk [1992] obtained a series of radiocarbon dating at different elevations above the sea level: at 3.5 m – 30,200 ± 800 yrs (GIN-2470), at 4.5 m – 28,600 ± 800 yrs (GIN-2638), 5 m – 25,100 ± 220 yrs (GIN-2471), 5.9 m – 21,900 ± 900 yrs (GIN-2469). The peatland at the elevation of 9.3 m had a radiocarbon age of 3,900 ± 100 yrs (GIN-2468).

Two layers of SPIW (Fig. 6) are exposed in the section: the upper-layer SPIW with the

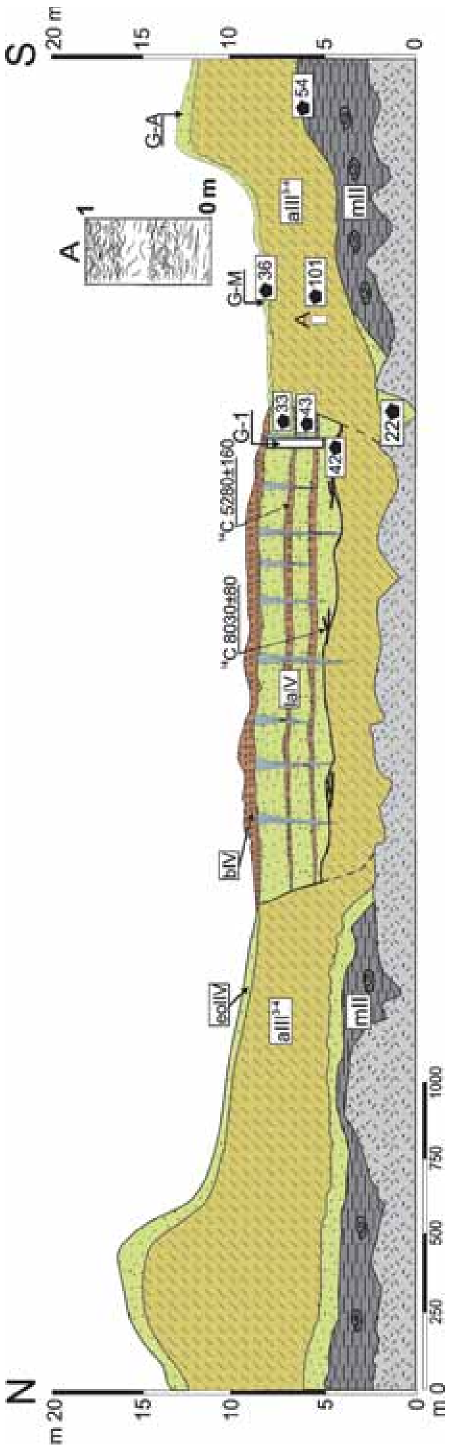

Fig. 7. Schematic representation of the structure of the coastal outcrops of Cape Pakha-Sale, the Gydan Bay (see legend of Fig. 3)

width of 1.2 m on top and the height of 3.6 m and the large lower-layer SPIW with the width of 2.5 m on top and the height of more than 10 m. The isotopic composition of the upper-layer SPIW changes from -23.6 to -18.3‰ for oxygen ($\delta^{18}O$) and from -179.9 to -134.3‰ for hydrogen (δD); the deuterium excess (d excess) changes from 9 to 12‰.

Large SPIW is not observed in the outcrop's southern part. It is possible that it was cropped by slope processes or partly thawed. Here, thin (with the width of up to 0.4 m) ice wedges with the average thickness of 4.5 m (observation point GD1) penetrate sands and sandy silts. The content of oxygen and hydrogen stable isotopes in the ice does not change with depth and is –24.6...–22.6‰ for $\delta^{18}O$ and –193.1...–176.5‰ for δD; the deuterium excess does not exceed 6–7‰.

The eastern coast of the Gydan Bay

The coastal cliff structure near Cape Pakha-Sale was another area of the research (Fig. 7).

Here, marine and coastal-marine sand-aleuric deposits outcrop in coastal cliffs with the height of 15–20 m. More ancient marine deposits are overlaid by the Late Pleistocene-Holocene continental sediments with plant detritus. A large amount of bone debris that was washed out of the coastal cliffs is scattered along the beach.

A lens of lacustrine deposits with the thickness of 4–6 m and the visible length of 1200 m contains layered sandy silts saturated with organic matter.

The age of wood inclusions at the depth of 2.6 m is 5,280 ± 160 yrs (LU 6540) and is 8,030 ± 80 yrs (LU 6541) at the depth of 6 m. The lacustrine deposits lens is embedded along the strike into a band of light dusty sandy silts that form the slopes of a thermokarst depression and surfaces 15 m high. Sandy silts consist of 83% of silt-sized particles. The lacustrine deposits include the SPIW complex. The ice wedges form a polygonal network on the surface with the polygon side of 18–55 m.

Ice-wedges have the width of 20–50 cm on top and the length of 2–5 m. The SPWI isotopic composition is –19.1‰ for oxygen ($\delta^{18}O$) and –146.2 ‰ for hydrogen (δD); the deuterium excess (d excess) is 7.2‰.

The filling of the thermokarst depression occurred in two stages. The deposits accumulated during the first stage in the beginning of the Holocene. They got into the lake during the destruction of the coasts formed by dusty sandy silts with high ice content. The coarser sand sediments accumulated at the end of the filling. A horizon with a relatively low ice content and post-cryogenic cryostructure points to the existence of talik under the lake.

DISCUSSION

The investigated Late Pleistocene and Holocene sediments of the Kara Sea coast were dated using radiocarbon AMS and infrared OSL. The radiocarbon AMS dates can be compared with the Kargino period (MIS3), because the Kazantsevo (MIS5) marine sands dated by IR OSL are located lower in the profile [Gusev et al., 2011; Nazarov, 2011; Gusev and Molodkov, 2012]. The radiocarbon age of peat near Sopochnaya Karga indicates the Kargino age; during the same period, the peat accumulation occurred at the Gydan Peninsula [Trofimov et al., 1986], Sibiryakova Island [Streletskaya et al., 2012], and Taymyr [Bolshiyanov, 2006]. Inversion in the dates in the profile of Sopochnaya Karga (Fig. 3D) can be explained by movement of large landslides from higher surfaces composed of marine saline sediments to the younger lower hypsometrical levels composed of freshwater alluvial sands and sandy loams.

The sediments of the second terrace of the Yenisey River, the coastal cliff of the Gydan Bay near the Ery-Maretayakha River mouth and the sediments including SPIW of the lower layer of the Dikson exposure accumulated during the Late Pleistocene (MIS2) with sedimentation ending about 10 thousand years ago. Climate warming around 10-9 thousand years ago led to thermokarst development and peat accumulation. The coastal exposures near the Khrestianka River mouth have the most complete, for the region, Quaternary geological profile. The lower part of the profile near the Khrestianka River mouth is represented by clay sediments formed in the conditions of a cold marine basin (Sanchugovo formation) in the Middle Pleistocene. Cold climatic conditions characteristic of forest-tundra landscapes along the coasts of the sea basin were confirmed by the palynologic analyses. The layer contains mollusks and single shells of foraminifera. Sediments were freezing right after the sea regression, which allowed preservation of marine salts.

Marine clays of the Sanchugovo formation are overlain by sands of shallow sea. The granulometric-mineralogical analysis indicated that sands were deposited in an underwater beach zone near the river mouth. Results of the palinological spectra from the sands indicated that taiga with vast meadows existed along the coasts, which means that the landscapes characteristic of the Kazantsevo (MIS5) period were present.

High soluble salt content in the sorted sand layer and high ice content indicate that the sands were frozen in shallow marine conditions. Such conditions were favorable for preservation of moss particles, horizontal ice lenses, and fragments of the lower part of SPIW.

Formation of the upper clay layer containing fragments of pebbles, gravel, and boulders and overlaying the sands of the Kazantsevo formation occurred under conditions of shallow ice covered sea. For the conditions of a cold arctic basin with lower salinity, the foraminifera represented by small undeveloped shells are characteristic. Herbaceous and spore plants dominated in forest-tundra along the coasts. The post-cryogenic structure indicates epigenetic type of sediment freezing after sea regression. Peat of the Kargino formation overlays TMGI, which means that their formation occurred in the pre-Kargino (MIS3) time under syngenetic freezing of saturated desalinated alluvial-marine sediments in a shallow sea. It is possible that freezing of sediments was accompanied by formation of large pingoes.

Stable isotope compositions for different generations of ice wedges were analyzed for reconstruction of the palaeoclimate evolution. It is given for 15 ice wedges of five geocryological units. The isotopic composition of ice wedges on the Kara Sea coasts is highly variable throughout time, ranging between -26.8‰ and –16.2‰ for $\delta^{18}O$ and from –209.2‰ to –117.8‰ for δD. Recent ice wedges, sampled in the active layer, have heavier isotopic compositions around -17.0‰ for $\delta^{18}O$ and –121.0‰ for δD [Streletskaya et al., 2011].

The Holocene ice wedges (units Sopochnaya Karga, Dikson, Gydan) can be differentiated by means of stable isotopes, despite heavy isotopic composition in all of them. The ice wedges show a mean isotopic composition around –20.4‰ for $\delta^{18}O$ and –154.2‰ for δD (Fig. 8a).

Formation of alluvial sediments occurred under conditions of drying shelf [Stein et al, 2002]. The composition of pebbles and large grain sands indicates that the Yenisey River mouth was extended more than 300 km north relative to the present position [Streletskaya et al, 2009]. Change from marine to terrestrial conditions occurred rather quickly as there are no signs of thawing found in the roof of icy marine sediments (TMGI). Severe climatic conditions during formation of the second river terrace of the Yenisei supported a gradual increase of silt content from the bottom to the top of the profile and presence of SPIW. A complex of large SPIW of the second river terrace is characterized by light isotope composition and prevalence of HCO_3^- and Ca^{++} in the chemical composition of ice. A similar isotope and chemical composition is characteristic of SPIW of the lower level near the Dikson settlement and SPIW near the Krestianka River mouth [Streletskaya et al., 2011].

Temperature assessment [Vasilchuk, 1992] indicated that mean January temperatures were –40 ± 3°C. This is 12–15°C lower than the present (the January climatic mean for the Dikson weather station is –25.5°C).

Winter precipitation was formed in the continental conditions, with land occupying the modern shelf during the last cold stage (MIS2) up to 120 m depth (see map in Fig. 9).

Presence of ice fine-grained sediments near Dikson is explained by widespread nivation processes corresponding to the development of cold wind-blown snowpacks during cold periods. Such conditions were reconstructed for formation of the ice-complex in the Laptev Sea coast. In their ratio of sand, silt, and clay fraction, the ice rich deposits in the Dikson area are almost identical to the

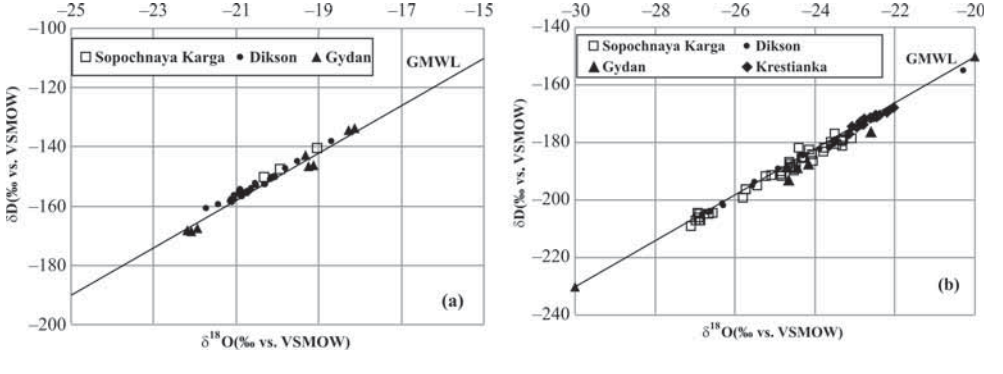

Fig. 8. $\delta^{18}O$-δD diagrams for ice wedges in all geocryological units for different age sediments:

Holocene (a); Late Pleistocene (b)

"ice complex deposits" of known sections of shores of the Yakutia coastal lowlands and Alaska.

The Holocene SPIW isotopic composition reflects a higher winter temperature and an impact of the sea. The number of stable oxygen isotopes in SPIW decreases from the coasts to the inland of the peninsula. The isotopic composition of the Western Taymyr SPIW of the Late Pleistocene/Holocene age is similar in its values to the isotopic

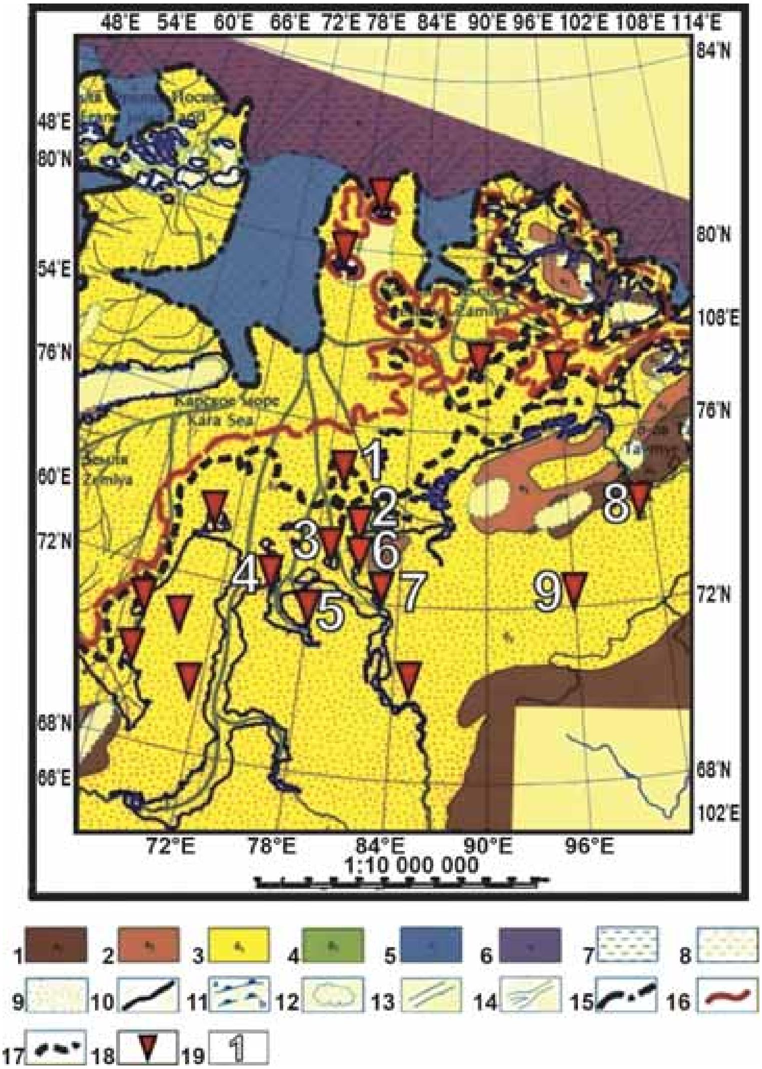

Fig. 9. Relict ice wedges in the Late Pleistocene – Holocene, the Kara Sea (based on the Atlas of paleographic maps (2004) and R. Stein et al., 2002 with additions).

1 – highlands; 2 – hills and lowlands; 3 – alluvial and lacustrine plans; 4 – river valleys and temporary lakes; 5 – continental shelf; 6 –oceanic areas; 7 –mud, clay/mudstone, shale; 8 –silt, siltstone; 9 – sand, sandstone; 10 – present day coastline; 11 – shelf edge at time of map a) determined b) inferred); 12 –ice sheets; 13 –submarine trench, canyon or channel; 14 –river paleovalley, submerged during transgressive phase; 15 –coastline at 18 000 y; 16 – coastline at 11 000 y; 17 – coastline at 9000 y; 18 – relict ice wedges. The sites with SPWI where isotopic composition was studied (see Table 2): 1 – the Sverdrup Island, 2 – the Dikson urban locality, 3 – Sibiryakov Island, 4- the Gydan Bay (west coast), 5 – the Gydan Bay (east coast), 6 – Krestianka, 7 – Sopochnaya Karga, 8 – Lake Taymyr, 9 – Lake Labaz composition of SPIW on the coasts of the Laptev and East Siberian Seas.

The Holocene and Late Pleistocene deposits have similar particle and mineralogical compositions. The Holocene deposits formed in the conditions of close redeposition and freezing of the pre-Holocene icy sediment during the cold periods of Holocene. The Holocene SPIW is characterized by a heavier isotope content relative to the Late Pleistocene. Mean January temperatures during formation of the Holocene SPIW are similar or slightly lower than at the present in the region. Extensive frost cracking and development or degradation of SPIW are attributed to changes in winter snow accumulation (rather than temperature).

CONCLUSIONS

The coastal exposures of the Gydan Bay and the Yenisey Gulf with and without inclusions of large bodies of ground ice were studied using comprehensive stratigraphic and geocryological methods, which allowed a reliable reconstruction of paleogeographic environmental changes in the Pleistocene and Holocene, including sedimentation and freezing conditions.

Transitions from the prolonged marine deposition environment to the terrestrial one were accompanied by freezing of marine sediments, formation of TMGI and SPIW. Marine sediments were replaced by alluvial-marine sediments during MIS5 to MIS4 transition. Reliably dated sediments of MIS4 were not found, but it is possible that the Zyran time (MIS4) corresponds to a break in sedimentation at the Yenisey North. After the terrestrial type of sedimentation, the new transgression occurred at the beginning of the Kargino time (MIS3). The sea level rise was quite short and by the second half of MIS3, the marine conditions of sedimentation transitioned to the terrestrial, which is confirmed by disappearance of foraminifera, sponge spicules, shells of marine diatoms, and their replacement of fresh-water diatoms, ostracodes, and, later, limnitic microflora and ostracodes. The majority of the loamy sediments of MIS3 are significantly saline in the lower part of the profiles with salinity decreasing toward the upper part of the profiles. The spore-pollen spectra derived from the samples of the sediments of the Kargino age (MIS3) are characteristic of the forest-tundra and tundra landscapes. Up the profile section in the direction of the sediments corresponding to the MIS2 age, the spectra are depleted until complete disappearance of palynomorphs.

Lower mean annual air temperatures, sea regression, and climate aridization occurred in the Late Pleistocene, which is inferred from the increase of the silt fraction content in the upper part of the alluvial terrace (Sopochnaya Karga) and on the slopes (Makarevich – Chrestianka), active cryogenic weathering (Dickson), and a light isotope composition of SPIW.

Dating of the sediments with SPIW indicates the Late Pleistocene – Holocene ages. Formation of SPIW occurred in two stages: in the Late Pleistocene (MIS2) and in cold periods of the Holocene, which is inferred from the stratigraphy, chemical and isotope analysis, and SPIW. A lighter isotope content (up to 6‰) and domination of calcium and the hydrocarbonate ions are characteristic of SPIW of the Late Pleistocene. A heavier isotope content and prevailing sodium and chlorine ions are typical for the Holocene ice.

In the Holocene, ice wedges were growing in the thermokarst depressions formed during the Holocene optimum and later filled with silty sediments with high ice content. The profiles are dominated by reworked pre-Holocene material and characterized by a higher organic content.

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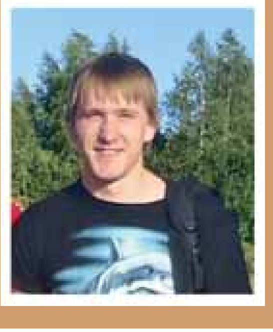

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QUANTIFYING REGIONAL SEA LEVEL RISE CONTRIBUTIONS FROM THE GREENLAND ICE SHEET

ABSTRACT. This study projects the sea level contribution from the Greenland ice sheet (GrIS) through to 2100, using a recently developed ice dynamics model forced by atmospheric parameters derived from three different climate models (CGCMs). The geographical pattern of the near-surface ice warming imposes a divergent flow field favoring mass loss through enhanced ice flow. The calculated average mass loss rate during the latter half of the 21st century is ~0.64 ± 0.06 mm/year eustatic sea level rise, which is significantly larger than the IPCC AR4 estimate from surface mass balance. The difference is due largely to the positive feedbacks from reduced ice viscosity and the basal sliding mechanism present in the ice dynamics model. This inter-model, inter-scenario spread adds approximately a 20% uncertainty to the IPCC ice model estimates. The sea level rise is geographically non-uniform and reaches 1.69 ± 0.24 mm/year by 2100 for the northeast coastal region of the United States, amplified by the expected weakening of the Atlantic meridional overturning circulation (AMOC). In contrast to previous estimates, which neglected the GrIS fresh water input, both sides of the North Atlantic Gyre are projected to experience sea level rises. The impacts on a selection of major cities on both sides of the Atlantic and in the Pacific and southern oceans also are assessed. The other ocean basins are found to be less affected than the Atlantic Ocean.

KEY WORDS: Greenland ice sheet; sea level rise; climate change; Earth system modling.

INTRODUCTION

Quantifying sea-level rise (SLR) predictions is major challenge (IPCC AR4, 2007). At present, the melting of land ice almost equals the ocean thermal expansion [Meehl et al., 2007] and may increase in a warming climate [Rahmstorf, 2007]. The IPCC AR4 has identified the melting of the Greenland Ice Sheet (GrIS) as a critical, but as yet poorly understood, process in determining global climate change in the 21st century (Fig. 1). The IPCC estimates the contribution from GrIS to be 24 mm by 2100, when compared with 1990 levels. This is likely an underestimate, as recent observations indicate peripheral outlet glaciers are highly sensitive to atmospheric warming [Rignot and Kanagaratnam, 2006; Mernild et al., 2009; Van den Broeke, 2009]. At present the astronomical background is stable and there also is a lack of other obvious concurrent global forcing processes outside the climate system that contribute to an accelerated melting of ice sheet. Thus, the likely cause resides in the climate system. During the past decade, the large mass loss (reaching ~0.7 mm/yr sea level contribution in 2010)

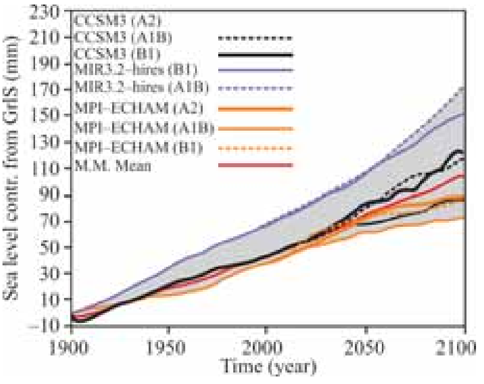

Fig. 1. The eustatic sea level rise (mm) contribution from the Greenland ice sheet for the 20th and 21st centuries. Atmospheric forcing parameters are provided by CCSM3, MPI-ECHAM and MIROC3.2-hires under the IPCC SRES A2, A1B and B1 scenarios, respectively.

The red curve is the multi-model multi-scenario mean. A 21-term binomial low-pass filter is applied on the annual time series to suppress short term (annual to decadal) variability. The color shades are the range of model spread

likely is the result of the impact of climate warming. The warming has lasted long enough for the already accumulated effects to be irreversible by just several opposing events, such as one or two years of cooler than annual mean temperatures. In fact, the recent eruption of the Iceland volcano did not slow the rate of melting. This modeling study attempts to reduce uncertainty in quantifying global SLR contributions from the GrIS, and its regional manifestations. A recently developed ice model, SEGMENT-ice, has a detailed, enhanced treatment of basal and lateral boundary conditions and "higher order" terms [Ren et al., 2010]. There are three positive feedbacks from the GrIS to a warming climate (see Supplementary Material, SM). SEGMENT-ice has been compared with other participants in the Sea-level Response to Ice Sheet Evolution (SeaRISE) project and shows skill in reproducing and explaining recent, dramatic ice sheet behavior [Ren et al. 2011a,b]. The present study is a modeling attempt to reduce the uncertainty range in quantifying the global SLR contribution from the Greenland Ice Sheet (GrIS), and its regional manifestations.

THE ICE MODEL

SEGMENT-ice is a component of an integrated scalable and extensible geo-fluid model (SEGMENT). Parameterization of viscosity is critical for ice creeping. SEGMENT-ice has two improvements over Glen's ice rheological law [Hooke, 1981; van der Veen, 1999], respectively for factoring in the flow induced anisotropy and granular basal condition. The flow enhancement by re-fabricating [Wang and Warner, 1999] is implemented so older ice, farther from the Summit, is easier to deform. SEGMENT-ice also allows a lubricating layer of basal sediments between the ice and bedrock which enhances ice flow and forms a positive feedback for mass loss in a warming climate (MacAyeal [1992], Alley et al. [2005], and [Ren et al. [2010], Fig. 2]). Because the ocean temperature is higher than that around Antarctica, there are no ice shelves around Greenland. There however are several water-terminating fast glaciers around the peripheral of GrIS, such as Jakobshavn (J), Kangerdlugssuaq (K), Helheim (H), and Petermann (P) glaciers. In SEGMENT-ice, ocean-ice interactions are parameterized so that the depressing of freezing point by solubles, salinity dependence of ocean water thermal properties, and ocean currents-dependent sensible heat fluxes are taken into consideration (SM).

As the climate warms, increased air temperature through turbulent sensible heat flux exchange increases surface melting and runoff. Similarly, changes in precipitation affects the upper boundary input to the ice sheet system. For the 200-year period of interest here, major ice temperature fluctuations are near the upper surface of the GrIS. The strain rate, however, can be large near the bottom and/or the surface, so SEGMENT-ice has a 31 vertical level stretched grid to better differentiate the bottom and near surface. The uppermost layer is 0.45 m thick near the GrIS Summit, fine enough to simulate the upper surface energy state on a

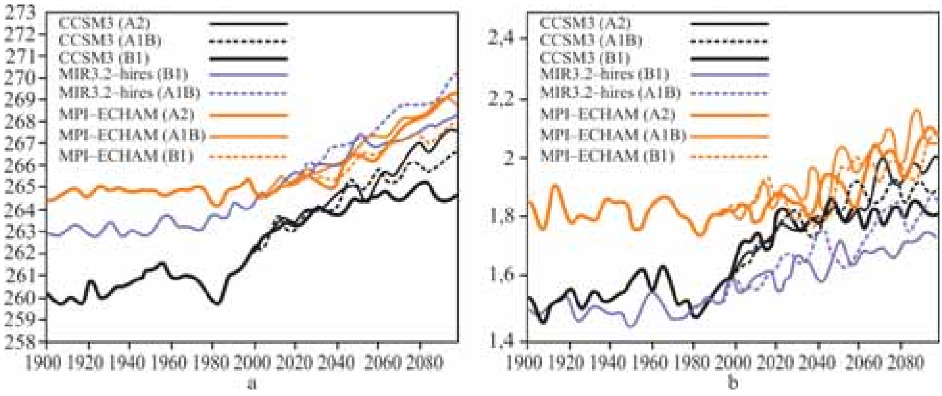

Fig. 2. Time series of low-pass filtered mean temperature (K) (*a*) and precipitation (mm/day) (*b*) over Greenland, from three climate model simulations with variations in anthropogenic forcing scenarios. Note that the SRES A2 simulation is not available for MIR3.2-hires

monthly time scale. Because of its location, the GrIS is an important contributor to eustatic SLR, ocean salinity and the North Atlantic thermohaline circulation [Yin et al., 2009; Alley, 2000]. In SEGMENT-ice, the total mass loss comprises surface mass balance and the dynamic mass balance due to ice flow divergence. Total mass balance is converted to water volume and is used here as a proxy for the eustatic SLR contribution.

In ice flow, inertial and viscous terms counteract pressure gradient forces. The full Navier-Stokes equations are used in the momentum equations of SEGMENT-ice. Because of comparably large aspect ratios, ice streams and surrounding transition zones are the areas where a full Stokes model is most needed [Zwinger et al., 2007]. Finally, there are two important improvements in the SEGMENT-ice numerics. Recently, the RAW (Amezcua et al. 2011; Williams 2009) filter has been adopted, in place of the more commonly used Asselin time filter. This treatment has improved both spin-up and the conservation energetics of the physical processes. A second improvement is in the optimization procedure of the data assimilation code. A quasi-Newton minimization scheme is now used instead of the conjugate-gradient scheme, which is less robust and less efficient for real, noisy data.

INPUT AND VERIFICATION DATA

SEGMENT-ice requires initial conditions and static inputs, such as ice thickness, free surface elevation, and the three-dimensional ice temperature field at the initial time of integration, obtained from the SeaRISE project (http://websrv.cs.umt.edu/isis/index.php), at 5 km horizontal resolution. The bottom geothermal distribution is assumed constant over the 200 year simulation. The SLR contribution from the GrIS is from the total mass balance: that is, input (e.g., snow precipitation, flow convergence) minus output (e.g., surface melt water runoff, flow divergence to open waters or calving). Atmospheric temperature, precipitation and near surface radiative energy fluxes are critical factors for the future total mass balance of the GrIS. The CGCMs provide the meteorological forcing. The large natural variability [Alley, 1993] justifies using extended atmospheric time series to extract the first-order feedback signal of the GrIS in a warming climate. The three independent CGCMs (MPI-ECHAM, NCAR CCSM3 and MIROC3.2-hires, see http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php) are chosen for having relatively fine resolution and providing all atmospheric parameters required by SEGMENT-ice. Their projections of precipitation and temperature, two key factors affecting ice sheet mass balance, produce a large spread in the multi-model assessments (Chapter 10, IPCC AR4) by 2100.

In addition to atmospheric parameters, investigating the ice ocean interactions at the water terminating glaciers (e.g., J, K, H, and P), the ocean flow speed ($\vec{V}$), potential temperature (*T*), salinity (*S*), and density (ρ) also are needed. Density is not an independent property because it is a function of temperature, salinity and pressure. For the outlet glaciers north of 70°N, the CGCM's ocean model output at depth 0, 10, 20, 30, 50, 75 and 100 m depths are interpolated to SEGMENT-ice grids. For the Helheim glacier, which resides in the Sermilik fjord, the 1-km resolution ice thickness data obtained from SeaRISE indicates that the terminus depth is about 700 m, close to the estimation of Thomas et al. (2000). Oceanic parameters up to 1000 m are used for this glacier. The University of Hawaii data (http://uhslc.soest.hawaii.edu/jasl.html) is used to evaluate the projections of regional SLRs.

RESULTS

SEGMENT-ice is integrated with climate model meteorological forcing over the GrIS, to provide the trend of total mass loss over the 21st century. The monthly atmospheric forcing and the advanced numerics of SEGMENT-ice can in principle produce physically realistic monthly fluctuations in ice sheet properties. However, interannual and decadal climate variations in CGCMs largely are random noise, as are ice model projected quantities on the same temporal scales. Thus there is no attempt to make a comparison with *in situ* observations of the model projections of inter-annual to decadal scales. Monthly (ice model output) quantities therefore are averaged to obtain annual mean values. A 21-point binomial smoother is applied to the annual means to remove any short-term variability. The smoothed lines in Fig. 1 show the eustatic SLR contribution from the GrIS for the 20th and 21st centuries. For each model, the atmospheric forcing is under the three non-mitigated IPCC Special Report on Emission Scenarios (SRESs): B1 (low); A1B (medium); and A2 (high rate of emission). Total ice volume is a highly aggregated metric and the trend is the resultant of several factors. Because inland GrIS remains cold, the feedback from increased precipitation (Fig. 2) is significant. Therefore, estimates of the GrIS contribution to SLR are less sensitive to scenario assumptions before 2030, even though the atmospheric forcing diverges from the year 2000. After 2030, as the atmospheric forcing diverges further, the differences become clear. The terms in the total mass balance indicate that the higher precipitation amounts from the strong scenario (Fig. 2) eventually is dominated by increases in ice flow divergence and surface melt water runoff. After 2060, there is an accelerated mass loss rate, as basal sliding becomes significant, especially beneath the southern tip and the north east ice stream, signifying a faster mass shed [Alley et al. 2005]. For the GrIS, the positive feedback from strain heating and reduced ice viscosity may have longer time scales (SM). The consensus is that weak scenario B1 causes far less total mass loss than the A2 and A1B scenarios, by the late 21st century.

As the climate warms, increases of temperature and precipitation scale nonlinearly with the emission strength (Fig. 2). Because increased temperature and precipitation are opposites as contributors to ice mass balance, a numerical model is needed to ascertain the sign of the total mass change and to quantify inter-scenario differences. SEGMENT-ice shows that the temperature signal is dominant. Both surface runoff and ice divergence increase as air temperatures increases. The relative contributions from surface melt and from ice flow divergence and calving indicate that the fraction from ice flow divergence increases during the transient climate change period. Thus, the total glaciated area varies little but the mass loss accelerates as the climate warms. At present, surface melt and ice flow divergence are almost equal [Rignot and Kanagaratnam, 2006]. This partitioning is symptomatic of near-surface warming. By the late 21st century, for the moderate A1B scenario, the ice divergence will contribute about 60%, outweighing the contributions from all other surface processes. After inter-model and inter-scenario averaging, the eustatic sea level contribution from GrIS is ~0.64 mm/yr for 2050-2100, significantly beyond the IPCC AR4 estimates. Inter-model and inter-scenario differences contribute ~20% uncertainty to sea level projections. Model simulations and observational studies [Mernild et al., 2009; Van den Broeke, 2009] of GrIS the last decade already indicate that 0.64 mm/yr is reachable (e.g., 0.7 mm/yr in Mernild et al. [2009]; 0.75 mm/yr in Van den Broeke [2009]). The lower bounds of the IPCC AR4 estimates should be raised by ~30 mm by 2100, assuming other SLR contributions are as estimated (by IPCCAR4). The eustatic SLR is an average of many factors on different time frames, including glacial isostatic adjustment [Peltier, 2001], expansion of water due to heat uptake (thermosteric), input from land ice, and changes in water storage on land and in the atmosphere. Because it is affected by wind stress, water temperature and salinity patterns, the absolute sea surface height (relative to the geoid) is high over tropical Pacific and Indian oceans and low over the Southern Ocean (south of ~ 55 °S surrounding Antarctica) and the Arctic Ocean. CGCM model projections of the dynamic sea level are similar in geographic distribution across both models and scenarios.

Sea surface topography is maintained by atmospheric parameters, so it is sensitive to climate changes and it produces corresponding regional sea level adjustments. In addition to factors affecting global SLR, the geographical distribution of SLR adds complexity, being further affected by changes in flow divergence/convergence from ocean currents [Landerer et al., 2007; Yin et al., 2009]. For example, owing to the Coriolis force associated with the Gulf Stream, the regional sea surface along the east coast of the United States has a slope tilting sea-ward. Fresh water discharge from the GrIS weakens the Atlantic meridional overturning circulation, suggesting a dynamic adjustment of sea surface elevation. For northeast coastal United States, this results in an additional SLR superimposed on the eustatic SLR. All CGCMs show the largest sea level rebound near the southern part of the Labrador Sea. However, the southern oceans are quite different. With the future strengthening of the Antarctic circumpolar circulation (ACC), the ocean surface slope maintained by the Coriolis force increases, with a significant SLR over an ocean belt at ~46 degree south. The mean change for 2091–2100, relative to 1981–2000, projected by three AR4 climate models under the A1B scenario, reaches 0.4 m over a 10^5 km^2 area of the southern Indian Ocean. A similar, smaller pattern occurs along the east coast of South America.

Contributions to SLR from GrIS melting are shown for 8 coastal cities, calculated from sea level changes with and without GrIS water routing. Southern hemispheric cities, Cape Town and Sao Paulo, are selected for their proximity to western boundary retroflection currents. Unlike the eustatic sea level change, which can be approximated empirically [Rahmstorf, 2007], quantifying the geographic manifestation of the 0.64 mm/yr global mean SLR requires including ocean currents. A CCSM3 sensitivity experiment was used to identify regional GrIS contributions to SLR. As the three major contributors: steric, melt water input and ocean dynamics are inter-connected, a coupled climate model is needed to investigate the effects of fresh water input. For a given scenario, a monthly injection is made from 1900 into the Atlantic Ocean. The GrIS net mass loss rate matches the time series in Fig. 2 but uses the geographical routing pattern from the ice model. Fig. 3 shows the geographic significance of the SLR, the sea level time series for three coastal cities: London, New York and San Francisco. The ensemble means of projected sea level change series from CCSM3 after 1900 and expected ensemble mean CGCM projections, neglecting GrIS contributions are compared. The CCSM3 rates are lower than observations (Fig. S4 has 5 other cities). For a 99.5% confidence interval, linear trends for observed and modeled SLRs are: 1.77 ± 0.35 and -0.13 ± 0.7 mm/yr for London; 1.84 ± 0.51 and 0.05 ± 0.1mm/

yr for San Francisco; and 2.64 ± 3.05 and 0.31 ± 0.67 mm/yr for New York. GrIS melting reduces the underestimation, especially for Atlantic Ocean cities (1.16 ± 0.7 for New York and 0.47 ± 1.0 mm/yr for London). The greatest rise, which is for New York City, is from 0.31 to 1.16 mm/yr and is 1/3 closer to reality. For the latter half of this century, the global 0.64 mm/yr SLR increases to ~1.69 mm/year near New York. Fresh water from the GrIS contributes most

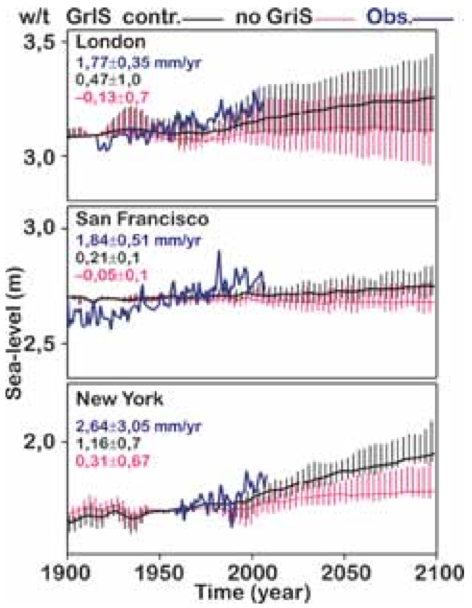

Fig. 3. CCSM3 simulated sea level evolution during 1900–2100. Model simulations are performed under the corresponding scenario run but with fresh water routing from the GrIS. The thick, 20-year smoothed black (red) curves are ensemble mean of the multiple model runs with (without) fresh water routing from the GrIS. Vertical bars are the upper and lower envelopes. Blue lines are from tide gauge observations (UHSLC research quality sea level station data). Climate model predictions are shifted so observed and modelled values match at the first observational data grid. The trends and uncertainty range (p = 0.05) over the observational period are also given. In generating the fresh water routing scenario, SEGMENT-ice is forced by CGCMs under different scenarios. For melting fraction of water, the routing scheme of the existing river transport model is used (over the GrIS, close to the basin division in Zwally and Giovinetto [2001]). The calving ice is transformed into a fraction of sea ice with zero salinity

to SLR northwest of the north Atlantic gyre, with greater vulnerability for cities like New York City. For ocean dynamic adjustment, alone, the London SLR slows and ceases after 2050 [Yin et al., 2009] as the water mass is redistributed to the west coast of the Atlantic Ocean, adapting to a reduced Coriolis force. However, fresh water from the GrIS increases sea levels near London. In contrast, melt water from GrIS is not a major SLR contributor in the Pacific Ocean (e.g., San Francisco) and in the southern oceans (e.g., Sao Paulo) where dynamic sea level adjustments are significant but the GrIS contribution is small.

DISCUSSION

Current CGCMs are not coupled with sophisticated land-ice models, so the uncertainty of the GrIS melting contribution to SLR is large. This study projects the eustatic SLR contribution from GrIS using a new ice dynamics model, SEGMENT-ice [Ren et al., 2011a]. Forced by CCSM3 atmospheric parameters, the SEGMENT-ice model is integrated for 200 years (1900-2100). The near-surface ice temperature increases for most of the GrIS (Fig. 5, [Ren et al. 2011b]). The greatest warming of over 3 °C by 2100, under SRES B1, corresponds to high precipitation areas in a band along the 2000 m GrIS elevation contour. The ice warming decreases inland and is minimal (~0.5 °C for SRES B1) at the Summit. As ice viscosity decreases with increasing temperature, the warming pattern adds extra divergence to the original flow field. This ice discharge process probably scales in proportion to surface temperature changes.

The average mass loss rate projected by SEGMENT-ice over the latter half of the 21st century is equivalent to ~0.64mm/year global mean SLR, significantly greater than the IPCC AR4 estimates. The lower limits of the IPCC AR4 estimation (0.01 m, under A1B) therefore should be increased to ~30 mm by 2100, with 95% confidence, assuming other sea level change contributors remain unchanged. To investigate the spatial distribution of the melt water, ice model simulated GrIS mass loss time series are used as input to climate models. The SLR is geographically non-uniform, reaching 1.69 mm/year for the northeast coastal United States, being amplified by a weaker meridional overturning circulation in the Atlantic Ocean. In other oceans, such as the Pacific and southern oceans, the projected changes are much smaller.

Both steric effects and contributions from melting mountain glaciers flatten with warming [Raper and Braithwaite, 2006] but the GrIS melting contribution accelerates before declining surface area becomes a limiting factor; this is highly unlikely during the 21st century.

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THE MORPHOMETRIC STRUCTURE OF THE *LARIX GMELLINII* RECRUITMENT AT THE NORTHERN LIMIT OF ITS RANGE IN THE FOREST-TUNDRA ECOTONE

ABSTRACT. The goal of the research presented herein is the investigation of the morphometric and age parameters of the recruitment of forest stands formed by *Larix gmellinii*, as an indicator of trends in the dynamics of the northern/upper forest boundary in the Russian Arctic, in Northern Central Siberia, in the Taimyr State Biosphere Reserve (the Ary-Mas site), and in the buffer zone of the State Biosphere Reserve "Putorana Plateau". The morphometric parameters clearly reflect the conditions of growth and regeneration of *Larix gmellinii* at the northern and upper limits of its range. Both sample sites have relatively harsh conditions for growth and survival. Despite coarse soils (high gravel content) of the Putorana slopes, their significant steepness, frequent landslides and creep, the conditions for *Larix gmellinii* growth are better than at the Ary-Mas site. This is also reflected in the rate of regeneration. Thus, at the comparable average height of the recruitment at the forest line, its age on the Putorana Plateau is almost half of that at the Ary-Mas site (9.7 and 17.3, respectively). However, the age of the recruitment at the tree line and at the forest line on the Putorana Plateau is practically the same, while at the Ary-Mas site, the recruitment age at the tree line is 1.5 lower than at the boundary of forest. These results could indicate a trend of *Larix gmellinii* expansion into the ecotone over the last 20–30 yrs., especially in the mountains of the Putorana Plateau.

KEY WORDS: recruitment of *Larix gmellinii*, morphometric and age parameters, ecotone, dynamics of the northern/upper forest boundary, State Biosphere Reserve "Taimyr" and "Putorana Plateau", Russian Arctic

INTRODUCTION

Studies on the effect of the recent climate change on ecosystem components are of interest from different perspectives: preservation of traditional forms of nature management of the northern indigenous peoples and biodiversity; extraction and use of resources; the thawing of permafrost; carbon balance; etc. This can be seen in a variety of topics and projects carried out within the framework of the International Polar Year (IPY). One of the issues addressed in the IPY projects *PPS Arctic* (Present Day Processes, Past changes, and Spatiotemporal Variability of Biotic, Abiotic and Socio-Environmental Conditions and Resource Components Along and Across the Arctic Delimitation Zone) and *Benefits* (Natural and Social Science Research Cooperation in Northern Russia and Norway for Mutual Benefits Across National and Scientific Borders) is the study of the dynamics of the northern/

upper limits of forests using data on the tree regeneration (tree individuals <2 m) as an indicator of this process.

These projects have developed methodologies for evaluation of forest stands' conditions, i.e., recruitment, age-structure, and morphometric parameters. These data allow assessing trends in vegetation cover. Changes in climatic and edaphic conditions and/or economic activities affect the ability of forest forming species to regenerate [Benkova, 2006; Bulygin and Yarmishko, 2001; Shiyatov, 2000]. Therefore, the abundance, morphologic features, and age-structure of forest stand recruitment are useful indicators of the recent succession processes and dynamics of the boundaries of the natural zones and belts.

RESEARCH OBJECTIVES AND METHODS

The goal of the research presented herein is the investigation of the morphometric structure of the recruitment of forest stands formed by *Larix gmellinii*, as an indicator of trends in the dynamics (expansion or retreat) of the northern/upper forest boundary in the Russian Arctic. The research used methods in the PPS Arctic and Benefits Programs. The research incorporated the results of the comprehensive field studies in 2010 in Northern Central Siberia, in the Taimyr State Biosphere Reserve (the Ary-Mas site), and in the buffer zone of the State Biosphere Reserve "Putorana Plateau".

In order to implement this goal, the following tasks have been addressed:

1. Investigation of the age of the recruitment of *Larix gmellinii* at the northern limit of its range (the Taimyr peninsula, Ary-Mas);

2. Investigation of the age of the regeneration of *Larix gmellinii* at the upper limit (elevation) of its range (the Putorana Plateau);

3. Identification of the morphometric and age parameters of the *Larix gmellinii* recruitment in the forest-tundra ecotone.

Following the guidelines of the PPS Arctic Project protocol, the samples of the *Larix*

Fig. 1. The area of the study on the dynamics of the northern/upper limits of forests under the PPS Artic Project

gmellinii recruitment were studied within the forest-tundra ecotone at the forest line (i.e. the border of the forest zone or the forest belt) and at the tree line (i.e. the boundary of isolated trees) for three size-groups: height <15 cm, 15–15 cm, and >50 cm, respectively. This methodology was also used in the arctic and alpine forest-tundra ecotones on the Kola Peninsula (Murmansk Oblast) near Lake Kanentiavr and in the Tuliok Ridge, Khibiny Massif (Fig. 1), respectively [Aune, Hofgaard, Söderström, 2011].

STUDY AREAS

<u>The site Ary-Mas</u> (the Taimyr Peninsula, the State Biopshere Preserve "Taimyrsky") includes the world's northmost forest "island" and is situated at the southern boundary of the arctic tundra [www.byrranga.ru]. This unique site was first described by A.I. Tolmachev and then was studied in detail by L.N. Tyulyna [1937] and the Polar Integrated Expedition of the Botanical Institute of the Academy of Sciences of the USSR [Ary-Mas, 1978]. The forest island is 20 km long and 0.5–4 km wide and is located on the high terrace of the Novaya River. The rest of the territory at this site is occupied by spotty and pit-and-mound sedgy-shrub-moss tundras, polygonal bogs, and, less frequently, by dwarf-birch tundras, floodplain shrubs, nival meadows, and meadow communities of floodplains. Larch forests (or rather sparse forests) in the central part of the "island" are relatively dense (canopy closure 0.3–0.4); they are much sparser to the east and west (canopy closure 0.1–0.2). The tree height is 4–7 m; isolated old larch trees are 10 m high with the trunk diameters of up to 25–30 cm; the average stem diameter is 10–14 cm. Trees of forest fringes with the canopy closure of less than 0.1, along the highest positions of the terraces, are 2–5 m in height; there, they are often lop-sides and have "flag" or "skirt" shapes (Fig. 2).

Fig. 2. *Larix gmellinii* (Ary-Mas) (photograph by A. Usacheva)

The understory of the *Larix gmellinii* includes dwarf birch *Betula nana*, *Empetrum subholarcticum*, *Ledum decumbens*, *L. palustre*, *Vaccinium uliginosum*,; in the floodplains, there are *Salix glauca*, *Salix lanata* and, sometimes, brier *Rubus arcticus*, *R. chamaemorus*, *Rosa acicularis*, and *Ribes triste*. The ground cover of the wet sites is dominated by typical tundra hypnum moss (*Hylocomium splendens, Aulacomnium turgidum, etc.)*; the dry high terraces have an abundance of lichens (*Cladina stellaris and C. mitis*, *Cladonia rangiferina*, etc.) The spotty and pit-and-mound tundras interspersed with open sparse forests are dominated by *Salix alaxensis*, *S. glauca*, *Dryas octopetala* and *D. punctata*, *Cassiope tetragona*, *Carex arctisibirica*, *C. glacialis* and the same moss species as given above.

<u>The Putorana Plateau.</u> The Plateau is a series of basalt formations 2000 m or greater in thickness that were formed beginning in the Carboniferous period [www.oopt.info]. It is dome-shaped and elevated with the highest mark of 1701 m. The territory of the Plateau

is covered by open boreal woodlands with two landscape provinces: East Putorana and West Putorana. The main climatic boundaries divide the Plateau in two directions. The first one defines the boundary between the northern taiga and forest-tundra, extending in the latitudinal direction along the cupola of the Plateau approximately. The second one divides the Plateau into the western and eastern parts between 93-94°E. The provinces have some similar geographic and orographic features but differ in terms of climate, hydrography, soils, and vegetation. The climate of the eastern part is very severe and sharply continental. From October through March, a persistent high-pressure region dominates; the average precipitation is 300 mm. The longitudinal boundary limits the range of the western taiga species: Siberian spruce, mountain birch, Siberian larch, and a complex of associated plants. To the east of this boundary, *Larix gmellinii* dominates in the forest zone, which reflects the increase in the continentality of climate in the eastern direction.

Altitudinal zonality is well pronounced in the vegetation of the Putorana Plateau: forest, forest-tundra ecotone, tundra, and polar deserts. Forest vegetation occupies the valleys: its vertical extent depends on the latitude (increasing to the south), on the amount of precipitation (the tree line is lower to the west), and on the local conditions (exposure, protection from the wind, etc.). On the outer boundaries of the Plateau, the vegetation of the valleys gradually transitions into the zonal. The dominant species in the forest belt is *Larix gmellinii* [Vodopyanova, 1976; Kuvayev, 2006; Malyshev, 1976; Pospelova, Pospelov, 2007].

DATA COLLECTION

The Ary-Mas site. To study the dynamics of the northern boundary of the forest area Ary-Mas located on the east bank of the Ulakhan-Yuriakh River, a 2,550 m long terrain profile was established. The profile with the positions of sample plots superimposed on satellite images is presented in the paper by V. Kravtsova, O. Tutubalina, and A. Hofgaard [2012]. Along this line, 197 samples related to the *Larix gmellinii* recruitment were studied; of these, 83 were from the forest line and 114 from the tree line; all samples were divided into the three studied size-groups.

The Putorana Plateau site. The upper limit of the forest was studied at the site of the Putorana Plateau in the low-reaches of the Omon-Yuryakh River. To identify the dynamics of the upper forest boundary, a 1,000 m long profile was established. The profile line and the location of the sample plots superimposed on the satellite images are also presented in the paper by V. Kravtsova, O. Tutubalina, and A. Hofgaard [2012]. Along this line, 261 samples of the *Larix gmellinii* recruitment were studied; of these, 116 were from the forest line and 145 from the tree line; all samples were also divided into the three studied size-groups

The field studies involved the identification of the position of each sample and recording of the total stem length and the vertical growth in 2010. The lab studies involved microscopic identification of the stem age (Fig. 3); its maximal, minimal, and the average root collar diameter; and the growth and damage (including frost, animals, etc.) [Budarina, Golubeva, Silenchuk, 2011].

Fig. 3. *Larix gmellinii* (A larch sample. The Putorana Plateau. The tree line. Age is 30 yrs.; diameter 2.12 cm; height 142 cm, the 2010-11 cm shoot length (photograph by K. Silenchuk)

DISCUSSION OF THE RESULTS

The averaged morphometric parameters of the sampled *Larix gmellinii* individuals are presented per area in the table below (Table 1).

The Ary-Mas site. At the forest line, the average age of the recruitment is about 20 yrs. The first group: the average age of the recruitment shorter than 15 cm is 8 yrs. The second group: the average age of the recruitment 15–50 cm in height is 20 yrs. The third group: the average age of the recruitment taller than 50 cm is 32 yrs. The diameter increases with age from 0.15 to 1.2 cm and the height from 13 to 82 cm. At the tree line, the average recruitment age is 19 yrs.; however, the first group of the recruitment, with the heights shorter that 15 cm, is absent. The recruitment of the second group (15–50 cm in height) has the average age of 17 yrs.; the recruitment of the third group (the height is taller than 50 cm) has the age of 24 yrs.; the average height changes from 34 to 76 cm.

The Putorana Plateau site. At the forest line, the average recruitment age of *Larix gmellinii* is 15 yrs. The recruitment shorter than 50 cm has the average age of 10 yrs.; the average age of the recruitment taller than 50 cm almost doubles and reaches 18 yrs. At the tree line, the average age of the recruitment is 12 yrs. The recruitment shorter than 15 cm has the average age of 7 yrs.; the recruitment 15–50 cm in height is younger than 10 yrs. on average; the average age of the recruitment taller than 50 cm is approximately 18.6 yrs. The average diameter of the recruitment increases with age from 0.2 to 1.2 cm; the average height increases from 13 to 93 cm.

The analysis of the morphometric parameters of the *Larix gmellinii* recruitment allows identification of the trends in the forest stand development in this region presented below.

The age of the *Larix gmellinii* recruitment at the tree line and the forest line on the Putorana Plato is practically the same, while at the Ary-Mas site, the recruitment age at the tree line is 1.5 lower compared to the forest line. This fact suggests expansion of the northern border of forest and the trend of advancement of larch into the tundra plains over the last 20–30 yrs. At the Ary-Mas site, the recruitment of the third group dominates (the height of 50 to 200 cm). The rate of the *Larix gmellinii* recruitment decreases with age; in the second group (15–50 cm), the annual vertical growth is almost 15% of the total stem height, while in the third group (taller than 50 cm), the annual growth of the recruitment does not exceed 7% (Table 1; Fig. 4). There are differences in the growth of the recruitment of larch along the studied profile: the speed (intensity) of the vertical growth increases to the north.

A similar pattern of growth of the *Larix gmellinii* recruitment is observed on the Putorana Plateau. The young growth of the second group prevails quantitatively (the height 15 to 50 cm) (Table 1; Fig. 5). The highest annual vertical growth of 10% is in recruitment of the first and second groups, while in the third group, it does not exceed 6%.

Table 1. The morphometric parameters of the *Larix gmellinii* recruitment. The test plots Ary-Mas and Putorana Plateau

Test plots		Ary-Mas				Putorana Plateau			
Position in the eco-tone	H of the regenera-tion, cm	H, cm	ΔH, cm	Ø, cm	Age, years	H, cm	ΔH, cm	Ø, cm	Age, years
Forest line	<15	13	0.7	0.15	8.0	–	–	–	–
	15–50	36	2.7	0.50	20.0	29.9	4.1	0.33	10.6
	50–200	81.9	4.6	1.20	32.0	93.7	5.7	1.26	18.3
Tree line	<15	–	–	–	–	12.7	1.7	0.2	7.0
	15–50	34	4	0.40	17.3	28.4	2.5	0.3	9.7
	50–200	76.4	7.5	1.40	24.0	93.0	6.1	1.2	18.6

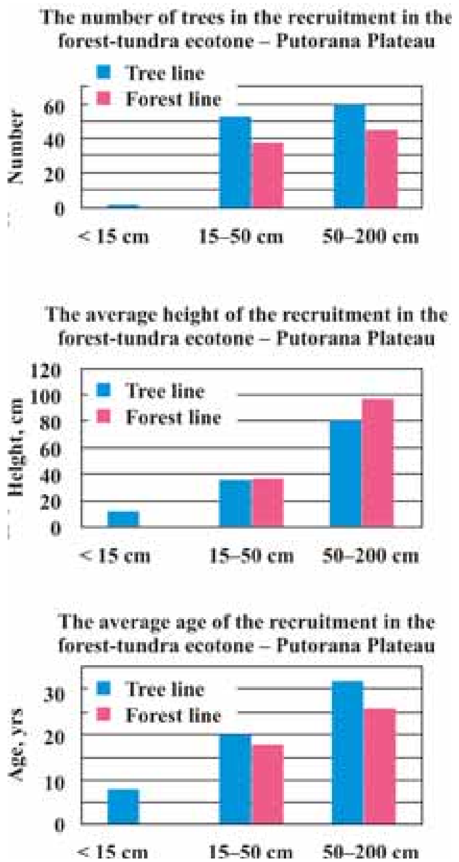

Fig. 4. The morphometric parameters of the *Larix gmellinii* recruitment in the forest-tundra ecotone at the Ary-Mas site (Taimyr Peninsula)

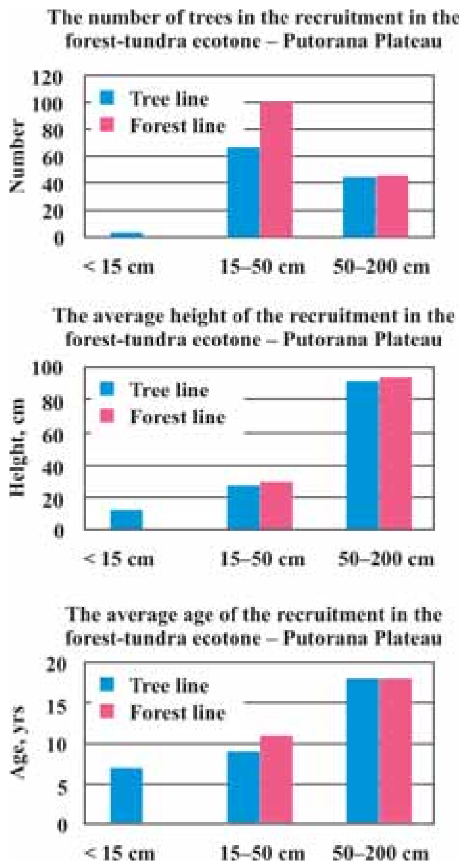

Fig. 5. The morphometric parameters of the *Larix gmellinii* recruitment in the forest-tundra ecotone

CONCLUSION

The research on the morphometric parameters of the *Larix gmellinii* recruitment at the upper and the northern boundary of the forest-tundra ecotone allowed drawing the following conclusions:

1. For the northern boundary of the forest, the average age of *Larix gmellinii* in sparse forest is 26 years; it is 32 years for the tree line. The recruitment with the heights of 50–200 cm dominates; the average height is 81 cm and 78 cm in the open stands and the isolated trees, respectively. The vertical growth of the recruitment differs and increases in the northern direction.

2. For the upper forest boundary, the average age of the *Larix gmellinii* recruitment is 19 yrs. (forest line) and 13 yrs. (tree line). The recruitment with the height of 50–200 cm dominates. Its average height is 77 cm and 71 cm at the forest line and at the tree line, respectively.

3. The morphometric parameters clearly reflect the conditions of growth and regeneration of *Larix gmellinii* at the northern and upper limits of its range. Both sample sites have relatively harsh conditions for growth and survival. Despite coarse soils (high gravel content) of the Putorana slopes, their significant steepness, frequent landslides and creep, the conditions for *Larix gmellinii* growth are better than at the Ary-Mas site. This is also reflected in the rate of regeneration. Thus, at the comparable average height of the recruitment at the forest line, its age on the Putorana Plateau is almost half of that at the Ary-Mas site (9.7

and 17.3, respectively). However, the age of the recruitment at the tree line and at the forest line on the Putorana Plateau is practically the same, while at the Ary-Mas site, the recruitment age at the tree line is 1.5 lower than at the boundary of forest.

These results could indicate a trend of *Larix gmellinii* expansion into the ecotone over the last 20–30 yrs., especially in the mountains of the Putorana Plateau and is likely primarily associated with the climate change because anthropogenic impact on the vegetation cover in the conditions of the Reserves' regime is practically absent. However, a firm conclusion can't be made, as the mortality rate within the three size groups of recruiting larch is unknown.

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INTERNATIONAL ECONOMIC COOPERATION OF THE ARCTIC REGIONS

ABSTRACT. The paper discusses the levels and intensity of economic cooperation of the Arctic countries and regions. There has been unprecedented economic interaction between the Polar countries over the last 20 years. The paper identifies the fundamental principles of international economic cooperation in the circumpolar area. It describes scenarios of development of the Russian Arctic to the year 2020, which vary depending on the intensity of economic cooperation in the circumpolar area.

KEY WORDS: international economic cooperation, circumpolar area, levels, fundamental principles of Arctic cooperation

INTRODUCTION

The volume of the Arctic economy in 2009, measured as GDP, amounted to about 180 billion USD, which is comparable to that of the economies of Finland, the Philippines, Nigeria, and Singapore; it generates 7% of the economy of the Russian Federation. In per capita terms, the Arctic is the world's leading economy: in 2009, the per capita GDP of the Arctic population was around 50 thousand USD. Population of no country in the world has such a high per capita GDP[1].

Although the Arctic economy is part of the national economies of very different levels of socio-economic development and political organization, it has the essential features which, on the one hand, distinguish it from other territories such as moderate or tropical zones, and, on the other hand, there exists supranational unity of the Polar territories of different countries and continents. All this creates objective preconditions for increased economic cooperation in the Polar regions and countries, which has been progressing over the past two decades. There is strong evidence that this modern growing trend will keep its intensity in the future.

DATA AND DISCUSSION

Three sectors of the Arctic economy – three directions of economic cooperation in the Polar regions and countries. The Arctic economy is formed by three essentially different, but closely interacting with each other, globally oriented sectors: global resources, transfer economy, and traditional economy[2]. The globally oriented resource sector supplies the world markets with diamonds, gold, oil, natural gas, nonferrous metals, and biological resources.

However, after all, doesn't the traditional sector, involving the indigenous small peoples of the North, concentrate around natural resources too? Yes. However, if the first one is focused on external supplies, the second one serves domestic needs of the local population, enhances its food self-sufficiency, and supports the age-old tradition of reindeer husbandry and traditional industry (fishing, hunting fur animals, gathering, etc.).

Of particular importance is the traditional sector in rural and peripheral areas of the Arctic. For example, studies show that in the mid-1980s in the ethnic villages of northern Canada, real income of the indigenous people from hunting fur animals was higher than income from employment in the budgetary or market sectors. More than

[1] Estimates of my foreign colleagues Ilmo Mäenpää and Lee Huskey.

[2] The concept of the three-sector Arctic economy belongs to Lee Huskey (Professor of University of Alaska, Ancorage) – a bright sicientist with a rare talent to express complex sicientifc issues in an easy and accessible way.

80 percent of Alaska households use fish and wildlife resources.

The transfer sector provides local economy with fiscal resources from all levels of government – federal, regional, and municipal, which guarantees a minimum set of services to local residents and often significantly raises local income of households in the Arctic.

The three-sector structure of the Arctic economy defines the cooperation between the participants of the economy of the Polar regions and countries. This involves cooperation in implementing resource mega-projects that target export markets; cooperation of governments, for example, in implementing international infrastructure projects, resource management, state and municipal management; partnership of budgetary research and educational institutions; collaboration of numerous non-profit organizations of the small-numbered peoples of different Polar countries for direct (through income and employment) and indirect (in the form of conservation as an integral part of traditional culture and the foundation of modern economy) strengthening of the role and value of the traditional economy (reindeer herding and traditional crafts). Economic cooperation is taking place simultaneously in the Arctic territories within major projects and initiatives and small, but very significant for the preservation of cultural identity, initiatives and projects (e.g., national small business).

Knowledge and experience is shared between the Polar economies through cooperation in the transfer and resources sectors. International cooperation of the structures of the indigenous small-numbered peoples of the North is occurring through fusion of culture and economy.

The Arctic as the zone of intense international economic cooperation. Arctic peoples for centuries have been involved in trade and information exchanges with each other implemented very often "above" the national borders. In the XXth century over the decades of the cold war and the superpowers' military confrontation, the intensity of the international economic cooperation of the Polar regions and countries was very weak.

However, after the period of the Arctic military confrontation in the early 1990s, economic cooperation of the Polar countries has increased unprecedentedly. Its most important modern feature is that it now goes without regard of proximity: earlier in economic history, the interaction of Polar territories always followed the laws of distances: the closer, the more intensively.

Today, due to emergence of new international economic and political institutions in the last 20 years, international cooperation in the Arctic is significantly freer from the pressure factors of proximity than ever before. Of course, this is also promoted by new telecommunication technologies that allow easy communication between the participants of economies and large and small firms of the most remote Polar regions.

With some exaggeration, it is possible to call the modern Arctic the unified area of economic cooperation. Here, it is appropriate to recall a statement by A. Marshall on the industrial regions where "atmospheric" phenomena of the geographic localization emerge, leading to increased productivity as a result of rapid pick-up of new ideas from each other: "The secret of trade is no longer a mystery, but as if in the air.... Good job is correctly evaluated, inventions and improvements in the overall business processes and organization are appreciated, if one person starts with a new idea, it is embraced by others and is combined with their own reasons, and thus it becomes a source for new ideas" [Marshall, 1993].

The crucial difference in the Arctic is that these effects there are achieved not by a localized high density of interaction of participants in the economy – in sparse polar environment there are no conditions for this, but by networking of close and distant participants and by their intensive internal and external communication in the same networks. Another difference is associated with the fact that this economic cooperation has not been yet implemented and joint projects and initiatives are only being discussed. The number of planned projects certainly dominates over already implemented. However, the unprecedented affinity for Polar cooperation of many participants of the economy of various countries and regions is meaningful.

In 2011, the author attended the Russia-Canada-Norway business forum at Carleton University in Ottawa and was taken aback by the variety of business ideas for building, strengthening, and broadening cooperation in the Polar areas: cross-polar flights, sled dog racing, Arctic eco-tourism, including icebreaker to the North Pole, a local heat supply technology, etc.

In hindsight, in the period of the development of an enticing and romantic concept of the Arctic region, there is a temptation to "rediscover" history of economic cooperation in the Arctic so that only the period that falls out of it, as not fitting in the general trend, is the cold war of the XXth century. However, it would be contrary to the truth. Periods of confrontation in the Arctic, existed previously.

It will be very instructive to refer to the X–XV centuries' history of colonization of Greenland by Norwegian Vikings. The major cause of the disappearance of the colony of Vikings was their lack of cooperation with the local Inuit. The Vikings of Greenland had awonderful opportunity to survive, if they would have learned techniques of hunting and fishing (which Eskimos managed to do, having learnt from Vikings the technique of knives making) and would have traded with the Inuit [Diamond, 2006, p. 255]. The cultural barriers to intermarriage were a significant economic loss in viability of the local colony and, eventually, caused its disappearance. Irony was that the Vikings were dying of hunger in the presence of significant food resources that they did not use for reasons of religious taboos [Diamond, 2006, p. 274].

Levels of international economic cooperation in the Arctic. Economic cooperation today is interconnected and simultaneous on several levels: the Arctic countries, regions, municipalities, individual businesses, non-profit organizations, and individuals. The structuring of international economic interaction is not specific to the Arctic zone and can be applied to any country of the world. The characteristic feature of the Arctic is substantive content of each level of international cooperation.

The critical nature of *inter-State* economic interactions of the Arctic countries is the participation of the unitary countries, fully or partly included in the Arctic zone (for example, Iceland and Greenland are fully in the zone, while Norway, Sweden, and Finland are only partially there) and the federated countries, e.g., United States, Canada, and Russia. Impetus for cooperation and its character in federated and unitary countries and in unitary countries fully or partially within the Arctic zone vary inevitably. Thus, in federated countries, as shown by the realities of the early years of the culmination of the cold war in the early 1990s, incentives to economic and humanitarian cooperation are seen coming more from below, at the level of the subjects of the economies of the Polar regions and municipalities, than from federal centers physically and mentally removed from the Arctic. Here, the lead of the booming "people's diplomacy" over more inertial official inter-State economic partnership is much stronger.

This contrast does not exist in the entirely unitary polar countries, where rate, interests, and the nature of inter-State cooperation, at the civic level and at the level of participants of the economy, often coincide. This conflict of interest and the two rates of economic cooperation, i.e., of the official top-down and of the bottom-up, are more evident in the unitary countries that are only partially in the Arctic zone. However, even there, it does not have the sharpness characteristic of the Northern federations.

Of course, the political structure of a country and its economic-geographical location in

Table 1. International cooperation in the functions of GosComSever of Russia[3]

	1999	1998	1996	1992	1991
Provision of proposals on international cooperation in the Arctic and the North, participation in their implementation	x	x	x		
Analysis of foreign experience of economic and social development of the Northern revival, culture, and traditional way of life of indigenous peoples				x	x
Promotion of foreign economic ties, expansion of the export base of the regions of the North, bringing in foreign investment, establishment and operation of joint ventures					x
Cooperation with international and foreign organizations and research centers, resource management, and restoration of indigenous peoples of the North				x	
Issuing of permits to Russian and foreign individuals and legal entities for tourism business in marine areas close to the northern coast		x			

the Arctic zone (completely or partially) define the accessibility and speed of the country's involvement in the international economic cooperation. In Russia, ideas and projects of economic cooperation in the Arctic were especially successful in the 1990s during the period of substantial decentralization of the federal power. Specifically at that time and at the federal level, the State Committee on the North (GosComSever) has been established. One of its functional responsibilities was participation in international economic cooperation in the North and the Arctic. Among more than 60 functions mentioned overall in all five governmental statutes on GosComSever (during the 1990s, the Committee was established, dissolved, and re-established five times), five related to international cooperation (Table 1).

In the course of establishment of the hierarchy of federal power in the 2000-s, GosComSever of Russia was eliminated, the grass-roots initiatives gave way to more inertial development of inter-State Arctic initiatives of the Russian Federation in international structures of the Arctic Council, the International Arctic Science Committee, and other Arctic associations and councils.

In the past five years, the issues of international cooperation, including economic, are defined in most Arctic policies of the Polar countries. However, most clearly this theme (international economic cooperation) was developed in the Norwegian document [The Norwegian Government's High North Strategy, 2006]. This document discusses numerous directions and structures of such cooperation and the ways of filling it with more innovative and knowledge-based substance.

The authors talk about the multilateral economic cooperation with Russia in matters of fisheries, oil and gas production, creation of special institutions and structures of international economic cooperation in the form of an industrial cooperation zone encompassing Russian and Norwegian waters and land, and establishment of an innovation center and a business-incubator for Norwegian companies involved in such cooperation. The document also talks about interdisciplinary cooperation between Arctic researchers and the institutions of Norway and Russia in sociology, law, and natural sciences for the sake of knowledge sharing. The document speaks about sharing of competency and practice in creation of an offshore oil cluster, including industrial associations and networks of suppliers established in the course of shelf hydrocarbon resource development. It also talks about feasibility of participation of Norwegian sub-contractors in the development of the Russian hydrocarbon fields on the Barents Sea

[3] The Table was compiled from the analysis of the five official statutes on GosComSever of Russia approved by the government of the Russian Federation in different years.

shelf. The government of Norway declares its support for creation of the Norwegian-Russian network of sub-contractors in the oil sector. The document lists programs that carry the mission of promoting international cooperation in the Arctic. These include the European Development Co-operation Instrument, the Kolarctic Programme, the Northern Periphery Programme, and some programs of the European Union.

A special place in interaction of Polar federations (United States, Canada, and Russia) is occupied by *a regional* level of international economic co-operation. For example, during a major decentralization of economic and political power in Russia in the 1990s, it was the northern and Arctic regions that were the main initiators of the joint projects of enterprises and of economic and cultural activities with foreign partners in the Arctic – initially, through cross-border cooperation, but, later, in a much wider area. The author had an opportunity to participate in scientific cooperation between the North-East of Russia and the State of Alaska in the first half of the 1990s and, then, to participate in a joint three-year-long project funded by the Eurasia Foundation on the transfer of experiences of socio-economic development of the State of Alaska as the northern territory for application in the Russian northern and Arctic regions.

During this time, the leaders of the Russian Arctic regions were clearly divided into those who were open to international economic cooperation and ready for a wide partnership with foreign partners and those who were not receptive to such cooperation in the name of protection of geopolitical interests of Russia and who attempted to limit its format and content in the Polar territories to the maximal extent possible. The contrast between these models of governments was especially apparent when, in the same region (for example, in the Chukotka Autonomous District) during ten years, there were two teams of governmental leaders adhering to absolutely different philosophy in respect to international economic ties. Despite all the risks of the first model of the regional government (for example, a possibility of penetration of foreign partners in defense-sensitive territories and regions), it allowed gaining new experience, knowledge, competency, and technologies for the development of the Russian Polar region.

Let us look at a concrete example of the northern region of Russia to demonstrate how international economic cooperation with other northern regions of the world was deploying. The initial formulation of policy in the sphere of international economic relations of the region began with a moment of radical economic reform and political decentralization, i.e. from 1992 onwards. The subsequent 20-year period of the international economic cooperation can be divided into three phases.

The first phase – 1992–1997 – *the establishment and expansion* of international relations in all areas: increase in the number of foreign partner-regions, growth in the number of structures involved in cooperation of regional authorities, and first international contacts of municipal entities. During this period, a special unit responsible for external economic relations was created within the regional government. Similar developments were taking place in many other Arctic and northern regions of Russia. Because of active building of first contacts with international organizations in the northern and Arctic regions, Russia has joined the International Association "the Northern Forum."

The second phase – 1998–2002 – *the deepening* of the region's external relations after the adoption of the basic regional laws, intensive work of the Committee on International Relations with customs offices, and active work on entering into and providing reviews of international contracts financed from the regional budget. In this period, there began international training programs, for example, a Russian-Canadian program INRIPP "The Institution Building for Northern Russian Indigenous Peoples Project" in the Yamalo-Nenets and Khanty-

Mansi Autonomous Districts. The specialists of the regional and municipal authorities and members of public organizations received training in Canada. The result was the creation of a regional national corporation of indigenous small-numbered peoples of the North.

The third stage – from 2002 onwards – *the significant increase* in international cooperation and diversification of many old and new tracks. There is an urgent need to "recycle" international relations of the Arctic regions of Russia into a dynamic sustainable development turning them into an active factor of progressive structural change and technological upgrading, ensuring through optimization the increase in the number of participating companies, types of export activity, and volume of attracted foreign investment, opening new markets and technological and institutional innovation, effective for rooting on local soil.

Many of Russia's Polar regions, even those actively involved in international economic cooperation with other Polar territories, have insufficient economic returns from external links in the form of foreign direct investment, new jobs, increasing income of the regional budgets, and the real income of households. In view of the enormous value of international relations for the open economy of the Arctic regions of Russia, it is particularly important to widen interpretation of the notion of "international relations" as much as possible – not just as foreign trade, but as material, energy, financial, and information flows (of migrants, products, resources, energy, and information) taken as integrity and collectively.

One of the main areas of attraction of foreign investments into the economy of the Arctic regions of Russia is the establishment of enterprises with foreign investments in the form of equity participation. Most large enterprises with foreign investments are usually created in the resource sector of the Arctic. The value of enterprises with foreign investments is not limited to quantitative indicators of employment and tax payments to local budgets. They facilitate the transfer of new knowledge to production and process of learning; they represent knowledge-based conductors to the basic sectors of the economy in the Arctic regions of Russia.

Common shortcomings of international economic cooperation of the Russian Polar regions, as the experience of the last two decades demonstrates, are: mono resource-based structure of the export economy, the lack of involvement in the sphere of international economic activity of enterprises of small- and average-size business and poor information support for their work on the part of the government, the lack of a list of investment projects developed in accordance with international standards and industrial zones that have developed infrastructure ready to host foreign investors with medium investment costs of projects, the lack of a quality control system similar to ISO-9000+ and the global certification of goods and services (no targeted actions in this area), the lack of international relations specialists (managers, logisticians, engineers, lawyers with knowledge of foreign languages, marketing, etc.) and, as a result, the lack of experience of successful implementation of big investment projects with foreign capital participation in most Polar regions.

There are several priorities in international economic cooperation in the Russian Arctic regions. It is necessary to orient this work toward pragmatic solution of their acute economic and social problems. It is very important that this cooperation works toward building their positive image and strengthening of investment attractiveness. The work of foreign economic relations must be well coordinated at the regional level by the special structure of the regional authorities. However, this requires constant improvement of professional skills of the staff in charge of international relations and external communications infrastructure. The problem here is that regional structures (Chamber of Commerce, Entrepreneurship

Support Fund, University, Statistical Board, etc.), which could potentially enter into a network of partners and become part of a unified infrastructure of international economic cooperation, in reality interact among themselves and with regional authorities, responsible for international relations, on an irregular and spontaneous basis.

For many Polar regions there is a challenge of systematizing of yet scattered data into a unified integral data base and of arranging sample surveys of international activities – via telephone and by mail with survey questionnaires as is customary in the activities of foreign and some Russian regional committees on external relations. Of course, the most important task is improving the effectiveness of budget expenditures in implementing international relations and ensuring the economic security of the Polar regions in international relations.

It appears that *the municipal* level of international economic cooperation has the greatest role and importance and the most developed in the unitary polar countries. In federated countries, it is typically constrained (is in the "shade" of partnerships of the Arctic regions). That is why we will review in greater detail the potential of the international economic cooperation of Russian Polar cities that remain unrealized.

In the Russian Arctic, one can distinguish three types of cities: large administrative centers with diversified economies, developed educational and scientific structures, the mid-tier industrial segment, and a substantial local budget; company towns of various sizes with significant volumes of industrial production; and port cities that are much weaker economically. For large administrative centers, it is important to become productive innovation and university centers, capable of dissemination of innovations within substantial surrounding territories. For company towns, it is important to overcome the industrial legacy, to enhance comfort and diversify the local economy and social environment, and to make socio-economic development more sustainable. For port cities, it can be feasible to create intelligent logistics facilities and comprehensive security centers along the Northern Sea Route, including forecasting service. Specifically these objectives should be targeted in the development of urban foreign economic relations of the Russian Arctic.

Despite the existence of the three types of the Russian Arctic cities, with theirs individual distinct characteristics, they have common problems of small business development and economic diversification; the task of reduction of the proportion of temporary and shabby housing and temporary housing using new technologies and materials; massive introduction of effective thermal technologies into the municipal sector; and adaptation of the urban economy and the social sphere for the inevitable process of aging of the population.

In the conventional cities, small business was traditionally understood as a guarantee of employment, flexibility, and, in some cases, the innovation potential of the local economy. However, for northern company resource towns, its role is different. Small business there is the key to diversification of the local economy and creation of a new face and new image of the town. Its development encounters certain local barriers associated with salary contrasts between large and small enterprises, greater loyalty of local authorities with regard to the core business (and not to small businesses), and the selfish and dominant economic behavior of the town-forming enterprise not willing to cede market share to small participants of the economy. As demonstrated by the border northern Russian regions, international cooperation in the transfer of advanced technology, infrastructure, finance, institutional support of entrepreneur could significantly advance the level of their development.

Table 2. Rating of the regions by the level of small business development in 2009

Region	Rank	Value index
Krasnodar Kray	1	10
St. Petersburg, Russia	2	8.9
Moscow	3	8.1
Kaliningrad oblast'	4	7
Stavropol Territory	5	5.2
Sverdlovsk oblast'	6	4.7
Sakhalin Oblast	7	4.6
Khanty-Mansi autonomous district-Yugra	8	4.6
Magadan oblast'	9	4.4
Moscow oblast'	10	4.2

Thus, as a result of a long-term education in the area of entrepreneurship development and support by technical experts from Alaska in Magadan in the Russian-American Scientific Educational Center for Business in the 1990s[4], the Magadan region (where the bulk share of small businesses is being formed in the regional center Magadan), according to the NISIP[5] rating, was among ten Russian leading companies in terms of small business development in 2009 (Table 2).

Another priority area for cooperation of the Russian Arctic cities is new technologies and materials for residential construction. Housing in an Arctic city has an exceptional role. It is directly linked to the domination of either temporary or long-term residency in the city. If the share of dilapidated housing is large, i.e., almost no individual residential construction, this could be a sign of the dominance of temporal residency. On the other hand, this situation can be changed toward more permanent residency of the population with enhancement in the housing quality and availability in the local community. The Canadian experience (for example, the Housing and Development Corporation in Yellowknife) suggests that housing construction, including timber houses and small hotels, in the circumpolar and northern cities of Russia is essential for the formation of comfortable urban environment. It needs to expand geographically and with application of other new technologies of Arctic construction used in foreign polar cities.

Russian polar cities have significant potential (reserves) in reducing the costs of heat and energy and strengthening thermal efficiency of the local utilities and the public sector. This includes a system of process, institutional, and financial activities aimed at reversing the trend in the wasteful use of imported, from hundreds of kilometers away, energy carriers and heating fuel and shifting to local sources of heat and energy where possible and economically justified. Such system has already been built in many foreign cities and it is feasible to be gradually implemented it in Russia.

Recently, Russian and foreign cities have encountered similar demographic problems of progressive ageing of the population, increase of the prevalence of female population of 40 and older yrs., and decrease in the population due to a negative migration balance not compensated by the natural increase. In the future, it is reasonable to expect growing trends toward increase of ageing population over the working age due to the growth of the number of retiring baby-boomers born in the postwar 1950s-1960s, growth of their life expectancy, and decrease of the population entering the working age group due to low birth rates of the 1990s. Practice of foreign, primarily, of Scandinavian periphery northern cities, in providing services to older citizens (e.g., in the Kiruna municipality) may prove to be very beneficial in Russia.

Common problems of the Russian and foreign Polar cities, even considering their differences caused by decades of development in industrial economies based on different systems of property rights to basic material and natural assets,

[4] This experience was presented in detail in a monograph by Pilyasov, A.N. and Talanov, S.G. Small business of the Magadan region (assessment of conditions, sectorial structure, and support options). Magadan: Russian-American Small Business Support Center. 1997. 50 p.
[5] Institute of Business Studies.

maybe addressed using institute of twin-cities in enhancing international economic cooperation. Unfortunately, this instrument of forming partnership networks at the municipal level has yet to be used to its full capacity. Even powerful, in terms of budgets, Russian Polar cities rarely have twin and long-term partnership relations supported by agreements with foreign Arctic cities. Meanwhile, this format of relations brings international cooperation of Russian cities to a new, more comprehensive, systematic, and integrated level.

The *primary or atomic* level of international economic cooperation in the Arctic is primarily partnership of non-for-profit entities and individuals, business, and corporate structures. In view of the special role played by universities (innovation and knowledge) in the new economy, we will review their international cooperation in more detail.

Russian Polar universities of Murmansk, Norilsk, and Yakutsk undertake cooperation in education, science, and culture with international scientific and educational organizations and with the University of the Arctic. Exchange of experience takes place during collaborative projects and international seminars. However, it appears that the potential of the form and depth of international cooperation is not limited by these activities only. Universities are able to inject a new quality of relations of Arctic cities and regions through non-formal and confidential communication with foreign partners on their sites (which is not possible, for example, within formal government structures) and to increase the power of partnership activities.

A very instructive example of the ***atomic*** cooperation at the level of individual Arctic structures is a two-decade-long international cooperation of the Russian Association of Indigenous Peoples of the North, Siberia, and the Far East, which promoted emergence of dozens of small national businesses (communities, farms, etc.) and adoption of foreign equipment and technology for support of businesses of indigenous people in Russia.

Another example of the ***atomic*** cooperation of individuals is the discovery by a Russian geologist Nikolai Pokhilenko in 1994 of a diamond filed near Snap Lake in the Northwest Territories of Canada. This representative of the Russian geological school helped increasing the revenues of the local community multifold and changed the structure of the world diamond market.

A Norwegian-Russian logistics company "Tschudi" with its headquarters in Kirkenes and Murmansk specializes in international Arctic transportation and customs clearance. It has been very constructive in promoting the Northern Sea Route as an attractive transit route for regular transport of energy and mineral resources between Europe and Asia. The company pragmatically uses recent objective trends: reduction of the area of sea ice in the Arctic Ocean under the influence of climate warming of the last two decades, the high prices of natural resources and global territorial imbalances between the areas with the growing potential of energy production and of the growing consumption (i.e. circumpolar and Asia-Pacific regions), and the growing threat of piracy in the Southern Ocean with the alternative transit routes of hydrocarbon to Asia. The company concentrates its efforts on simplifying the institutional barriers to international transit traffic along the Northern Sea Route and on the gradual formation of a global market of Arctic transit.

On the Russian side, these same objectives are the target of a non-commercial partnership "Association of Users of the Northern Sea Route," which is marketing the route to major international corporations engaged in exploitation of natural resources in the Arctic (e.g., Corporation" Nana" at the Red Dog field in Northern Alaska) in order to reorient their cargo flows from the traditional indirect routes to a shorter route via the Arctic Ocean.

Table 3. The ratio of incoming and outgoing mail flows of the city Gubkin, Yamalo-Nenets Autonomous District

Indicator	Unit of measure	2007	2008	2009	2010	2011
Incoming flow:	*Pieces*	*2 056 874*	*2 298 634*	*1 638 351*	*426 234*	*500 322*
ordinary letters	– " –	1 805 988	2 095 092	1 469 475	263 729	337 841
first-class mail	– " –	212 028	158 920	132 031	127 198	125 578
registered mail and letter packets	– " –	13 313	16 654	13 157	12 164	12 079
parcels	– " –	25 545	27 968	23 688	23 143	24 824
Outgoing flow:	*Pieces*	*266 964*	*202 985*	*234 440*	*268 462*	*232 806*
ordinary letters	– " –	124 720	111 208	136 825	178 027	145 633
first-class mail	– " –	132 157	79 785	85 136	77 651	72 740
registered mail and letter packets	– " –	5702	7101	7159	7012	8103
parcels	– " –	4385	4891	5320	5772	6330

Unfortunately, little is known about international cooperation of large resource corporations in the Arctic, even though the example of the Shtokman project, with expected participation of Norwegian and Russian corporations in the development, represents a positive example and is a pilot project for the Russian Arctic.

Fundamentals (specific character) of Arctic cooperation. It seems that materialization of V.V. Mayakovsky's ideal of "a world without Russia, Latvia, and life as a single human home" is most likely in the Arctic region. In comparison with other macro-regions of the world in the past two decades, international cooperation is occurring here most actively and effectively. What features of the Arctic and of its communities have secured the latest success of economic (and increasingly, humanitarian) partnerships in the Polar regions?

First, this is the common features of the economic behavior of local communities: reliance on non-market factors of trust, social capital in business transactions, and business-to-business contracts. In the world of low-density spaces and of extreme natural conditions, cooperative values, not competition, receive priority value. Our study of the folklore of the small-numbered indigenous peoples of the Russian North has identified the unconditional value of generosity, donating, and gifting and the taboo on greed, which imperatively sounds in many fairy tales, stories, and poems of these peoples[6].

The initial openness of Arctic communities to distant relation and external information and tolerance to new migrants are extremely important for international cooperation. For example, the postal statistics of the northern and Arctic cities reveals a significant preponderance of incoming over outgoing correspondence everywhere (Table 3).

Second, as the history of humankind shows, international economic cooperation within the same latitudinal zone is always inherently embed objective favorable conditions in contrast, for example, to the cooperation of peoples and nations living on the same meridian. This drew the attention of J. Diamond in his book "Guns, Germs, and Steel." The orientation of the continental axes influenced the speed of propagation of economic and technological innovations: domesticated plants and animals, the wheel, writing, etc.

The sites located at the same latitude, in the East and the West, have similar day length

[6] The general features of the economic behavior of the Arctic communities are described in Pilyasov, A.N. The Arctic Mediterranean: Conditions for Formation of the New Micro-Region. EKO. 2010. N 10. pp. 54–75.

and seasonal variations of temperature and precipitation, and often similar types of vegetation; therefore, the speed of diffusion of agricultural and technological innovation from their origin was high in the Eurasian continent. On the other hand, differences in climatic conditions, vegetation, and wildlife prevented penetration of innovations from the South to the North and vice versa within the meridianally positioned Northern and Southern Americas (Diamond, 2005, p. 188).

The natural affinity of the Arctic communities makes it easier to transfer technology, competency, and institutes from one country to another. Modern circumpolar cooperation and broad international knowledge transfer might be analogous to agricultural and technological cooperation of Eurasian peoples in antiquity.

If the peoples and states are located along the same meridian, it is simply impossible to complete agrarian cooperation: to perfect and implement innovations, it is necessary to have several independent pilot sites, in each latitudinal zone. For example, in the Altai Kray located in seven landscaped areas, individual crop-research test sites are needed in each region.

Third, the Arctic international partnerships are promoted by the low number of Polar countries (and countries of the Arctic Council): there are only eight. With this number, negotiability of the participants greatly increases and communication can be conducted on a consensual basis, that is coming to an agreement on all proposed international norms and rules. For international relations, numbers seven or eight are like a Dunbar number that defines the limits of the population in a settlement when every person knows another and, therefore, there is no need for public institutions of enforcement and control (police, fire protection) – forces of self-organization of the local community are engaged.

Economic effect of the Arctic international cooperation is hard to assess using formal methods only. Within the framework of the *The Strategy for the Development of the Arctic Zone of the Russian Federation*[7], we attempted to identify this effect as the difference between innovation and inertial scenarios. The specific feature of our approach was that we defined this difference between the two trajectories of the development of the Russian economy not in terms of "lower-greater" for the growth of the economy, gross regional product (GRP), and employment, but as comparison of two ideological and value positions: "*For* or *against* the Arctic Mediterranean?" We assumed that the success of the modern economic development in the Arctic depends greatly on the international economic cooperation resulting in fruitful transfer of technologies, competency, and institutions. The scenario "For the Arctic Mediterranean" meant that Polar countries follow the policy of partnership and cooperation in the circumpolar zone. "Against" meant that the trends of confrontation and isolated development of individual Polar countries prevail.

Key external factors that have an important impact on the development of the Russian Arctic in the forecast period up to the year 2020 is the degree of its involvement in the system of global trade and information exchange and migration flows, conjuncture of the world energy markets, connection to the Russian intellectual centers, the overall macroeconomic situation in the Russian Federation, and actions of the federal social and fiscal policy and policy on subsurface resource management; and activities of Russian and foreign resource corporations.

Key internal factors are the dynamics of natural resources, human capital, the structural change of the economy of Russia's Arctic territories, infrastructure security, the system of resettlement, and demographic and ethno-cultural situation.

The *inertial scenario* assumes a conflict of interests of the Polar countries and increasing competition between them in relation to the rich natural resources in the

[7] The author thanks his colleagues V.N. Razbegin, A.M. Konovalov, I.V. Grishina, V.I. Pavlenko, etc., for their contribution to the development of this document.

disputed areas. Pressure intensifies on the Russian presence on the Svalbard archipelago. Russia's attempt to obtain legal recognition of its new northern boundary on the Arctic Shelf fails. The conjuncture of the world prices for the main natural resources extracted in the Arctic remains favorable, but fragile.

This scenario represents the prolongation of the modern trends in the key sectors of the economy of the Arctic and is based on conservative estimates of forecast growth of key indicators of the Arctic zone. For reasons of timing delays of mega-projects, they have very little impact on the economic development of the Russian Arctic.

It is likely that the rate of the growth of the gross product of the territories in the Arctic zone (for 2010–2020 are assumed to be ***lower*** than for Russia on average, as defined in the Concept for the Long-Term Development of the Russian Federation), of real per capita income of the population, and of federal expenditures will lag behind the trends of the Arctic development that have formed before the world crisis of 2008-2010; and the expected structural changes in the Arctic economy will occur slowly.

Of all the major construction projects of the national and world importance in the zone of the Arctic Shelf, the projects of the Shtokman and Prirazlomnoye oil fields development projects will be implemented much later than expected today. Other projects, for reasons of lack of funding from the federal budget and major domestic and foreign institutional investors, will be deferred in the forecast period.

The decrease of the population size due to the outflow of the working age population and retirees will continue. Unemployment in the Arctic regions estimated using the International Labor Organization (ILO) methodology will increase and reach 12–14%. Contrasts in the development of the dynamic Western and depressive Eastern sectors of the Arctic will increase substantially.

The *innovation scenario* for the development of the Arctic Polar countries involves close collaboration in the joint development of large fields of the Russian Arctic offshore and, therefore, a substantially faster, compared to the inertial scenario, pace of development. The world energy markets conjuncture is favorable with the upward trend in the price of oil and gas during 2010–2020.

This scenario is based on optimistic assessments of the development of key industries and sectors of the economy of the Arctic and reflects the implementation of major investment projects in the energy sector and transport infrastructure. The scenario is based on the hypothesis of the implementation of the plan of strategic actions in extremely favorable internal and external conditions – high world energy prices, the dynamic development of the national economy, successfully implemented modernization of enterprises of the core, infrastructure, and services sectors in the Arctic regions in the direction of post-industrial environment, and the economy based on knowledge. The implementation of the innovation scenario utilizes a strong inflow of foreign investment by attracting funds of domestic and foreign corporate investors and of resources of development institutions.

The characteristic features of the innovation scenario will be, on the one hand, consistent implementation of existing competitive advantages based on the rational use of the natural resource potential of the Arctic territories and, on the other hand, a new quality of economic growth based on the impact of new technologies in various sectors of the economy and the rapid development of information technology and the sub-sector of the Arctic intellectual services.

The rates of the development in the Arctic zone will be ***higher*** than the Russia's average because of the implementation of several major industrial and transportation mega-projects. The development of the Shtokman and Prirazlomnoye oilfield-giants will begin; there will be also developments of the Pomorskoye, Dolginskoye, Varandey-

Table 4. Inertial and Innovation Scenarios (2020)

	Inertial	Innovation
External conditions:		
The annual growth of the national economy, %	2.5	5.0
Annual inflation, %	4.0	3.5
The price for a barrel of oil Urals, USD	Below 50	Above 75
Internal condition:		
GRP growth to the level of 2008, % (in comparable prices)	125	185
Oil production on the shelf, mln. tons	3–5	10.0
Production of gas, bln. m^3	1.5	40.0
Northern Sea Route traffic load, mln. tons	5–7	30-35
The population of Arctic Russia, thous. people	1500.0	1650.0
Unemployment rate (ILO methodology), %	More than 10.0	5.0

Sea, and Medynskoye-Sea projects. As a result, the oil production from all offshore fields in 2020 will be about 10 million tons and about 40 billion cubic meters of gas, respectively (Table 4). The development of the Bovanenkovskoye field on the Yamal Peninsula will begin and the construction of new mainlines "Yamal-Europe" will continue.

The scenario includes radical modernization of the Northern Sea Route and increase of its traffic up to 30–35 million tons annually due to transport from the new offshore facilities and first transit flows from Europe to Japan and Korea.

By the end of the period, there will begin the implementation of the integrated projects "Ural Industrial – Ural Polar" and the construction of a railway line "Belkomur."

In both scenarios, the economic performance of the Arctic zone in the near future will depend critically on the dynamics of the resource systems, whose share in GRP will be decisive. In the innovation scenario, positive trend is projected: of the main parameters of socio-economic development, i.e., the growth of employment, a more rapid increase in the real incomes of the population, a significant increase in GDP, a significant increase in oil and gas production, and the active development of new economic activities, i.e., marine biotechnology, aquaculture production, gas processing, and gas chemical, mining production services. In both scenarios, a significant increase in the population of the Russian Arctic due to the reduction in the working age population of Russia in this period is not expected. It is assumed that the increase in labor productivity and attraction of rotational workers from the CIS countries will compensate the unfavorable situation in the dynamics of labor in the 2010s.

The inertial scenario represents the maximal risk for the Arctic because it only partially uses its existing capacity. And only the innovation scenario contributes to the maximal, in all its entirety, implementation of the competitive advantages. However, the implementation greatly depends on the intensity of international economic cooperation in the Polar regions.

CONCLUSION

The ideas of global unity of landscapes and peoples living in the Polar zone, as an objective background to their close cooperation, have been expressed a long while ago. Among our national scientists of the XXth century, the works of A.A. Grigoriev and V. B. Sochava on the Subarctic stand out[8]. The end of the cold war and global climate change that made the Polar territories more open to cooperation with one another, made the modern stage to be very

8 [8] Grigoriev, A.A. The Subarctic, 2nd Edition, M.: Geophyz. 1956; the works of V.B. Sochava in the Proceedings of the Institute of Siberia and the Far East of the 1960s–1980s.

favorable for the practical implementation of those ideas.

The importance of the Arctic international economic cooperation extends beyond the Arctic itself. Against the background of local conflicts and confrontation in the Middle East, Africa, and Asia, its unprecedented speed and energy in the past two decades can become a positive example and lesson for the humankind. The Arctic today (even without any special legal status) is an experimental laboratory for the international cooperation.

In these circumstances, the goal for Russia is to strengthen and sustain this cooperation at all levels, between various entities, institutions, and individuals in the name of diversification of the economy of the Polar territories, strengthening of its innovative character, and enhancement of their attractiveness and quality of human resources in the Russian Arctic through active transfer of technology, new knowledge, information, and experience between the neighboring Polar countries. ■

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THE KETS ETHNOS AND ITS "FEEDING LANDSCAPE": ECOLOGICAL-GEOGRAPHICAL AND SOCIO-ECOLOGICAL PROBLEMS UNDER GLOBALIZATION AND CHANGING CLIMATE

ABSTRACT. The paper discusses the modern state of the Kets ethnos, its cultural heritage, and existing problems. The paper analyzes the role of social factors in the transformation of traditional economy and the Kets philosophy at the modern stage. Using analysis of the data collected, the climatic impact on the traditional resource use of the Kets people has been identified. The paper suggests possible ways of diversification of traditional Kets economy under the existing organization of economy in the remote regions of the country. Global climate warming increases the dependency of traditional Kets economy on the environmental and geographical factors (natural-environmental resources of the taiga, natural disasters, natural risks of different origin, etc.).

KEY WORDS: Kets ethnicity, "feeding landscape", geographical environment, traditional economy, changing climate, natural and environmental resources of the taiga, cultural heritage and globalization.

INTRODUCTION

At present, the processes of globalization and global warming make a quite pronounced impact on the lives of indigenous people in the northern regions of the country, e.g., Nenets, Chukchi, Kets, etc. For them, fishing, hunting, herding, and natural landscapes are not only a source of livelihood resource, but also part of their traditional culture. Climate change (impact on productivity of "feeding landscapes," increase of natural hazards, etc.), social factors (alcoholism, loss of the Kets language, poaching, etc.), and new worldviews that have emerged and have been growing in the post-perestroika period are the main causes that threaten the well-being, livelihoods, and the preservation of cultural traditions of the Kets ethnos and its identity. The issues of developing appropriate measures and strategies for adaptation of the traditional economy and way of life of Kets and other ethnic groups to a changing climate and market economy become extremely relevant.

The Kets is one of the smaller nations of Central Siberia that consists of dispersed groups mainly in the middle and lower reaches of the Yenisei River, as well as in the lower reaches of the Podkamennaya Tunguska River (Yenisei Ostiak, Yenisei). They became known in the XVIIth century through the first Russian Yenisei explorers. The modern name of the people – Kets – appeared in the 1920s. This is not a self-ethnic name; it was imposed superiorly. This was due to the fact that the Khunt (with whom Ket were in contact in the upper reaches of the Taz River) and the Kets immediate neighbors – the Selkup – continued to be called Ostyak. The total number of the Kets is close to 1,200 people. There are three large groups of Kets with the names of the rivers along which they settled: Yelogui, Kureyka, and Podkamennaya Tunguska. The traditional territory of their settlement is the Turukhansk and Evenk Municipal Districts of the Krasnoyarsk Kray (Fig. 1). In terms of the linguistic and national characteristics,

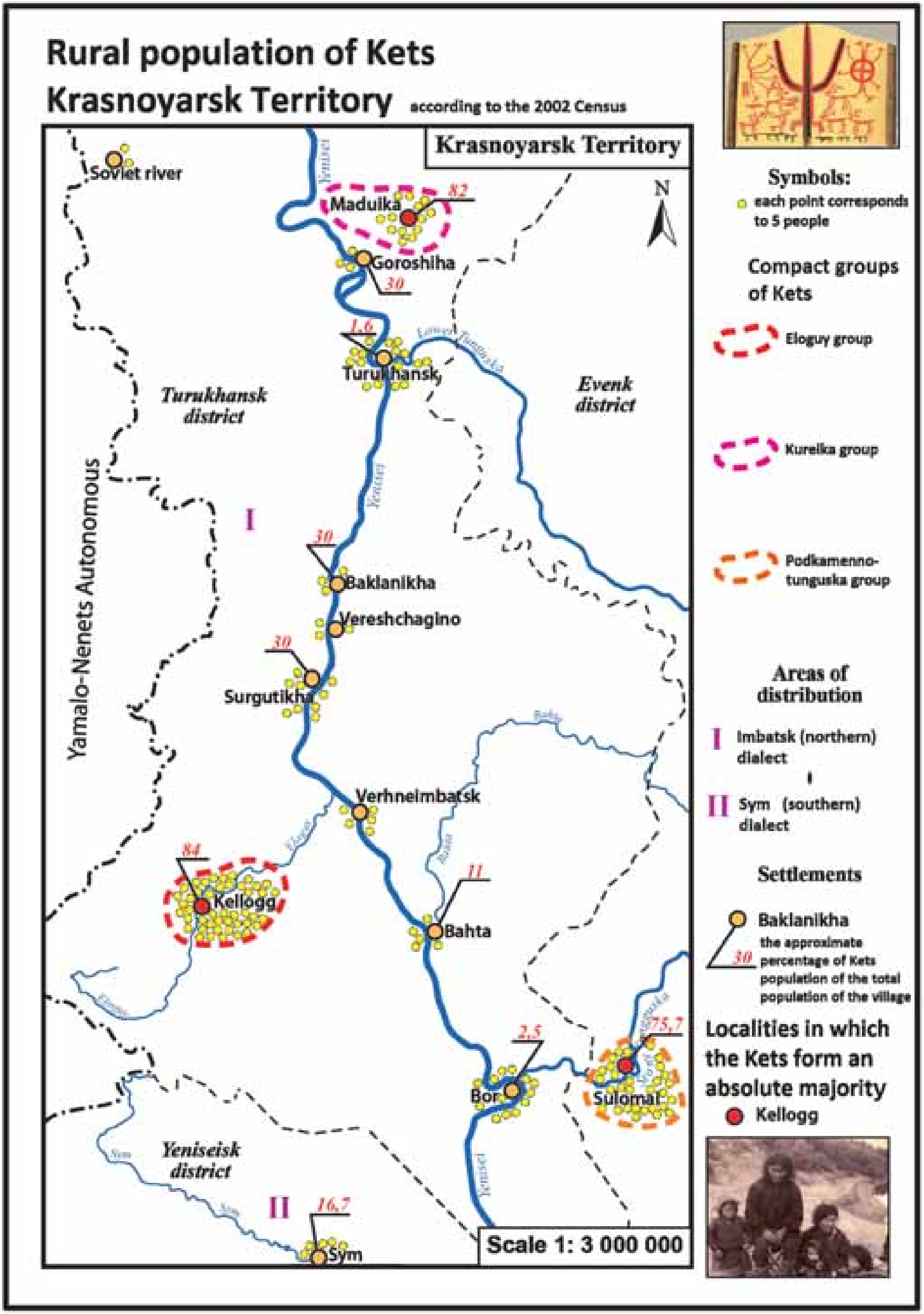

Fig. 1. Settlement and the numbers of the Kets in the Krasnoyarsk Kray. Compiled by the author

the Kets are classified as the most unique ethnic group not only in Russia, but in the world. The uniqueness of the Kets is evident in the fact that their language has a distinctive formation that has no analogues among the neighboring nations. The Kets language (now the relic) is the last of the living languages of the big family of the Yenisei people. The Kets culture has being adapted well to the riverine conditions. This includes experience in economic activity, the means of material life support, and many skills and knowledge necessary for the development of the riverine areas. The basis of the traditional life support prior to the arrival of the Russian people on the Yenisei North was fishing (especially in summer) and hunting on large ungulates (moose, caribou) and waterfowl. With the arrival of Russians and the introduction of the ***yasak*** (tribute paid off as furs) and then with the development of trade relations in the region, trapping has spread (hunting a squirrel, sable, etc.). Reindeer herding has always had a secondary role for the Kets because of the late migration of deer and small feed resources for the development of reindeer herding. Deer was used solely for transportation purposes; to date, the Kets reindeer has completely disappeared.

MATERIALS AND METHODS

Hydro-meteorological data of the local weather stations and the general Russian reference sources were processed to identify fluctuations of the temperature and precipitation parameters in the Central-Siberian region in the XXth century. The monitoring data based on the surveys of the Kets families were used to assess changes of environmental parameters and the fodder value of the natural systems of the middle taiga (at the level of complex natural boundaries) under climate warming. The traditional economy is "rigidly" tied to the landscape and all the stressful situations in the natural complex are immediately reflected in their self-sufficiency and social well-being, which suggests a high degree of reliability of the information we have collected. The total number of households surveyed is 25 (the number of hunting areas within the hunting community Sulomai); 57 respondents represent about half of the residents of the village Sulomai. All respondents pointed the declining yields of berries (especially blueberry and bilberry), and during dry summer – of rowan and cranberry; there are fewer mushrooms. One of the examples identified during the Sulomai survey is especially revealing: a woman noted that prior to the 1990s, she could gather and hand over 30 pails of cranberries and now she can hardly gather 2 pails. There are similar examples for other berries. The respondents noted an increase in the number of "sick" (rotten) berries, increasing the probability of its abscission in the last 15–20 years. They associate the increase in the number of bears attacks on people with low berries yields.

The Kets families that have their own hunting areas transferred through inheritance have important information about the dynamics of the production of any type of animal or berry crop over rather long period, i.e., a few decades. Many Kets have their own environmental calendars that mark important hydro-meteorological and phenological events. In the absence of the established system of monitoring in the taiga zone of Central Siberia such data have an important scientific value for identification of the response of natural and environmental resources of the taiga and the traditional economy of the indigenous population to climate warming. The author has also conducted field surveys (over 5 field seasons since 2008) during which he recorded the yield and percentage of flowering berry and estimated resources of commercial plants in different types of natural systems.

RESULTS AND DISCUSSION

The cultural-economic type of Kets (resident anglers and hunters) continue to exist. Modern Kets still fish, hunt elk and forest reindeer, gather mushrooms, berries, and nuts, and procure furs (sable, squirrel). Some families grow potatoes and vegetables. On average, a hunter produces 60–70 skins in a season. There was an abundance of squirrel earlier and in some areas they are at the heart of the hunting. However, in recent years, their production fell (300-400 skins to 100). Today, the main source of income for the majority of the Kets is the sale of sable skins. The cost of a sable skin ranges from an average of 3 thousand rubles to 4.5 thousand rubles. The darker the sable skin, the more expensive it is. A big family, i.e., a father and two – three adult sons, can get from 40 to 60 sable skins in a year. Since 2012, there is practice of transporting Kets by helicopter to their hunting areas. In the past, the flight cost was 6–7 churns of grayling on average.

Fishing also plays an important role. There are several species of commercial importance: grayling, lenok, burbot, tugun (of the primary importance), Yenisei omul, and Yenisei sturgeon (to much lesser extent because of depletion and environmental degradation in the Yenisei basin). The price of one (10-liter) pail of tugun is 2.0–2.5 thousand rubles. In the past, this valuable whitefish was available for fishing throughout the entire Yenisei. After the construction of the dams in the Angara-Yenisei cascade, tugun on the Yenisei River is only in its upper and lower reaches. Tugun is delicacy and is practically never caught for sale; its consumption is localized to the fishing areas in small towns. Tugun is usually not salted; this delicate and rich fish does not last – it is either immediately frozen or smoked. The tugun trade is done through commercial helicopter flights Baikit-Sulomai-Bor-Baikit. It is only available to acquaintances after agreeing the terms over the phone. Such trade relations are not widespread and residents of the mono-ethnic Kets village Sulomai complain about problems with the sale of these products. In the past, before the mid-1990s, the fish was procured on the site.

The problem of employment of the local population is quite urgent in the ethnic villages. In the post-perestroika times, a motivation to enrichment emerged, which is not typical to the traditional Kets culture. Meanwhile, the preservation of the traditional foundations of nature management and of "feeding landscapes" is a matter of survival for the Kets. This also contributes to the preservation of their traditional culture. The main ways of transfer of the spiritual foundations of the environmental culture and its most important elements are the historical memory and traditional knowledge.

In the Central Yenisei region, the modern climate change has been registered since the 1980s, which is clearly seen in Fig. 2. Analysis indicates that all 4 stations have observed a positive trend of changes in the annual air temperature. The annual average temperature grew by 1–2°C and greater compared with the previous period of cooling. Winter became warmer; spring and fall are longer than in 1959–1970. However, periodically, there are years with shorter summers.

The warming waves appear to be associated with increased western convection from the Atlantic (this is especially evident in the winter season due to the influx of "warm" air masses)_and, accordingly, the weakening of the Asian anticyclone (its western branch, or the Voyeikov axis) because of the large loss of ice cover in the Arctic. Most of warming is during the winter period.

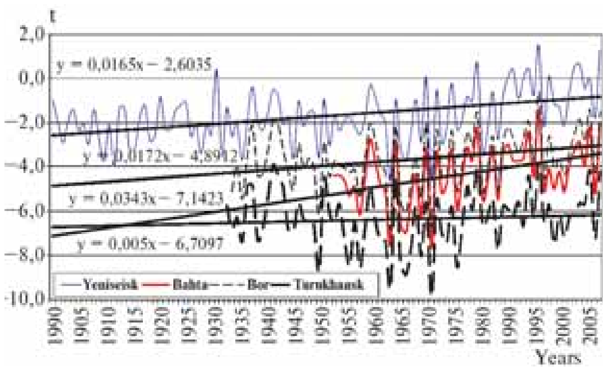

Fig. 2. Fluctuations in mean annual air temperature in the Central Yenisei region in 1900–2009. Compiled by the author

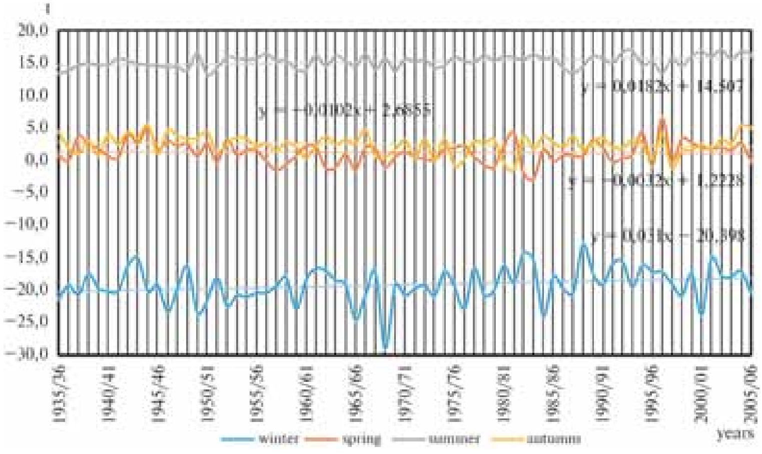

Fig. 3. The seasonal distribution of the average air temperatures measured at the Bor station in 1900–2009. Compiled by the author

The growth of climate variability can be seen in Fig. 3. The curve of winter temperatures is very indicative. As in the second quarter of the XXth century, the period from the beginning of the 1980s is characterized by mostly mild winters; very cold winters happen only occasionally. Against this background, the first and third quarter of the XXth century look less contrasting.

Warming of the climate, characterized by frequent mild winters and longer springs and falls, affects feed resources of the taiga. Famine years became more frequent. Thus, in 1997 and 1998, in the Central Siberian Reserve (one of the largest reserves of the planet with the size of the territory of Lebanon or Jamaica), blueberry, huckleberry, bilberry, honeysuckle, and red and black currant were almost completely absent. Their meager harvests were also in 1999; a similar situation persists to the present day, which is confirmed by the data of monitoring studies in the Reserve and surveys of local residents. The locals say that in the years with cool summers and mild winters, there are few places where pine nuts can be found, despite the widespread availability of cedar pine in the dark taiga. Such changes are especially important to the traditional nature management of the Kets since they do not have a well-developed subsidiary farming.

The Yelogui Kets. Their ancestral territory is located in the middle taiga, in the basin of the Yelogui River – the left tributary of the Yenisei River (Fig.1). The territory is dominated by the spruce – cedar pine and pine forest, interspersed with wetland areas; there are quite a number of burnt sites. The rivers do not have high fish productivity, but at the depth of the taiga, there are a few rich fishing lakes. There are deer-lichen pine forests that are good pastures for forest caribou, but they suffered from the fires. It is known that lichen pine forests is the type of forest mostly prone to forest fires in the taiga zone, and in the fire season in the summer of 2012, they were the main centers of large forest fires. Hunting resources include sable, squirrel, elk, upland game, mink, muskrat, and reindeer.

According to B.O. Dolgykh [1972], the Yelogui Kets had a well developed economy. Hunting, primarily squirrel with reindeer sleds, played a prominent role. In the Yenisei taiga, it allowed covering large areas. Another important sector of the economy

Photo by the author. Lichen pine forest after a ground fire on the left bank of the Yenisei River. These complexes are characterized by skeletal sandy soils, depletion of ground cover, and the lack of berry-beds

was fishing. Kets families covered distant, tens and hundreds of kilometers of travel, areas to places of fishing, which was possible due to their use of ilimka, i.e., a large (about 8 m long) boat with a cabin made of birch bark [Alekseyenko, 1968]. Eight out of ten Yelogui Ket's families had ilimkas. In summer, the families descended on them right up to the mouth of the Yelogui River. They almost never went to Yenisei. There, the fishing sites were used by Russians.

The first offender of the Kets lifestyle was the Abakan Expedition that conducted exploratory drilling for oil in the 1950s in the Yelogui River basin. According to K.B. Klokov [1999], old-timers told that many of its employees had shot a lot of domesticated reindeer. And since that time in the forest, there began frequent persecuting moss fires. By the end of 1970s, there were no reindeer left on the Yelogui [1].

From 1970–1980s, the population of Kellog – the largest Kets settlemet – grew due to the inflow of immigrants [Klokov, 1999]. This was promoted by growing hunting of sable, whose number had increased by that time, and income grew for everyone who hunted. The immigrants started families, established household farms, obtained hunting sites, and felt independent. The newcomers were filling the state farm procurement quota and its management depended on them as much as they depended on it.

The state farm was not interested in developing the economy of the periphery settlement; it was in the state of degradation. After the collapse of reindeer husbandry, the fur farm was closed, the cows of the state farm were liquidated, gardens were abandoned, and commercial fishing was phased out. Only gathering of cranberry and hunting remained. Fishing only provided food for the citizens themselves.

In the period of perestroika, the settlement was separated from the state farm and reformed into an individual «family farm.» Removed from the Yenisei River, the economy faced serious difficulties in selling the products, which caused the farm closure. Its former employees, left alone, have switched to self-procurement, felt more independent, and began to spend more time in the forest. However, the freedom had another side. The villagers began engaged in continues drinking. The number of crimes significantly increased.

The Kureyka Kets. This group of Kets lives in the Kureyka River basin that is in the northern taiga, on the border with forest-tundra (Fig. 1). The territory is dominated by sparse spruce and larch forests in the valleys and foothills adjacent to the tundra on the flat tops of the ridges of the Putorana Plateau. There are many large lakes rich in fish and good pasture for reindeer. However, nevertheless, according to the local residents and hunters, the number of game animals per unit area is not high. The main target species is sable; reindeer, squirrel, muskrat, elk, ermine, and ptarmigan are less important. In some years, there is arctic fox migrating from the north. The leading sector of the Kureyka Kets economy was hunting followed by fishing and reindeer husbandry for transportation – they used reindeer sleds for commercial hunting too. Now, the bulk of revenues are brought by the first two sectors.

The Podkamennaya Tunguska Kets. They live in the lower reaches of the Podkamennaya Tunguska River (Fig. 1). The hunting grounds are located in pine-fir taiga, rich in game animals, especially sable. Squirrel, elk, mink, and upland game have commercial importance. Fish resources are limited. These Kets were not engaged in reindeer husbandry. The village Sulomai became the central location of this group.

Modern Sulomai is the only settlement with the compactly living Kets population of about 200 people outside the Turukhansky area. The village is located in the territory of the Evenk Municipal District (former Evenk AO). According to the B.O. Dolgykh [1972], in the early 1930s, the Podkamennaya Tunguska Kets spent summer on the Yenisei River fishing; in fall, having stocked the essential goods, they went by ilimkas upstream the Podkamennaya Tunguska, sometimes more

Photo by the author. Fragments of the high (up to 60–70 m) red dene – the outcropping of the Evenk Suite of the Middle-Late Cambrian composed of cherry-red and, sometimes, light-green argellites and aleurites interbedded with gypsum and stromatolite limestone. In the Kets language, Sulenkhai or Sulemkai mean "red mount"

than 200 km from the Yenisei Range. Fur hunting was their primary occupation since it made up for over 90% of their total income.

In the 1930s, 80 km from the mouth of the Tunguska River, a field-hunting station was organized specifically for the Kets, where a settlement was founded with its present-day name Staryi Sulomai [Klokov, 1999]. There was a collective farm specializing in fur hunting. The second position in the economy was occupied by fishing, which after the loss of ilimkas (plank boats with a sharp beak and a cut aft), was centered on a small area of the Podkamennaya Tunguska River and its tributaries.

Unlike many other ethnic communities of northern Central Siberia, where in the 1960s the collective farms and non-traditional sectors of the economy began to actively develop along with the traditional natural resource use, the Sulomai economy for a long time remained completely traditional.

In the early 1990s, logging was severely limited and fishing trade ceased. Only consumer fishing and hunting remained. As long as a promhoz (a local industrial facility) provided helicopter transport of the Kets to the hunting grounds, they provided fur at a low price. In the perestroika, the promhoz went bankrupt and the furs were sold to dealers at their prices.

Nowadays, the economy of the village and its revenues are primarily associated with hunting and, to a lesser extent, with fishing and gathering of berries and mushrooms. Today, about half of the male population of Sulomai has their own hunting sites. Sable is the main commercial species. A small number of the female population of the village is occupied in the social sector – health and education, while the rest are engaged in housekeeping.

Photo by the author. Dorozhkina, Tatiana Orlovna is a member of the Kets small ethnic group, a resident of the village Sulomai. She is estimating the evening catch of tugun, i.e., a valuable whitefish

Photo by the author. Tyganovs – a typical Ket family from the village Sulomai, i.e., the Kets "Petersburg" (the second largest mono-ethnic Kets settlement)

Photo by the author. The Kets at their hunting site in the middle reaches of the Bolshaya Chernaya River

Photo with the author. Collection of tugun on the bank of the Podkamennaya Tunguska River. Seine fishing is done in the areas of fish concentration. Such places are called "tanyas." When a seine is unfolded, two people ("berezhnyk" – a shore-person and "begun" – a runner) take two ends of the seine and drag it at the bottom. The seine with small mesh (as in the photo) is called "chastyak." Such seine is used to catch chastyk (small mesh fish). One casting of the seine returns a pail of tugun

PROBLEMS OF PRESERVATION OF THE KETS ETHNIC AND CULTURAL TRADITIONS

The main problems of the Kets are alcoholism, unemployment, unfavorable demographic situation (increased mortality in middle age, the younger generation leaving for cities in more populated areas), and the loss of the Kets language. Penetration of Baptism plays a certain positive role in the fight against alcoholism. Having become Baptists, the Kets stop drinking alcohol, become more economically and socially active. However, with acceptance of the evangelical faith, the Kets have to pay 1/10 of their meager incomes: fish, furs, or cash. These processes lead to the transformation of some elements of the traditional worldview of their pagan religious system, culture, and ritual practice. The Orthodox Christianity "combined," as a rule, with the traditional beliefs and cults, never behaved as aggressively as evangelism.

Along with the gradual disappearance of traditions and the assimilation processes in relation to Kets, the Kets language is dissapearing too. In elementary school, the Kets language is now taught and a primeir and other tutorials have been created. However, this is not sufficient to revive the language of indigenous people and this does not always find understanding and support even among the Kets themselves. Today, education remains the only area of the use of the Kets language. The students of senior classes, who studied the Kets language in the first three classes of elementary school, do not remember its basics. This is due to three main reasons.First, in the vast majority of settlements, there are only elementary schools, while students can continue their studies only in the regional centers and in larger towns where the Kets language is not included in the curricula and there is lack of qualified teachers on the subject. Therefore, unfortunately, the effectiveness of teaching the Kets language in school is extremely low. Given the specificity of the region and of its transport and remoteness, there are good prospects for the development of distance education.

Second, in daily communication the younger generation of Kets do not speak their language in their national settlements with parents, friends, and peers.

Third, the attempts to revive the Kets language are not always understood, even among the members of the ethnic group, not to mention the district-level authorities. For a long time, the language has been transmitted only from parents to children. In the period from the 1920s to present, the Kets language has not been widely used. Today's young generation and their parents do not know their language, perhaps only a few words. According to various estimates, only 15% of the aboriginal population has command of the Kets language. It indicates the widespread destruction of the process of natural language transmission within families from parents to children. Some even claim that the Kets language is not needed for communicate either for themselves or for their children. We have identified such trends through surveys of the local population even in mono-ethnic villages.

LIFE SUPPORT SYSTEMS UNDER CHANGING CLIMATE

The Kets life-style is based on the traditional methods of economy and the use of a wide spectrum of the bio-resource component of the environment. Today, the land of their traditional habitation is widely used by poachers; management of the hunting sector began to transition to entrepreneurs who are removed from the interests of the Kets ethnos. Through the present day, there has been the process of alienation of the Kets from their resource base.

In the modern period of impoverishment of indigenous peoples, the use of bioresource potential often takes a variety of forms of poaching. In order to preserve and restore the natural resources, it is necessary to allocate territories of the traditional natural resources use (TTU), establish the rules of their use, and create federal stimuli for external and internal sources of the economic development of these peoples.

Due to climatic changes (Fig. 2 and 3), there is a reduction of productivity of natural systems: reduced yields of berries, pine nuts, and mushrooms (the impact of short strong frosts in the spring, during the flowering, and of dry heat), reduced number of sable and other game animals because of poor food supply, increase of the number and extent of forest fires due to lower water content and reduction of water logging of permafrost landscapes, as in many of them according to our observations, the roof of permafrost went down 1–2 m and, sometimes, deeper.

The years of low reproduction of game resources became the rule rather than the exception, especially in the areas east of the Yenisei River. This can be explained by a greater degree of frost-danger in the right-bank areas compared to the left bank because of the geomorphologic features of the area: the higher degree of dissection of the relief, presence of deep valleys, higher altitudes, etc. Cold air flows into the valleys causing more frequent frosts in the spring. It is important to note the smaller depth of the snow cover on the right bank, compared to the left. In the era of global warming, there has been observed increased frequency of thaws. For example, the Kets pointed out that 20 to 25 years ago, cold weather lasted at least one month, and now, it is no more than 2 or 3 weeks. These observations of Kets are supported by the weather stations in the region, indicating more frequent thaws and warming in winter. As a result, the depth of the snow cover is lower, which impacts the productivity of berries. It is known that the reduction of snow cover increases the likelihood of freezing of billberry and blueberry. Many Kets note that a decrease in snow cover makes it more difficult to hunt moose. The result of these processes is the phenomenon of "hungry taiga" inherent in the last two decades.

There are marked changes in the habitat of tick-borne encephalitis; the tick is now detected around the 63°N. The ixodes ticks (*Ixodes persulcatus*), over the past 25 years, have moved 250 km to the north and now occupy the middle taiga subzone of our research area. The likelihood of tick-borne infections has increased. The activity of the ticks has been especially strong in the last 10 years. According to our surveys, it affects the population of the local villages Vorogovo, Bor, Sulomai, Kuzmovka, and other settlements; there, people have been frequently requesting vaccination against tick-borne encephalitis.

In the third quarter of the XXth century, during the stable cold winters, vipers (*Vipera berus L.*) were virtually absent in the middle-taiga geosystems at the right-bank of the Yenisei River. The local population began noticing the expansion of poisonous snakes after the abnormally warm years of the second half of the 1990s, which coincided with the time of the mass melting of ice in the rock glaciers (kurums). Now snakes are everywehre on the melted kurums.

Kurums is a type of the permafrost landscapes of the Yenisei Siberia that was the least stable in the era of global warming. Within kurums, even on slopes with poor heat-supply, the goltsy ice thawed, small depressions formed, and cold streams disappeared. They were overgrown with lichen, shrubs, and scattered trees. Pika, which plays an important role in the diet of sable, is abandoning kurums. These processes are promoted by late spring frosts and the loss of underground water resources at the base of kurums.

Due to the reduction of food resources, the number of sable and other game animals is decreasing. The increase in the share of

Photo by the author. A kurum overgrown with lichen and young birch in the Bolshaya Chernaya River valley (the left tributary of the Podkamennaya Tunguska River in its lower reaches)

birch and aspen in the dark taiga contributes to this process. At the stage of modern warming, it is harder for dark-needled species to maintain their dominant position in the tree layer; they are being replaced with the pioneer-species, which leads to worsening of forest and food resources.

Instances of hydrological anomalies also increased. A sharp warming in early spring and existing frozen impervious layer cause high and even catostrophic flooding that coincides with melting and drifting of ice. For example, in the snowless winter of 2001, an ice dam 30 m high formed, which caused serious flooding. As a result, the Kets settlement on the Podkamennaya Tunguska River was completely destroyed. The old-timers do not recall floods of such magnitude. Now, due to the increased frequency of floods of ice-dammed origin, the Kets are forced to move their homes to the watershed areas. After 2001, the regional services has been conducting blasts of ice dams.

CONCLUSION

We can assume that the trophic pyramid of the middle taiga has been significantly disrupted due to global warming and the growth of climate instability. Naturally, these changes adversely affect the traditional natural resource use of the Kets who cannot meet their growing material needs. The issue of development of appropriate measures and strategies is becoming increasingly relevant; they should become the leading adaptation basis of the traditional economy and way of life of the local population to a changing climate.

The reduced life-support functions of the «feeding landscape» (in the terminology of L.N. Gumilev) requires a focus on the comprehensive development of the traditional forms of natural resource use and their diversification, support of their resource and manufacturing base, and the organization of processing of raw materials and products. At the present stage, the Kets subsidiary farms are weak, though, they could become an important sector of food self-sufficiency of the local population. It is possible to establish plantations growing valuable species of mushrooms, berries, and herbs to increase the volume of commodity production. This would create additional incentives for the traditional Kets natural resource use. The creation of local plantations of medicinal plants would contribute to the formation of the region's production of environmentally friendly raw materials for medicines. These resources are available in the Kets TTU, where gathering of medicinal plants was carried out in the Soviet time. The volume of such procurement has been identified for some species of medicinal plants. Some Siberian regions have a successful experience with the use of non-timber forest resources.

Currently, a concept of creation of market for non-timber resources for 2005-2015 has been developed in the Krasnoyarsk Kray with the efforts of two administrations; this concept is focused on developing the competitive conditions for the buyers of mushrooms, berries, and medicinal plants who come from the neighboring Russian regions. In addition, non-timber forest management is rightly seen as a way to preserve the most valuable land from logging, primarily of the dark coniferous taiga. It is also necessary to set up small processing facilities that could receive caught fish and gathered wild plants from the local population and process and sell these products, thus increasing the employment in the taiga settlements.

The way out of large-scale poaching and logging could be the creation of the ethnic cultural natural protection complexes, for example, the environmental-ethnographic parks, reserves, etc., where the priority rights to land and economy of the indigenous people are realized. Our surveys of the Kets population confirm our views on the significance of this strategy. According to the residents of the village Sulomai, if the Central Siberian Reserve receives the environmental-ethnic status and the hunting and fishing grounds of Kets are included in it this could protect against poaching and would strengthen the Kets right to the TTU. Such experience exists in other countries, where the creation of biosphere reserves meets the objective of preservation of both natural and cultural environment and support of traditional forms of the natural resource use and of landscapes with the balanced resource use. It is apparent that government handouts in the form of small payments that promote social anemia in mono-ethnic villages should be replaced with support for their quality work and traditional crafts.

The use of renewable bio-resource potential and diversification of the traditional economy on its basis is environmentally acceptable and economically feasible and represents an adaptation of the traditional natural resource use of the local population to the new social and natural environment.

It seems that in the context of global warming and growth of climate instability, a close relationship between the traditional economy of indigenous peoples, the natural resources, and environmental, and geographical factors of the environment becomes even more pronounced.

Similar processes in a changing climate require serious comprehensive research on various aspects of the relationship between the geographical environment and the indigenous population that use environmental resources and services as a life-support system. ■

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THE ARCTIC HUB – REGIONAL AND GLOBAL PERSPECTIVES (THE ARCTIC SCIENCE SUMMIT WEEK, ASSW – 2013)

About 400 participants from 25 countries attended the Arctic Science Summit Week (ASSW- 2013), which was held on April 13-19, 2013, in Krakow (Poland) in the auditoriums of Jagiellonian Univesity. Most participants were from the Arctic countries: Norway – 37, United States – 33, Russian Federation – 29, Sweden – 23, Canada – 23, Germany – 20, Finland – 16, and Denmark – 10. However, non-arctic countries were also relatively well presented: Poland – 92, Czech Republic – 15, Japan – 13, France – 11, Republic of Korea – 11, Italy – 7, United Kingdom – 6, and Iceland – 5. The ASSW was established by the International Arctic Science Committee (IASC) in 1999 to provide opportunities for coordination, cooperation, and collaboration between various scientific organizations involved in Arctic research. Any organization engaged in supporting and facilitating Arctic research may participate and use the Summit to hold its business meetings. Since 2009, every second ASSW includes a three-day science symposium. The 2013 symposium focused on the interactions between the Arctic and the lower latitudes and the regional and global implications of changes in the Arctic. Five disciplinary and four crosscutting sessions, dealing with both environmental and socio-economic conditions and addressing multidimensional changes and linkages, were convened. For the first time in the history of the ASSW, the engagement of the Arctic Council Indigenous Peoples Secretariat (IPS) made it possible to fully integrate Arctic people in the scientific program of the symposium. Thanks to the efforts of the Association of Polar Early Career Scientists (APECS), about 25% of the participants were early career scientists. A political panel "Arctic Dialogue, Science-Policy Interface," organized by the Polish Ministry of Foreign Affairs, complemented the program of a very productive and highly interesting week in Poland.

The 2013 IASC Medal was awarded in recognition of Leif Anderson's pioneering work on the functioning of the Arctic Ocean and his groundbreaking scientific contributions to understanding the chemistry and carbon cycle of this very special ocean system. The Medal Lecture entitled "Utilizing Chemical Signatures to Study the Arctic Ocean" was presented during the ASSW 2013 Science Symposium.

The IASC Working Groups (WGs). The IASC Action Group on Geosciences Data is central to the mission of the IASC. The IASC promotes cooperation in all aspects of Arctic research and seeks to act as a scientific and moral authority that promotes the freedom and ethical conduct of science. In this spirit of open collaboration, the IASC Council recently endorsed a new Statement of Principles and Practices for Arctic Data Management. The document asserts that all IASC-endorsed scientific results shall be verifiable and reproducible through ethically open access to all data necessary to produce those results. Data should be made fully and freely available with minimal delay and with only limited ethical, not proprietary, restrictions. According to the

IASC Data Policy Action Group, all data have to be professionally preserved and readily accessible as described in data management plans, which are required for all new IASC projects. It is also important to recognize the intellectual effort that goes into producing and maintaining good data. The IASC encourages fair attribution and use of data and strongly promotes the practice of data citation. The IASC Council has also established a new Standing Committee on Data Management to maintain the Principles document, to review and provide guidance on data management plans and archives, and to promote sound data stewardship.

The five WGs (re)elected their Steering Group members during the ASSW – 2013 and the current Steering Groups are: Atmosphere WG: Jim Overland (Chair), Hiroshi Tanaka (Vice Chair), Michael Tjernström (Vice Chair), Kathy Law (Vice Chair); Cryosphere WG: Martin Sharp (Chair), Julian Dowdeswell (Vice Chair), Walt Meier (Vice Chair), Jon Ove Hagen (Vice Chair); Marine WG: Bert Rudels (Chair), Rolf Gradinger (Vice Chair), Jinping Zhao (Vice Chair), Savithri Narayanan (Past Chair); Social and Human WG: Peter Schweitzer (Chair), Gail Fondahl (Vice Chair), Peter Sköld (Vice Chair), Louwrens Hacquebord (Past Chair); Terrestrial WG: Inga Svala Jonsdottir (Chair), Warwick Vincent (Vice Chair), Torben Christensen (Vice Chair), Terry Callaghan (Vice Chair). The Working Group activities discussed during the ASSW – 2013 will be summarized in the upcoming IASC Progress Report shortly.

The WG on the International Science Initiative in the Russian Arctic (ISIRA, Chair – Arkadiy Tishkov) discussed the prospects of international scientific activities in the Russian Arctic after the International Polar Year 2007–2008. The majority of the participants were from the Arctic countries. The presenters included David Hik –IASC Presindent, Rahold Volker –IASC Executive Secretary, V. Pavlenko – Russia's representative in the IASC, heads of the Association of Polar Early Career Scientists (APECS) in Russia, and young Russian Arctic researchers (I. Sokolov, P. Glazov, A. Medvedev, V. Stepanenko, S. Lebedeva, and others). Young scientists made short presentations at the end of the meeting. The discussion focused on the need for the countries that conduct international research in the Russian Arctic to present national reports and to broader involve young scientist in research.

Social problems of the Arctic. Almost 4 million people live in the Arctic today and the interests, prospects, and insight of Arctic residents were an integral part of the ASSW, in particular of the crosscutting sessions of the Science Symposium, dealing with (1)

Applying Local and Traditional Knowledge to Better Understanding of the Changing Arctic; (2) Arctic People and Resources: Opportunities, Challenges & Risks; (3) Arctic System Science for Regional and Global Sustainability; and (4) Changing North: Predictions and Scenarios Preparing for the third International Conference on Arctic Research Planning (ICARP III). Over the past few months, the IASC Executive Committee developed a concept of the third ICARP to be held in conjunction with the IASC's 25th Anniversary at the ASSW – 2015. IASC's many partner organizations and IASC Working Groups were invited to contribute; at the ASSW – 2013, the IASC Council gave the go-ahead for the implementation of the plans.

The scientific symposium "The Arctic Hub – Regional and Global Perspectives" included 4 keynote lectures, 9 disciplinary and cross-cutting sessions, and 2 poster sessions.

Session I, "Atmosphere Processes and Global Climate Connections," had several interesting presentations by Russian participants. Thus, **V. Sokolov и A. Makshtas** (Arctic and Antarctic Research Institute, St. Petersburg, Russia) in their presentation "Russian drifting stations in XXI century" discussed the main directions of field investigations executed on the drifting stations "North Pole – 32" – "North Pole – 40" in 2003–2012. They talked about new instruments for observations and some results in polar oceanography, sea ice studies, processes of energy – gas exchange between ocean and atmosphere in presence of sea ice cover. In 2007 – 2011, the boundary layer structure, including low-level jets and surface inversions were investigated in collaboration with scientists from Alfred Wegener Institute (AWI Potsdam, Germany). Four years of continuous measurements of low cloudiness were conducted in collaboration with ESRL NOAA. The observation data are used for examination of existing parameterizations of air – sea interaction processes in high latitudes.

A. Vinogradova with colleagues **(**A.M. Obukhov Institute of Atmospheric Physics, RAS; P.P. Shirshov Institute of Oceanology, RAS), in report "Black carbon in the atmosphere of the Russian Arctic" talked about the Arctic ice covering decrease during the last 20 years reaching the minimal level in 2012. The Russian Arctic, including approximately half of the Arctic and its coasts, is likely to make an important contribution to this climatic effect. The experimental part presented the results of the air black carbon (BC) concentration measurements made during different expeditions to the Russian Arctic Seas, islands, and coasts from the early 1990s to 2011. In addition, they compared these data with the BC concentrations measured regularly in the Arctic – at the Barrow and Alert stations. The comparison of their estimates with measured data proved to be very valuable.

Klaus Dethloff with colleagues (Alfred Wegener Institute for Polar and Marine Research, Research Unit Potsdam, Germany) in the presentation "Interaction between Arctic sea ice and the atmospheric circulation," talked about simulations coupled with the regional Arctic atmosphere-ocean-sea ice system model from 1948 to 2008. As the atmospheric circulation in winter is much stronger constrained by the lateral boundary forcing, the coupled regional model has higher degrees of freedom to develop internal circulation structures in summer. A significant sea ice loss during the summer months is either associated with a higher frequency of high reaching warm anticyclones or reduced cyclone frequency over the Arctic Ocean.

Several reports were made by scientists from the USA and Japan, who have been long engaged in research on atmospheric phenomena in the Arctic. **Jun Inoue** with colleagues, (Japan Agency for Marine-Earth Science and Technology, National Institute of Polar Research, Kyoto University, Japan) presented **"**The impact of radiosonde data over the ice-free Arctic Ocean on the atmospheric circulation in the Northern Hemisphere" on the results of investigations of the impact of radiosonde data from the ice-free Arctic Ocean, obtained by the Japanese

R/V Mirai during a cruise in the fall of 2010 and on the AFES-LETKF experimental ensemble reanalysis version 2 (ALERA2) dataset. The analysis used radiosonde data over the ice-free region. Coupled with observations, it better captured the Arctic cyclogenesis along the marginal ice zone, including a tropopause fold. A 5 K cold bias in air temperature was found, suggesting that radiosondes over the Arctic Ocean are vital for reproducing the change in tropopause variability.

Session II, "Cryospheric Changes: Drivers and Consequences," had presentations by **Tetsuo Ohata** and **A. Fedorov** with colleagues (Japan Agency for Marine Earth Science and Technology; Kitami Institute of Technology; National Institute of Polar Research, Japan) and **P.I. Melinikov** (Permafrost Institute, Siberian branch of RAS, Russia) made a report on "Cryospheric Changes in Suntar-Khayata Mountains in North-East Siberia." The glaciated area in the Sunta-Khayata Mountain Range, which exists between the large cities of Magadan in the Pacific Coast and Oimyakon, is known for its low air temperature and is said to be 156 km^2 in 1945 decreasing to 162 km^2 in 2002–2003. This change should have been accelerated during the recent ten years due to the strong warming occurring in the 2000s. In-situ research in this region was conducted in the IGY period (1957–1959) by Russian scientists and, after that, in 2000 and 2004-2005, by the joint Russian and Japanese teams. Since information related to the past exists in this region, it is a good area for studying cryospheric changes due to the recent strong warming. A new project has started; it targets observations and study of the glaciers' basic parameters and their changes, the permafrost changes, and the future variability applying glacier models. This is the project between the Cold Region Program of JAMSTEC (Yokosuka, Japan), GRENE Project of NIPR (Tokyo, Japan), and P.I. Melnikov Permafrost Institute (Yakutsk, Russia) that started in 2011(the in-situ observations were done in 2012 and continued in 2013). Another report by **I. Sokolov (**Institute of Geography, RAS, Russia) "Recent changes of glaciers on Franz Josef Land from remote sensing data" presented data of the glaciological monitoring on the Franz Josef Land. According to the Glacier Inventory of the USSR (1965–1982), the glaciated area on the archipelago was 13,735 ± 14 km^2 or 85% of the entire area. However, current estimates of the glaciers' mass balance and monitoring of changes indicates their reduction. The aim of this research is the determination of the current conditions of the glaciers on the Franz Josef Land archipelago and identification of morphometric parameters. Hall Island, Wilczek Island, and Graham Bell Island were chosen for the modern glacier outline detection because the glaciers very by type and because the data of satellite images ASTER, TM, ETM+ on board Terra and Landsat are available. Monitoring of glacier areas using remote sensing data, such as ASTER with a spatial resolution to 15 m, obtained within the framework of international project GLIMS (Global Land Ice Measurements from Space) and other types of sensors allows compiling databases of the glaciers. A series of reports of Polish scientists was devoted to the dynamics of glaciation and the cryosphere of Spitsbergen.

Session III, "Marine Processes and Variability," was one of the largest scientific conferences –about 30 oral presentations. Among the guest speakers at the session, were **Paul Wassmann and Eddy Carmack** (University of Tromsø, Norway; Fisheries and Ocean, Canada) with the presentation "The contiguous domains of Arctic Ocean advection: trails of life and death." The authors posed important questions of life of the Arctic Ocean and tried to answer them. Their presentation discussed the circulation in and transport to and from the Arctic Ocean and how advection supports contiguous and macroecological domains. In particular, the talk focused on the distribution and advection of mesozooplankton and addressed a set of related issues. One of them was the interaction between local versus advected "production" in the Arctic Ocean. They concluded that the mesozooplankton's death march into the Arctic Ocean is part of the persistent invasion/withdrawal battle of subarctic versus arctic species where death is a "calculated" risk for potential progeny.

Several reports were on the results of the research in the Russian Arctic. For example, **I. Kryukova**, **Ye. Polyakova, and E. Abramova** with colleagues (Water Problems Institute RAS, Moscow; Lomonosov Moscow State University, Moscow; Lena Delta Reserve, Tiksi, Russia; Saint Petersburg State University, St. Petersburg; Arctic and Antarctic Research Institute, St. Petersburg; Helmholtz Centre for Ocean Research, Kiel; Alfred Wegener Institute for Polar and Marine Research, Germany) made a collective report "Phytoplankton in the Laptev Sea: distribution, dynamics and environmental forcing (comparison of two autumnal seasons 2008/2010)." This research is the part of the environmental monitoring of the Laptev Sea ecosystem under the multidisciplinary Russian-German Program "Laptev Sea System." Analysis of the long-term data series leads to a better understanding of changes in the pelagic ecosystem and provides background for the further assessment of ecosystem changes connected with climate variability in the Arctic. In September 2008, a total of 82 taxa were identified: Bacillariophyceae (40 taxa), Dinophyceae (40 taxa), Chlorophyceae (1 taxon), and Dictyochophyceae (1 taxon). Maximal algal abundance was observed near the Lena Delta. The lowest values were found in the westernmost part of the study area. Microalgal communities had a high abundance of dinoflagellates, which exceeded the abundance of all other taxonomic groups. In the 2010 fall season, phytoplankton communities were composed of 80 taxa. Most of the species were diatoms (53 taxa), while dinoflagellates were represented by 26 taxa. Maximal values of algal abundance were observed in the central part of the Laptev shelf northwest of the Lena Delta.

Also, among the guests, was Professor **Jan Marcin Weslawski** with colleagues (Institute of Oceanology PAS, Sopot, Poland; Norsk Polar Institutt, Tromsø, Norway; University of Gdańsk, Poland) with the report "Tidal glaciers retreat – loss of specific marine habitat in Arctic?". The well documented melting of tidal glaciers on Svalbard leads, in many cases, to the retreat of ice on land and loss of tidal waterfront (glacial bay). The glacial bay seabed is generally impoverished in terms of species and biomass; yet, cold-water species may find a refugium and rich food resources there. Some of the specific physical functions of the glacial bay may be provided by river mouths (fresh and seawater mixing, estuarine circulation), while others (sedimentation regime, upwelling) are not likely to happen in small river deltas on Svalbard. The presentation showed possible scenarios for the evolution of marine biodiversity and top predators survival connected with glacial fronts on Svalbard.

Session IV, "Terrestrial Ecosystem Responses to Environmental Stressors," had over 30 reports on: "Landscape change," "Biodiversity," "Cyanobacteria: from water to soil," "Northern freshwaters," and "From Biogeochemistry (lakes and soils) to Environmental Change." An invited report by **Ingibjörg Svala Jónsdóttir** (University of Iceland; University Centre in Svalbard) "Shaping forces of biodiversity in the Arctic" addressed important theoretical positions. One reason for why this issue has not yet received full attention is the complexity of the Biodiversity term, encompassing all organisms and their diversity at various levels of organization (genetic diversity within and among populations, species diversity within and among communities, and community and ecosystem diversity within and among landscapes and regions). Different factors and processes may be responsible for shaping diversity for different organisms. In addition, for each organism group different factors may operate at different scales both in time and in space. Therefore, often, the key factors may be overlooked. Finally, it is a great challenge to address overarching biodiversity questions because different methodologies need to be applied for different organism groups.

A. Tishkov (Institute of Geography, RAS, Russia) in his report "The major factors affecting the modern condition terrestrial biota and landscapes in Russian Arctic" presented data on the current status and the factors of the dynamics of ecosystems of the Russian Arctic. The following main integrated parameters define the stability of Arctic landscapes: (1) Low-level biodiversity; (2) The exceptional vulnerability and susceptibility of ecosystems to chemical pollution (prevalence of non-vascular plants – lichens, mosses); (3) The sharp seasonality of functioning, the brief vegetative period, and the prevalence of migrating species; (4) Low rates of biota and soil self-restoration following disturbances; (5) Presence of permafrost formations and their "mobility"; and (6) The vulnerability of broken landscapes and new anthropogenic habitats for alien species. All of the above integrated parameters of stability or instability of arctic landscapes can be quantified and can be used in simulating of their modern climatogenic dynamics.

The report by **P. Glazov** (Institute of Geography, RAS, Russia) "Island Ecosystems of the Pechora Sea (Vaigach and Kolguev Islands), as the Centers of Arctic Animals Biodiversity**"** demonstrated that both islands can be considered centers of Arctic biodiversity and have the highest density of nesting water birds, including geese. The protection of these areas not only does have the national, but also international value. These activities help preserving biodiversity of the Arctic.

Also, the problems of terrestrial ecosystems in the Russian Arctic were discussed in a report by **A. Chetverova**, **I. Fedorova** and **M. Makhotin** (Saint-Petersburg State University, Arctic and Antarctic Research Institute, St.- Petersburg, Russia) "Geochemical characteristic of the Lena river delta, East Siberia, Russia." The report presented the results of the recent Russian-German expeditions to the delta. They showed different sources and role of different factors in formation of geochemical flow of the delta.

Session V, "Impact of Global Changes on Arctic Societies," Session VI, "Arctic People and Resources: Opportunities, Challenges and Risks," and Session VII, "Applying Local and Traditional Knowledge to Better Understanding of the Changing Arctic", had only 6, 14, and 9 reports, respectively, related to the variability of life of local communities, their vulnerability, and adaptation to modern natural and anthropogenic factors, including globalization. The Russian theme was practically not represented in the session. The exception was the presentation by **Natalia Malygina** and **Valter Snedzana** (Ural Federal University) "Rural tourism at Extreme North: examples and tendencies for development" and a collective report by **A. Oscal** with colleagues (incl. **M. Pogodaev**, Russia) "Traditional knowledge, adaptation to climate change and globalization in circumpolar reindeer husbandry: the voice and knowledge of reindeer herders".

Session VIII, "Arctic System Science for Regional and Global Sustainability," had 11 reports where discussed. Among them, were several reports of the IASC WGs, for example, by **M. Parson, R. Huber, P. Pulsife, A. Tishkov, H. Yabuki and R. Volker** "An open data policy for IASC" and by **D.A. Walker** with colleagues "An international arctic vegetation database for panarctic vegetation classification, ecosystem models, and biodiversity studies."

Session IX, "Changing North: Predictions and Scenarios," had 12 reports on results of international projects and programs ("Adaptation of actions for a changing Arctic," "Multidisciplinary drifting observatory for the study of Arctic climate – MOSAIC,""Simulating the effects of clinate change on fire regimes in Arctic ecosystems: implications for conservatiom of tundra to scrubland and forest," etc.). There were no participants or reports from Russia on results of research in the Russian Arctic.

The next Arctic Science Summit Week (ASSW – 2014), including the 2nd Arctic Observing Summit, will take place in Helsinki, Finland on April 5–11, 2014, on Helsinki Kumpula Campus, in the facilities of the Finnish Meteorological Institute and Physics Department of the University of Helsinki. For more Information see: www.assw2014.fi

The Arctic Science Summit Week – 2015 will be held in Japan on April 23–30, 2015, in conjunction with the ICARP III Symposium, planned on April 27–28, 2015, and the International Symposium on Arctic Research (ISAR-4) on April 29–30, 2015. Also in planning is the IASC 25th Anniversary Celebration during the ASSW.

Arkady A. Tishkov, Rachold Volker

INSTRUCTIONS FOR AUTHORS CONTRIBUTING TO "GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY"

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The scientific English language journal "GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY" aims at informing and covering the results of research and global achievements in the sphere of geography, environmental conservation and sustainable development in the changing world. Publications of the journal are aimed at foreign and Russian scientists – geographers, ecologists, specialists in environmental conservation, natural resource use, education for sustainable development, GIS technology, cartography, social and political geography etc. Publications that are interdisciplinary, theoretical and methodological are particularly welcome, as well as those dealing with field studies in the sphere of environmental science.

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2. The **title** should be concise but informative to the general reader. The **abstract** should briefly summarize, in one paragraph (up to 1,500 characters), the general problem and objectives, the results obtained, and the implications. Up to six **keywords**, of which at least three do not appear in the title, should be provided.

3. The **main body** of the paper should be divided into: (a) **introduction**; (b) **materials and methods**; (c) **results**; (d) **discussion**; (e) **conclusion**; (f) **acknowledgements**; (g) **numbered references**. It is often an advantage to combine (c) and (d) with gains of conciseness and clarity. The next-level subdivisions are possible for (c) and (d) sections or their combination.

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7. **References** must be listed in alphabetical order at the end of the paper and numbered with Arabic numbers. References to the same author(s) should be in chronological order. Original languages other than English should be indicated in the end of the reference, e.g. (in Russian) etc.

Journal references should include: author(s) surname(s) and initials; year of publication (in brackets); article title; journal title; volume number and page numbers.

References to books should include: author(s) surname(s) and initials; year of publication (in brackets); book title; name of the publisher and place of publication.

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9. When using a word which is or is asserted to be a proprietary term or trade mark, authors must use the symbol ® or TM.

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