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DYNAMICS OF PERMAFROST IN THE COASTAL ZONE OF EASTERN-ASIAN SECTOR OF THE ARCTIC

ABSTRACT. The study summarizes results on the cryogenic dynamics in the coastal zone. The paper shows that ongoing climate warming and shrinking of ice extent of the Arctic seas triggers both thermogenic and cryogenic processes at the same time. The first group includes thermal abrasion, thermal denudation, degradation of submarine permafrost, and the second one is the syncriogenesis of the new-formed coastal-marine sediments. The first group results in an increase of the retreat rate of coasts, the second results in the islands formation on banks and shallows where the domination of bottom thermal abrasion and deepening of the sea bottom has been taken place previously. Arguments for stamukhas and cryogenesis role in islands formation are presented.

KEY WORDS: coastal zone, coast retreat, degradation of submarine permafrost, coastal-marine sedimentation, formation of permafrost, stamukhas

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INTRODUCTION

Studies of coastal dynamics in cryolithozone are often conducted disregarding the processes along the submarine near shore zone. However, changes of above-water part of coastal zone (onshore) are determined by changes of its underwater part (offshore) (Zenkovich, 1962; Are, 2012). The variations of hydrometeorological parameters have definite impact on the changes of the both parts of coastal zone triggering the changes in other components of natural environment. Thus, at the end of 20th Century – in the beginning of 21th Century there the decreasing of ice coverage of the Arctic Seas and longer ice-free period can be observed, along with the increasing of mean annual air temperatures. The mentioned above changes lead to the increasing of retreat rates of icy shores. Simultaneously, the temperature of bottom water is increasing that causes further degradation of permafrost that slides into submarine conditions. Both processes facilitate the increasing percentage of suspension and melted sediments at the submarine near shore zone. This, in turn, stimulates sedimentation here and on the nearby seabed.

Recent permafrost dynamics in the coastal zone is determined by climate and sedimentation in the late Pleistocene and Holocene. In the cold period of the Late Pleistocene, syncryogenic deposits of the Ice Complex (IC) were formed at the drained shelf and the coastal lowlands of the Eastern sector of the Eurasian Arctic. These deposits make up the upper 30-50m of the Late Pleistocene accumulative coastal plain. They are characterized by volumetric ice content of 70-95% and thick ice wedges. In the Holocene, as the result of destruction of IC by lake thermokarst, the syncryogenic deposits of the Alas Complex were formed. They are also of high ice content (60-70%) and contain ice wedges. They both compose the significant part of the shores of the Laptev and East-Siberian Seas. The vulnerability of icy deposits towards the thermal influence causes the shores retreat as a result of thermal abrasion and thermal denudation, and then, the degradation of offshore permafrost. These processes determine the environmental conditions at the coastal zone of the East-Arctic seas.

At the same time, coastal-marine sedimentation and emergence of recent permafrost often exist at the coastal zone. As a result, the coastal zone is the particular place on the Eastern sector of Eurasian Arctic shelf where there are widely spread multidirectional cryogenic processes under natural conditions. Their characteristics in connection the sea ice coverage and climate changes in the second part of the 20th Century and the beginning of the 21th Century is the matter of consider in this paper.

MATERIALS AND METHODS

The study area covers the coastal zone of the Laptev Sea and western part of the East-Siberian Sea (Fig. 1).

The study of coastal dynamics of eastern part of Russian Arctic has been constantly conducted since the late 60s – the mid-70s of the 20th Century (Grigoriev 1966; Molochushkin 1970; Are 1980; etc.). It became of special importance at the end of 20th Century – in the beginning of 21th Century (Coastal … 1984; Are 1985, 2012; Novikov 1984; Grigoriev 1993, 2008; Grigoriev et al. 2006; Razumov 1996, 2010; Dynamics … 1998; etc.). From the mid-1990s to the present time the coastal zone research is being carried out with the participation of German scientists (Overduin et al. 2007, 2013; Rachold et al. 2007; Junker et al. 2008; Günther et al. 2013, 2015; etc.) within the framework of Russian–German collaboration. Now field instrumental methods are being replaced by studies with using multi-temporal remote sensing data more and more often (Pizhankova and Dobrynina 2010; Pizhankova 2011, 2016; Günther 2013, 2015; Lantuit 2011; etc.). Such studies are more effective, especially for considerable length of coastlines. We resolve the problem of shores survey with application of space

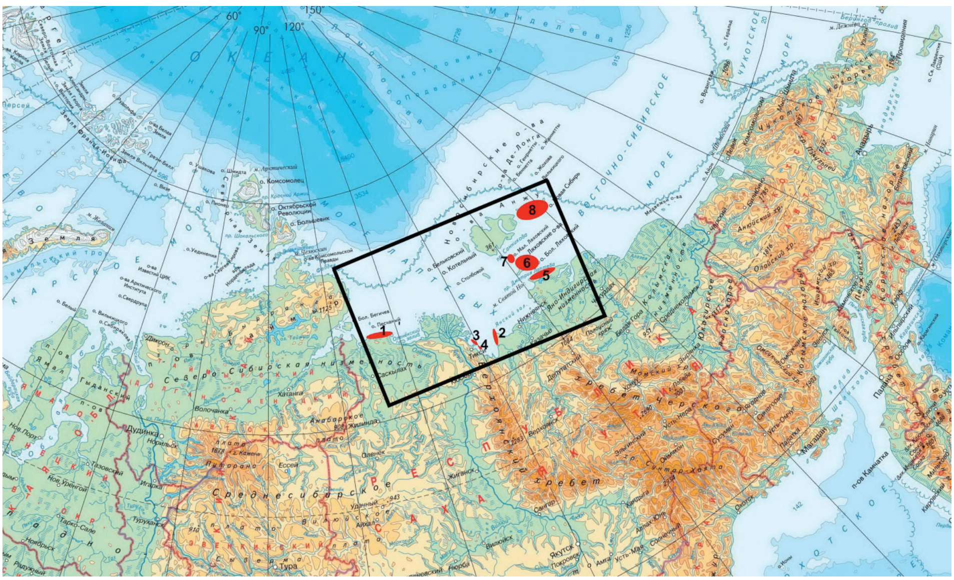


Fig. 1. The research area. Numbers indicate the sites for which the coastal dynamics were studied using remote sensing data

imagery of medium resolution (Landsat-7, 8) with overlapped archival aerial photography of the Novosibirskiye Islands with the aim to investigate the spatial patterns of their dynamics. Such surveys were conducted for the New Siberia Island (Dobrynin et al. 2005), the Bolshoy and Maliy Lyakhovsky Islands (Pizhankova and Dobrynina 2010; Pizhankova 2011). There was revealed the acceleration of coastal retreat rate for the region of Dmitry Laptev Strait in the 20st Century (Pizhankova 2016). ScanEx Image Processor and MapInfo Professional were used in the survey. Almost 1,000 km of shores was studied using remote sensing data.

The study of cryogenesis of offshore sediments is associated closely with the study of spread and depth of permafrost table. This study conducted with the help of drilling profiles was initiated in 1950s. Permafrost studies and geothermal monitoring in boreholes were carried out in various regions of submarine coastal zone of the East-Siberian Arctic in 1960-1980s, for the purposes of geological survey, search for and exploration of mineral resources. The work was accompanied by a complex of laboratory studies of sediments. They were conducted in the area of the Tiksi Bay and Muostakh Island, the Vankina and Sellyakhskaya Bays, the coastal zone of the Novosibirsk Islands, the mouths of the rivers (Grigoriev 1966; Molochushkin 1969, 1970, 1973; Are 1980, 2012; Zhigarev 1981, 1997; Zhigarev and Plakht 1977; Fartyshev 1993; Fartyshev et al. 1983; Neizvestnov 1980, 1999; Soloviev 1981; Soloviev et al. 1987; etc.). In 1970 Molochushkin E.N. (1973) sampled bottom sediments with a vibration-based piston tube in the interval from 10 to 40 m isobaths for the first time. These works were continued in the 21th Century (Grigoriev 2008).

Since 1970s, mathematical modeling started to apply in studies of distribution, thickness and evolution of permafrost (Romanovskii et al. 2006; Gavrilov 2008; Nicolsky et al. 2012). These results supplemented the drilling data on the submarine permafrost degradation from the top by data on their degradation from the bottom.

Echolocation at shallow depths was carried out within the framework of Russian-German scientific collaboration. In 2003 and 2005, two very informative meridian cross-sections were established from the Mamontov Klyk Cape to open sea (Grigoriev 2008; Junker et al. 2008).

The mathematical simulation of the permafrost current state for the East Siberian shelf was carried out on the basis of the latest achievements in paleogeography and software implementing the solution of the Stefan task under various conditions (Romanovskii et al. 2006).

The electronic archives of Arctic and Antarctic Research Institute (AARI) (http://www.aari.nw.ru/projects/ECIMO/) and the All-Russia Research Institute for Hydro- and Meteorological Information — the World Data Center (ARRIHMI – WDC) (http://aisori.meteo.ru/ClimateR) serve as the important source of information about the changes in ice cover and climate of the East-Arctic Seas.

THE MAIN FACTORS OF THE COASTAL CRYOGENIC DYNAMICS

As mentioned above, the high ice content of the main relief-forming complexes (Ice and Alas Complexes) is due to the history of its development. The latter is also related closely to the geological-tectonic structure and location of the research area in the eastern most continental high-latitude part of the Arctic. It was the Late Cenozoic subsidence and climate continental conditions that led to the underground freezing of the region in the Late Pleistocene. At that time glaciers were forming in the western sector of the Eurasia. They melted away 17-15 ka BP (Hughes et al. 2016), while the ground ice of the Eastern sector still exists. This one determines the increased rates of coastal retreat and seabed deepening. The geological and tectonic structure determines the direction of contemporary vertical movements, the composition and ice content of the deposits in the wave action zone, and the height of the cliffs. These factors determine the general direction of the cryogenic dynamics in the coastal zone, as well as the specific spatial confinement of processes and their rates.

Another group of factors is presented by the hydrological and climatic conditions. They include the duration of ice-free period, currents, the strength and direction of winds and wind-induced surges, the sum of positive air temperatures, the distribution of snow accumulation, the radiation-heat balance of the coastal outcrops surface, and the features of surface runoff in the coastal zone.

Both groups of factors determine coastal retreat under the influence of thermal abrasion and thermal denudation. The mechanism of coastal erosion depends on the structure of the cliffs. The first (block) mechanism is most typical for shores of 8-12 m height, predominantly inherent to Alas Complex. At the cliff bottom, the sea produces wave-cut niches with a depth of up to 10-15 m. The overlying deposits break down along the cracks, and then the sea washes them away (Fig. 2).

The second type of destruction was observed on the shores of more than 15-20 m height, composed of deposits of Ice Complex. They are characterized by the formation of thermo-cirques (Fig. 3) with ice cliffs at the top (so-called "kygams") and thermo-terraces at the base. Thermo-terraces form when the kygams retreat at a rate exceeding the rate of thermal abrasion. The retreat of such shores is due to the thermal denudation of icy cliffs under the influence of air temperatures, solar radiation and atmospheric precipitation, as well as coastal erosion of thermo-terraces.

The third type of shore destruction is typical for marine and alluvial-marine terraces less than 3-4 m height. Thermo-abrasive niches do not form there. The deposits thaw down to the water's edge and the debris are washed away by the sea.

Detail studies, conducted by international groups (Günther 2013, 2015; Lantuit 2011) on many sections of the retreating Laptev Sea coasts using remote data (Mamontov Klyk, Buor-Khaya, Bykovsky Peninsula, Muostah Island, Oyogos Yar, Fig. 1), showed significant variations in values of retreat rates (Table 1). However, they were not always able to reveal the significant factors that affect these variations. It should be noted that this was also hampered because of different averaging period used in these studies.

Fig. 2. The block collapse mechanism of coastal erosion. Southern shore of the Laptev Sea, 2010. Photo by A. Dereviagin

Fig. 3. Coastal erosion with forming the thermal cirques. Southern shore of the Laptev Sea, 2007. Photo by A. Dereviagin

The role of individual factors was the most fully determined for the Lyakhovsky Islands (Pizhankova and Dobrynina 2010; Pizhankova 2011). The most important factors were the following: neotectonic position of the coast, which determines the structure of the coastal section; the depth of the submarine near shore zone, the presence of shoals and foreshores; exposure of the coast through the intensity of storm surges; the presence of alongshore currents; the effect of solar radiation and the nature of snow accumulation (the formation of snowpacks on leeward shores); the regime of surface runoff contributing to the change in the ice situation in the near shore zone.

Thermal denudation in our studies was taken into account only for the Ice Complex shores, where it can be characterized on the basis of interpretation of medium-scale space imagery. For the Lyakhovsky Islands, there was revealed that the nature of the appearance and the parameters of thermal denudation are significantly various for the shores of different exposures. Both thermal abrasion and thermal denudation are proved to be more rapid on the shores up to the water's edge (and below) entirely composed of the Ice Complex, while the coasts with the ice-less quaternary deposits, underlying Ice Complex, retreat slower (in 1.2 times or more). For the first of them, the rate of thermal denudation in 1.4 times exceeds the speed for the latter. This is not only due to the corresponding difference in the rates of thermal abrasion, but also, apparently, to the more significant influence of the radiation-heat balance on the large cliffs that are entirely composed of the Ice Complex.

We analyzed the changes of the Arctic ice coverage and climate warming from the 40s-20s of the 20th century to 2014 and their role in increasing of the coast retreat rates (Pizhankova 2016). This analysis showed that until 2000 the fluctuations in ice cover, with the exception of the explicit maximum of the 1960s in the Kara Sea, are weakly exposed: the ice coverage fluctuates around the average value for the period from the beginning of observations to 2000. And for the period after 2000, the common feature for all the seas is steady and rather sharp reduction in ice coverage up to values significantly below average figures. Fig. 4 shows data on the ice coverage for the Laptev Sea and the western part of the East Siberian Sea.

In our opinion, that is why it is advisable to use remote sensing data obtained in 2000 or a little earlier in order to measure the rates of coast retreat of different sections along the Arctic shores and compare them with data for previous and subsequent years.

Table 1. Information of the coastal retreat of the Laptev and East Siberian Seas, obtained in the early 21st century by use of remote sensing data

№	Name and location of the shore		Coast retreat rate, m / year	Measurement period	The source of information
1	Mamontov Klyk		2,1± 1,2	1965-2011	Günther et al. 2013
			4,6± 1.2	2007(2009) -2011	
2	Buor-Khaya		0,5± 0,4	1965-2011	
			1,2± 0,7	2007(2009) -2011	
3	Bykovsky Peninsula		0,6	1951-2006	Lantuit et al. 2011
4	Muostah Island		1,8± 1,3	1951- 2013	Günther et al. 2015
			3,4± 2,7	2010 -2013	
5	Oyogos Yar		3,2± 1,1	1965-2011	Günther et al 2013
			8,3± 2,8	2007(2009) -2011	
			2,4	1951- 1999	Pizhankova 2016
			3,4	1999 -2013	
6	Bolshoy Lyakhovsky Island	South coast	3,4	1951- 2001	Pizhankova and Dobrynina 2010; Pizhankova 2016
			7,7	2000 -2013	
		West coast	4,3	1951- 2001	
			9,4	2000 -2013	
		Northeast coast	2,7	1951- 2001	
			4,2	2000 -2013	
7	Maliy Lyakhovsky Island	Southeast coast	2,1	1951- 2001	Pizhankova and Dobrynina 2010
8	New Siberia Island	North coast	1,5	1952- 2002	Dobrynin et al. 2005; Gavrilov et al. 2012
		South coast	2,5		
		Southeast coast	4,1		
		East coast	3,6		
		West coast	2,3		

The study of multi-temporal remote sensing data (1951~2000 and 2000-2013) showed that reduction of sea ice coverage after 2000 (and correspondingly an increase in ice-free period duration) led to a significant increase in the rates of shore retreat in the 21st century (Fig. 5). The scale of the increase (in 1.5-2 and more times) is clearly visible in Fig. 6.

Similar results were obtained for the western and eastern shores of Bolshoy Lyakhovsky Island and the Shore Oyogos Yar. In the papers of Günther et al. (2013, 2015) in the short-term observations of 2007-2011 and 2010-2013 (see Table 1), there is also an increase of retreat rates, although it should be noted that Are (1980) pointed to the effect of higher values of retreat rates obtained during measurements in a short period.

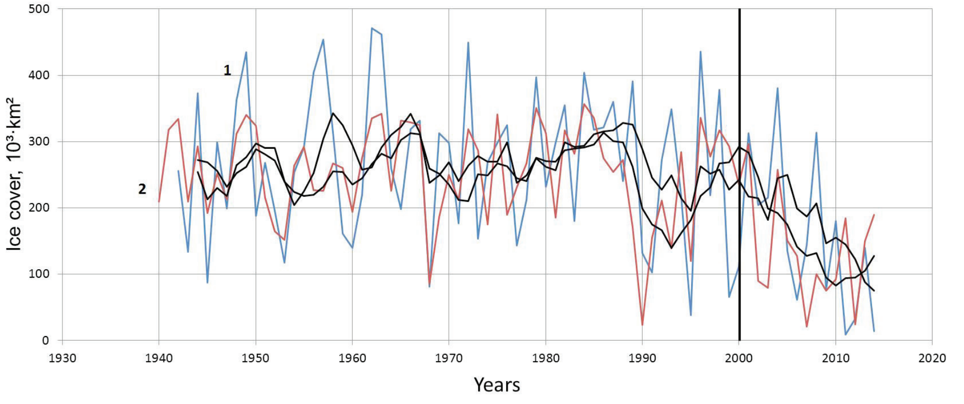


Fig. 4. Ice coverage dynamics of the Laptev Sea (1) and the western part of the East Siberian Sea (2) (august) and the trend curves based on averaging results for a five-year period

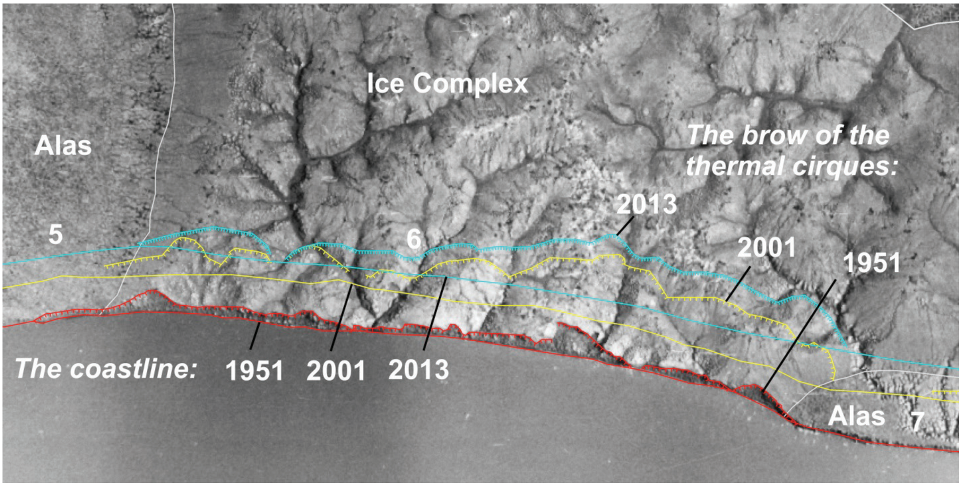


Fig. 5. The coastal dynamics of the southern coast of the Bolshoy Lyakhovsky Island. 5, 6, 7 – segment numbers for which the retreat rates have been calculated. Air photo of 1951

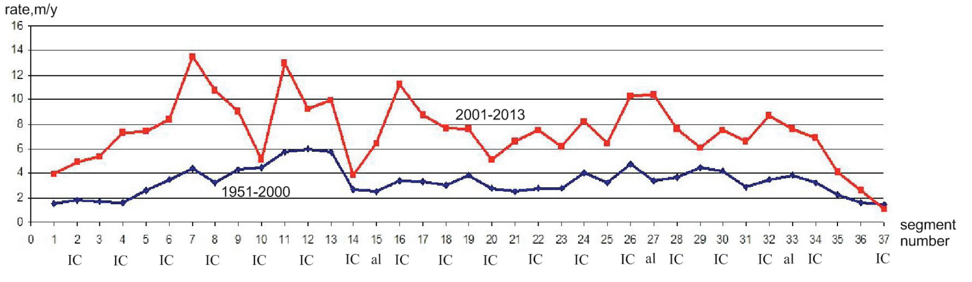


Fig. 6. Changes in the retreat rates for different segments of the southern coast of Bol. Lyakhovsky Island. The length of the coast is 70 km. IC – segments of the Ice Complex; al – segments of alluvial deposits; no letter indications – segments of the Alas Complex (Pizhankova, 2016)

Data based on comparison of different positions of coastlines of the Novosibirskiye Islands and the southern coast of the Dm. Laptev Strait (Pizhankova and Dobrynina 2010; Gavrilov et al. 2012; Pizhankova 2016), have shown that for 50 years (from 1951 to 2000) the total area of the washed out coasts was: 27.2 km^2 for the Bolshoy Lyakhovsky Island, 1.7 km^2 for the Malyi Lyakhovsky Island, 12.4 km^2 for Oyogos Yar, and 36 km^2 for the New Siberia Island. Over the past 13 years (from 2001 to 2013), they were enlarged by 10.3 km^2 of the coast of Bolshoy Lyakhovsky and 6.5 km^2 of the Oyogos Yar. The average retreat rates were 3.2 m/y for the period up to 2000 and 6.4 m/year from 2000 to 2013 for all the eroded coasts of this region. Thus, the retreat rates in 1.3-2.9 times increased in 2000-2013 in comparison with the period 1951-1999. The rate of thermal denudation increasing was not that much dramatic - by 1.7-1.9 times (Pizhankova 2011, 2016). In our opinion, this shows that the influence of reducing ice coverage on the shore retreat process is more dramatic than the influence of increasing air temperatures.

DEGRADATION OF PERMAFROST UNDER SUBMARINE CONDITIONS CAUSED BY COASTAL RETREAT

The transition of permafrost from subaerial to submarine conditions (from onshore to offshore) simultaneously increases the average annual temperature of sediment surface from -11...-15 to -0.5...+0.5°C. This triggers the degradation of newly formed submarine frozen ground. This degradation is represented by the transformation of ice-bonded permafrost into ice-bearing permafrost (ice-bearing permafrost in the crystal lattice contain together with ice unfrozen water), and then thawing. The submarine permafrost thaws from the top as well as from its bottom as it acquires a gradientless temperature profile. Thawing from the top is due to salinization of sediments, which lowers the freezing-melting point, and high temperature of the bottom water. The latter factor is due to summer radiative warming.

Dependence of bottom water temperature from air temperature determines the relationship of submarine permafrost degradation with climate dynamics. The rate of degradation from top can be judged according to drilling profiles from the coast towards the sea for the Muostakh Island, the Bykovsky Peninsula and the Mamontov Klyk (Grigoriev 2008; Overduin 2016). The highest rate of permafrost table lowering was fixed for the period 1983 - 2013/2014 along the profile of Muostakh Island. For the subsea Ice Complex, the rate was 13.5-18.5 cm/year, and for its underlying deposits - 6 cm/year. If we take into account that on the average 1/3 thawed sediments separating the permafrost table from the seafloor are excited by waves (Are 2012), then the rate of degradation is 28 cm/year for the first case and 9 cm/year for the second one. However, such velocities are the maximum and are observed in the first years and decades. The rates for the periods of thousands of years are estimated at least lower by an order of magnitude. Thus, at Mamontov Klyk, thawing of 35 m of top of permafrost occurred for at least 2500 years at the site of the borehole most remote from the shore (11.5 km), so the average speed was 1.9 cm / year (Grigoriev 2008). The thawing time duration was calculated basing on the current rate of shore retreat. Meanwhile, his reconstruction shows a lower retreat rate in the past, especially in the Little Ice Age. It was 3-4 times slower (Razumov and Grigoriev 2017). Therefore, the average rate of permafrost degradation from the top should be considered substantially lower than the indicated value, and its duration was longer.

When studying the degradation of submarine permafrost by drilling methods, thawing from the bottom is not usually considered. Meanwhile, its contribution into the general permafrost degradation is not only comparable with the degradation from the top, but also can exceed it. This is evidenced by the results of mathematical simulation. The decrease in the permafrost thickness from the bottom varies from 1.5 to 3 cm/year and depends on the density of the geothermal flux. The first value corresponds to a flux density of 50 mW/m^2, the second one is to 75 mW/m^2 (Romanovskii et al. 2006; Gavrilov 2008). The region of the Bykovsky Peninsula and Muostakh Island belongs to the Ust-Lena rift, for which the second value should be taken. Thus, the rate of permafrost degradation from the bottom can be at least two or more times higher than the rate of degradation from the top.

RECENT FORMATION AND FREEZING OF COASTAL-MARINE SEDIMENTS

The coastal-marine sedimentation was studied in the region of the Lyakhovsky Islands using remote sensing data. These studies have shown that the coast increment occurs in the areas of tectonic uplift, and due to the input of a significant volume of solid runoff to the coastal zone. In this case, spits, bars and foreshores are formed in the places where the capacitance of landshore drift decreases. Subsequently, the submarine coastal slope turns into beach level, and with the continuation of sedimentation - to the march level.

Studies indicated that the increment of shores is the most typical for Malyi Lyakhovsky Island. The northern, western and northeastern coasts of this island are accreted because of the formation of beaches and marches; the southern and southwestern ones are due to the formation of spits. The accretion of the spit on the southern coast of the island is quite pronounced, the extension of the coast to the sea averaged about 70 m for the 6 km section of the spit for 50 years.

On the Bolshoy Lyakhovsky Island, the shore accretion is typical for the north-northeastern coastal areas and for the areas adjacent to the east of the Kigilyakh Peninsula, where the accumulation occurs through the filling an incoming angle of a coast contour. Accreting spits subsequently form the surface of terraces, which stepwise rise up to the root slope (Fig. 7). The total area of the shore increment was 1.8 km^2 for Bolshoy Lyakhovsky Island and 1.6 km^2 for Malyi Lyakhovsky Island for 50 years (from 1951 to 2000) (Pizhankova and Dobrynina 2010)

Coastal-marine buildings are characterized by explicit variability in the coastline. This is particularly evident in the dynamics of the areas of Sellyach and Ebelyach foreshores, the dimensions of which are measured by many tens of kilometers. The western parts of these foreshores are washed away; the sediments are transported and deposited in the east. Debris of the Late Pleistocene Ice Complex, which is affected by thermo-abrasion and thermo-denudation, is the main source of their formation, as in the case of the Lyakhovsky Islands. The sediments of the foreshores usually consist of saline

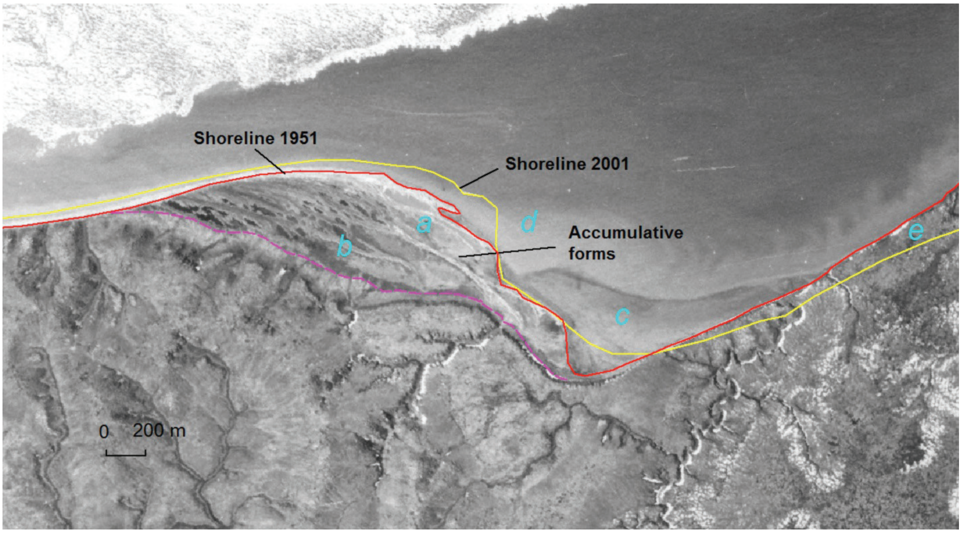


Fig. 7. Accumulative relief forms of Bolshoy Lyakhovsky Island: above sea water ones: a- recent (1950-2001), b - recent and Holocene; underwater forms: c - recent; d - formed in the past. The retreat of the shore - e. Air photo of 1951

aleurites, silty material, and fine dust sands. In Vankina Bay, recent syncryogenic submarine permafrost is estimated as 25 m thick (Zhigarev and Plakht 1974). They generally merge with the underlying permafrost relict layers.

The formation of coastal-marine sediments is accompanied by its syncriogenesis. This is evidenced by the numerous islands located to west of the Lena delta. These are elevated fragments of bars bordering the delta for many tens of kilometers. The largest of them is a chain of islands stretching along the western coast of the Arga-Muora Ceese Island. The Aeros'yemki and Samoleta Islands can also be the same elevated parts of bars, formed several thousand years ago. The remains of the eroded parts of the delta are in close proximity to them.

Contemporary activation of sedimentation in shallow waters is quite interesting. It is identified due to the new formation of the islands in recent years. Yaya Island at Vasilyevskaya Bank was revealed in aerovisual observations (Gukov 2014; Fig. 8). The Island Zatoplyayemyy, in 60 km east of the Lena delta and the Neizvestnyye Islands near the southeastern shore of Bunge Land were recently marked on topographic maps.

The way of formation of such islands is disputed. In our opinion, ice hummocks locating on the ground - stamukhas, most likely facilitate their formation. This is consistent with available data (Fig. 9). For three decades of visual ice reconnaissance surveys, according to incomplete data, 2086 stamukhas were found in the Laptev Sea (Gorbunov et al. 2008) and 7962 stamukhas in the East Siberian Sea (Gorbunov et al. 2007).

In summer, as sea is cleared from the ice, warmed bottom water on shallows induces thawing of bottom sediments, which turn to be mobile. Accumulation occurs under wind surges and storms, when the thawed sediments are stored around stamukhas

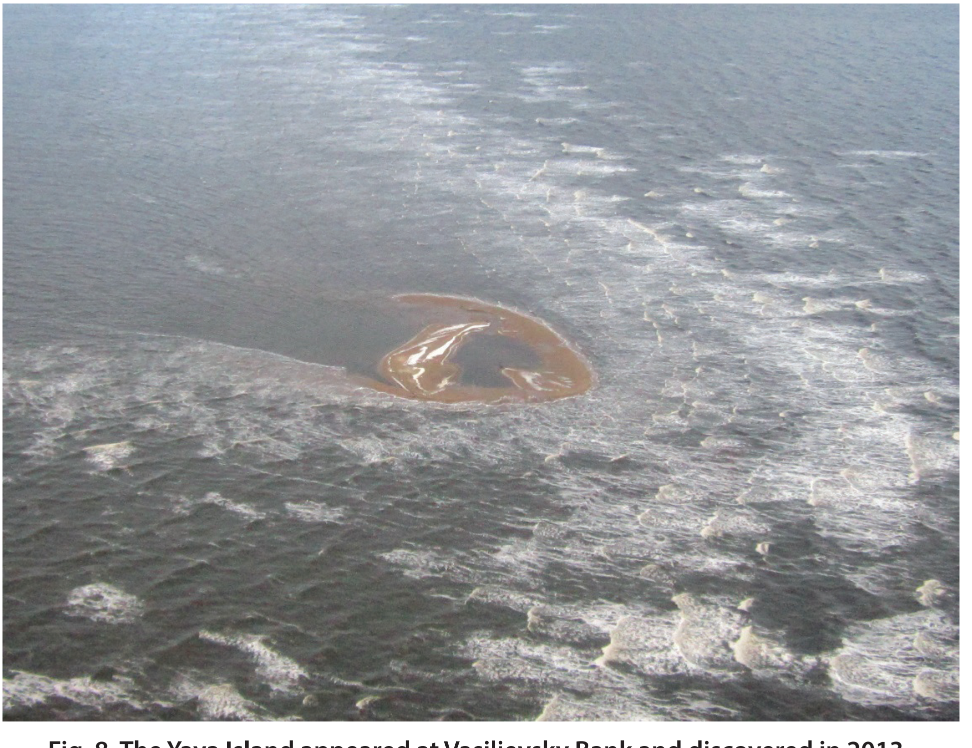
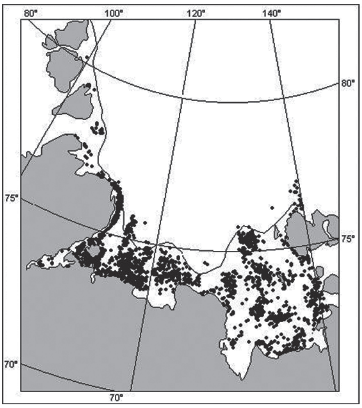


Fig. 8. The Yaya Island appeared at Vasilievsky Bank and discovered in 2013. Photo by Pavel S. Sayapin (https://commons.wikimedia.org/w/index.php?curid=30168239)



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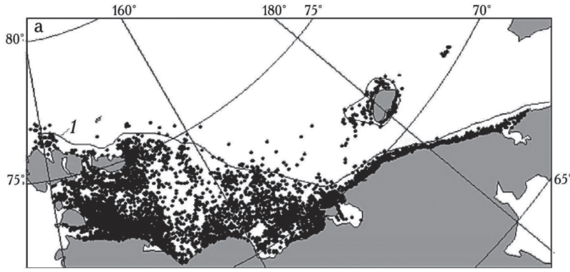

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Fig. 9. The average long-term position of the stamukhas (black dots) and the fast ice border (black line) in the Laptev Sea (a) and East Siberian Sea (b) (Gorbunov et al. 2007, 2008)

adfreezing with the bottom near the coastline. Stamukhas melts at the end of summer, and the accumulative formation remains in the shape of atoll, which was frozen in next winter. Freezing is facilitated by the fact that the bottom sediments located at the site of the stamukhas after their melting may be low or non-saline.

Freezing plays a key role in formation of such islands in the process of sedimentation. Freezing fixes them for a long time. Indeed, on shallows, the summer radiation warming of the bottom water and ice play an important role in the formation of the average annual temperatures of bottom permafrost (Zhigarev 1981, 1997). There are three sea depths intervals, 0...2-2.5 m; 2.5...6-8 m and more than 6-8 m. The first one corresponds to the thickness of the seasonal ice cover in the Laptev and East Siberian Seas at 70-76° N. This is the fast ice zone. Here, intensive conductive cooling of the bottom deposits occurs through the ice adfreezing with the bottom during the long winter time. Despite the summer warming of the bottom water up to 10-14°C, the annual sums of winter negative temperatures exceed the sum of summer positive temperatures, especially significantly near the sea edge. Therefore, the deposits freeze if the rising surface of coastal-marine accumulation falls into the upper part of the interval of isobaths of 2.5 to 0 m. According to the data obtained for Vankina Bay (72°N, Katasonov and Pudov 1972, Molochushkin 1973), the forming average annual temperature of bottom sediments is -10...-11.5°C. On foreshores, near the coasts of the Lyakhovsky Islands (74°N), where the temperature of the subaerial permafrost is -12...-15°C (Geocryology of the USSR, 1989), the temperature of bottom sediments in the fast ice zone is even lower.

The depth interval from 2.5 to 6-8 m is also significant. In the conditions of contemporary warming, the bottom water here has a positive average annual temperature, causing the existence of thawed and seasonally thawing sediments freely transporting by the waves. This interval of depths within the underwater elevations is a supplier of terrigenous material to accrete their tops and form islands. Below these depths, negative mean annual temperatures of the bottom water and bottom deposits are mainly formed (Zhigarev 1981; Grigoriev and Razumov 2005; Are 2012).

Sedimentation and formation of islands in the shallows also occurred in the past. The topographic maps of the 1950-80 period show several islands, a shape of which is completely similar or close to that shown in Fig. 8. These are Islands Peschanyy (Fig. 10), Nanosnyy. A shape of an atoll is rather unusual for islands of the Arctic seas. The possibility of their formation according to the pattern described above seems very plausible due to the constant presence of stamukhas throughout the summer.

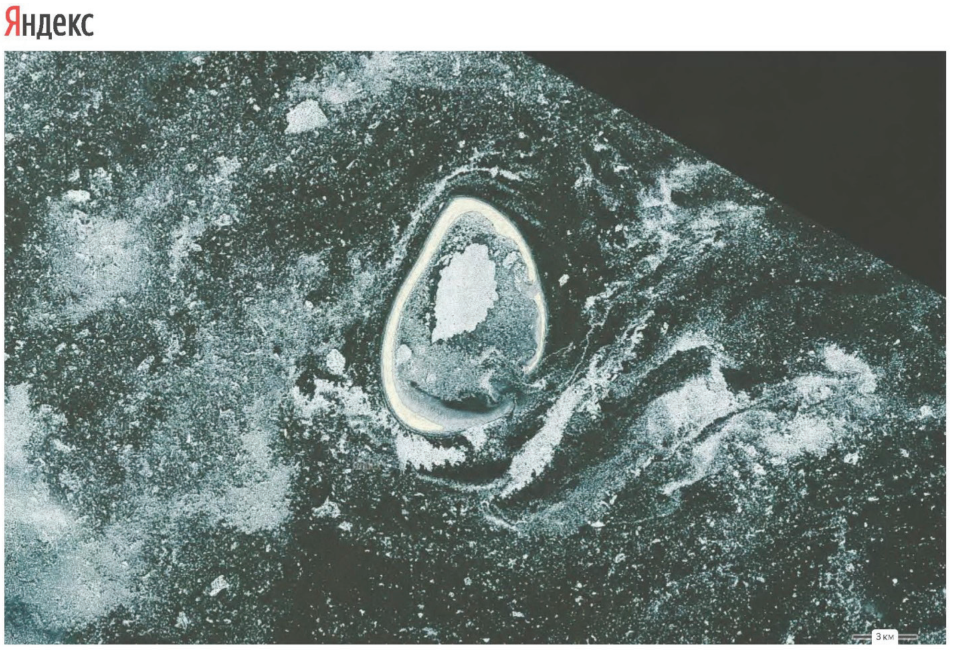

Fig. 10. Peschanyy Island (https://yandex.ru/maps/?clid=2220323-129&win=196&ll=116.290258%2C74.310081&z=10&l=sat)

The possibility of a present formation of islands and frozen ground, in our opinion, is closely related to warming and an increase in the duration of ice-free period. During the 19th and 20th centuries, the relicts islands of the Late Pleistocene Ice Complex were continuously destroyed, disappeared, and the shallows that they inherited were deepened (Gavrilov et al. 2003; Dudarev et al. 2003). However, according to the hydrographic monitoring of the Pacific Oceanological Institute, FEB RAS (Dudarev et al. 2003, 2008, 2015), the constant deepening of the Semenovskaya, Vasilievskaya and other shoals in the seas of Eastern Siberia, that occurred in the past, was replaced by the stabilization of their depths and even the formation of islands. In our opinion, the change in the orientation of lithomorphogenesis in shallow waters was caused by the increase of contemporary warming scale. Warming causes an increase in the volume of sedimentary material as a result of accelerating of coastal retreat and intensification of bottom erosion. The duration of the ice-free period, the wave length, the frequency and the strength of storms, and the wind-induced surges has increased. The large-scale increase in the volume of terrestrial material and wave energy in conditions when stamukhas exist up to freezing-over results in accumulation of sediments along their perimeter. The freezing of accumulated sediments preserves the formed islands.

CONCLUSIONS

1. The coastal zone of the East Asian sector of the Arctic is the area with highly dynamic permafrost environment. On the one hand, here the onshore permafrost is transformed into degrading offshore permafrost, and, on the other hand, modern submarine and subaerial syncryogenic permafrost are under formation.

2. The high activity of cryogenic (primarily thermogenic) processes in the coastal zone of study area is due to the participation of ice-rich syncryogenic deposits of the Late Pleistocene Ice Complex and the Holocene Alas Complex in its structure. The main processes are thermal erosion, thermal denudation causing a rapid coastal retreat, and degradation of the submarine permafrost.

3. The current decrease in the sea ice cover (an increase in an ice-free period) and climate warming result in an increase in the retreat rate of studied coast sections by 1.3-2.9 times in the 21st century compared with the second half of the 20th century. The rate of thermal denudation increased by 1.7-1.9 times during this time.

4. Degradation of the offshore permafrost from the top is caused by salinization of bottom sediments, their high ice content, and high annual average temperatures of the bottom water. Dependence of the bottom water temperature on air temperature allows us to assume higher rates of this process in the 21st century. The average rate of permafrost degradation from the top may be 1.5-2 cm/year, and from the bottom - 1.5-3 cm/year.

5. Contemporary accumulation and freezing of coastal-marine sediments occur in the areas of modern uplifts and where the coastline features contribute to sedimentation. Seasonal freezing first and then perennial freezing begins when the rising accumulation surface falls within a depth interval of 2-2.5 to 0 m and occurs through fast ice.

6. The large-scale increase in wave energy and in the amount of sediments coming from the coastal and bottom thermal abrasion, owing to the increasing duration of ice-free period, leads to a distinctly pronounced activation of sedimentation. The sedimentation occurs on banks and shallows, where, from the depths of 1-1.5 m, there is the possibility of fixing its results by freezing.

7. The activation of sedimentation in the shallows and the numerous stamukhas located in the zone of fast ice show the pattern of the formation of the islands around them. Stamukhas thaw shortly before freeze-up, and accumulative formations in a shape of an atoll are fixed by freezing. One of these islands – Yaya – was recently formed at Vasilyevskaya Bank. Similar islands were also formed in the past and designated on published topographic maps.

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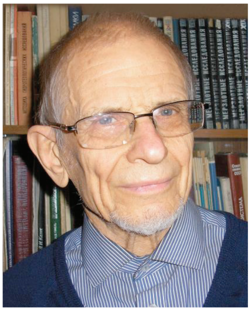

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