EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Kriosfera Zemli, 2021, vol. XXV, No. 3, pp. 3–18

CRYOLITHOGENESIS

NATURAL ENVIRONMENT DYNAMICS AND MORPHOLITHOGENESIS IN SHALLOWS OF THE EAST SIBERIAN ARCTIC SHELF

A.V. Gavrilov, E.I. Pizhankova

Lomonosov Moscow State University, Faculty of Geology,
Leninskie Gory, 1, Moscow, 119991, Russia; gavrilov37@bk.ru, epijankova@mail.ru

The shallows of the Laptev and East Siberian seas formed on the site of islands composed of the sediments of the Late Pleistocene Ice Complex which eroded in the 17^{th}–20^{th} centuries and are linked to positive morphostructures. The present article considers factors of modern sedimentation in marine shallows with the formation of islands (Yaya, Nanosny, Zatoplyaemyy, Leykina, etc.). Among these factors are a decrease in sea ice extent, an increase in the duration of the ice-free period, and the activation of destructive cryogenic processes triggered by the current climate warming. A decrease in ice coverage led to the dominance of hydrodynamic processes in sedimentation, unlike the primary role of sea ice in this process in the 17^{th}–19^{th} centuries. Sediment deficit in these centuries is substituted by its excess owing to the activation of cryogenic processes at the turn of the 20^{th} and 21^{st} centuries. As a result, the erosional shoreface profile is transforming into an accumulative one. Sedimentation is occurring parallel to a rising sea level related to a warming climate. A rise in the surface of islands and sandbanks is recorded on satellite images where there are modern positive vertical movements. The formation of islands and sandbanks is accompanied by their syngenetic freezing.

Key words: *morpholithogenesis, sedimentation, morphostructures, modern climate warming, remote sensing data, marine shallows.*

INTRODUCTION

The main direction of the development of the Laptev and East Siberian sea shelf (Fig. 1) during the Holocene is the destruction of a thick (up to 60 m) Late Neopleistocene Ice Complex (IC) sediments by destructive cryogenic processes (lake thermokarst, thermal abrasion and thermal denudation) [*Romanovskii et al., 1999; Are, 2012*]. The inability to resist heat influence is explained by the structure and composition of the IC, which includes thick syngenetic ice wedges, and its high summative volumetric ice content (70–95 %). The lake thermokarst began to develop in the negative morphostructures of the shelf of the East Siberian sector of Russia, which was drained at the time, at the end of the Late Neopleistocene (14–13 ka) [*Romanovskii et al., 1999*]. It has led to their initial flooding during the Late Neopleistocene–Holocene marine transgression. Having been land for a long time the elevations of positive morphostructures composed of the IC, were destroyed by thermal abrasion and thermal denudation, turning into peninsulas and later into IC remnant islands.

Historical data begins to trace the process of destruction of these islands from the 17^{th}–18^{th} centuries. The book "Noord en Oost Tartarye" by the Dutchman N. Witsen, published in 1692 and 1705, discusses an abundance of shallows on the way north from the "Ice Cape" (Cape Buor-Khaya) to an island located "opposite the mouth of the Lena River at the time" [*The history..., 1954*]. Supposedly, this was one of the islands-remnants of IC [*Gavrilov et al., 2003*]. The draft of koches (Russian Pomor sailors' vessels used in the 15^{th}–17^{th} centuries) was 1.0–1.5 m [https://ru.wikipedia.org/wiki/Коч]. In the second half of the 20^{th} century there were no such depths left in these places because the sea was becoming deeper. The average rate of deepening which was determined based on the time of the disappearance of Diomede Island (between 1761 and 1811), which had existed in the Dmitry Laptev Strait, and the depth within the bank at the site of this island in 1934 (7.4 m) [*The history..., 1954*] is approximately 5 cm/year. Thus, over the course of many thousands and hundreds of years of geological and historical data, respectively, the IC islands, and later shallows and banks which remained in their place, were eroding.

In September 2013 it was discovered from a helicopter that the top of Vasil'evskaya Bank is drained in the Laptev Sea on Semyonovskaya Shallow, within which Late Pleistocene IC islands existed. The formation of the island on Vasil'evskaya Bank was confirmed by a hydrographic expedition in September 2014. Its surface area at the time was approximately 0.038 km^2, elevation above sea level was less than 1 m. The island was named Yaya [https://ru.wikipedia.org/wiki/Яя_(остров)] (Fig. 2).

Fig. 1. Research area:

1 – islands which had disappeared in the 18th–20th centuries; *2* – sandy banks; *3* – shelf edge; *4* – isobaths.

Uplands (both terrestrial and underwater) are usually an object of denudation. The formation of an island within a very short (by geological standards) period of time is an extraordinary occurrence. In addition to Yaya, islands composed of contemporary and Holocene sediments formed at the location of the Late Pleistocene IC remnants, presently and earlier.

Fig. 2. Yaya Island, which had appeared at the location of Vasil'evskaya Bank, discovered in 2013.

Breakers around the island indicate the highest parts of the shallow. P.S. Sayapin's photo.

The scientific community's interest in this phenomenon and the relevance of understanding its reasons became the driving factor in the development of ideas explaining a change in the morpholithogenetic regime and the formation of islands at the turn of the 20th and 21st centuries. The results of a study of the present phenomenon are provided below.

MATERIALS AND METHODS

The geological structure of the studied islands was not researched by drilling methods, so the main research materials were Landsat, Sentinel, and Terra/MODIS satellite images (SI) from 1973–2020, as well as a series of geological materials. The latter include maps at scales of 1:1,000,000 of the third [*State... Map..., 2014, 2016, 2017; Burguto et al., 2016*] and second generations, tectonic and neotectonic maps, seismoacoustic data of Semyonovskaya Shallow profiling by VNIIOkeangeologia [*Rekant et al., 2009*] and Pacific Oceanological Institute (POI) FEB RAS monitoring. Topographic maps at scales of 1:200,000 and various published historical data related to the given problem were also used. The synthesis and combining of temporally different remote data, the identification of new formations and suspended loads in sea water were performed using the ScanEx Image Processor program suite. Calculations for the study of coast dynamics, as well as interpretation of coastal landscapes, were performed using MapInfo Professional GIS software. Data on the ice coverage of the Laptev and East Siberian Seas were obtained from the AARI digital archive [http://www.aari.nw.ru/projects/ECIMO//?im=100, 2020].

NATURAL ENVIRONMENT

From a geologically structural perspective the studied area is related to the epi-Cimmerian platform, which occupies the Laptev and East Siberian seas' shelf. A Late Cretaceous-Cenozoic sedimentary cover and a base represented by Verkhoyansk-Kolymsk and Novosibirsk-Chukotka fold belt rock are revealed in its structure [*State… Map…, 2016*]. The distribution of the region's morphostructures is due to the areal distribution of the cover and basement rocks and the direction of the latest vertical tectonic movements. Two main morphostructures stand out on a regional level: a subsidence zone (plate) of the Epi-Cimmerian Platform (A) and an East Laptev zone of uplift where basement rock exits at its surface (B) (Fig. 3). The developing continental margin basin of the studied seas corresponds to the first. The East Laptev zone is part of the stretching Lomosov-Svyatonosskiy uplift zone [*Ivanov et al., 2004*]. The submeridional positive neotectonic structure which includes the Kotelnichesko-Lyakhovskoe Uplift on the shelf and the Chokurdakh Uplift on the continent correspond to this zone [*State… Map…, 2016*]. The zone plays the part of an ancient divide of the Laptev and East Siberian sedimentational basins [*Patyk-Kara et al., 1989*] and sharply contrasts with the shelf morphostructure of the Laptev and East Siberian Seas in megarelief.

Local morphostructures stand out on the borders of the Laptev Sea Cenozoic graben-rift system morphostructure. These are trenches and grabens on the one hand and uplifts and horsts on the other hand (Fig. 3). Within the first, the thickness of the cover reaches 5.5 km, while in the second it is typically less than 1 km. The smallest value (0.5 km) is typical for the horst where Yaya Island formed [*State… Map…, 2016*].

The East Laptev zone represents an ensemble of positive and negative local morphostructures. The first include the Islands Belkovsky, Kotelny, Stolbovoy, Maly Lyakhovsky and Bolshoy Lyakhovsky, and a series of elevated massifs on the continent: Syurekh-Tas, Khaptagay, Ulakhan-Tuguttakh, Chokurdakh,

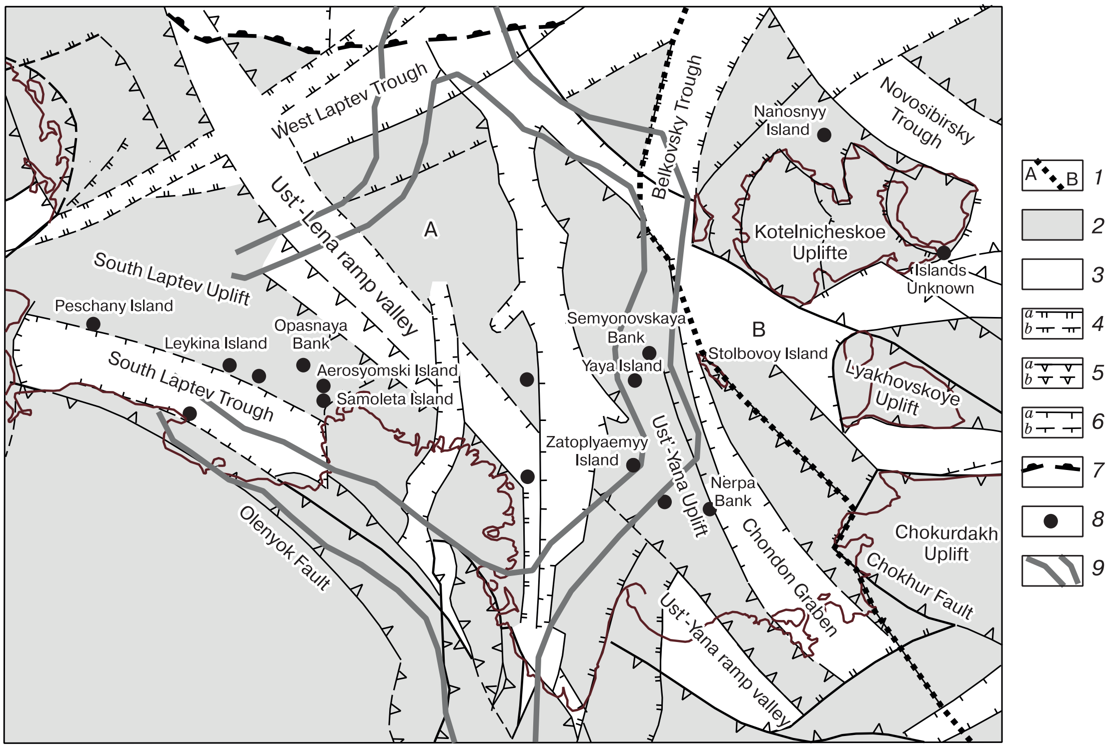

Fig. 3. Shelf morphostructures of the Laptev Sea and the western part of the East Siberian Sea [*Lukina et al., 2003; State… Map…, 2016; with changes*].

1 – regional morphostructures: A – Epicimmerian platform subsidence zone, B – East Laptev zone of uplifts. Local morphostructures: *2* – positive, corresponding to uplifts and horsts, *3* – negative, corresponding to depressions and grabens. The newest faults: *4* – normal faults (*a* – real, *b* – assumed), *5* – reverse faults (*a* – real, *b* – assumed), *6* – unspecified type (*a* – real, *b* – assumed). *7* – shelf edge, *8* – newly-formed and forming banks and islands, *9* – boundaries of earthquake distribution areas along the boundaries of the Eurasian, North American plates and the Laptev microplate [*Avetisov, 2004*].

Uryung-Khastakh, Khar-Stan and others. Negative morphostructures form the Sannikov, Eterikan, and Dmitry Laptev Straits. The sedimentary cover in this zone is discretely developed, not exceeding 500 m in thickness [*Burguto et al., 2016*].

There is permafrost on the shelf that was formed during its draining in the Late and Middle Neopleistocene. Its degradation, primarily from the bottom, is taking place presently under the influence of heat flow from the depths. Degradation from the top occurred during the Late Neopleistocene–Holocene marine transgression and continues presently owing to an increase in the mean average temperature of bottom water, which is especially significant in the coastal zone, and the salinification of bottom sediments, which lowers its freezing point. According to the results of mathematical modeling [*Fartyshev, 1993; Romanovskii et al., 2003; Dmitrenko et al., 2011; Nicolsky et al., 2012*], the permafrost is described primarily by a continuous distribution. Discontinuous and sporadic frozen thicknesses are distinguished in the outer part of the shelf. Their top can be 50–100 m deep, the thickness varies from 500 m (near the coast) to 100 m and less (on isobaths 60–80 m).

According to lithological maps of the bottom surface [*State... Map..., 2016, 2017*], the shallows within the water area are composed of pure and monogranular sands with a dominating size fraction of more than 85 % and 75 %, respectively. Freshwater and brackish water plankton communities dominate above shallows [*Dudarev, 2016*], since the waters and their sediments are desalinated. The desalination may be related to long-term existence of grounded hummocks (stamukhas) in the shallows.

The bottom of the IC on positive morphostructures usually occurs above sea level. According to seismoacoustic data Neopleistocene sediments are overlaid by a layer of Holocene marine sediments on Semyonovskaya Shallow [*Rekant et al., 2009*]. A level of cooled sediments which covers the permafrost level is distinguished in the cryolithozone structure of the shallow. Its thickness is minimal on the flat surfaces of the tops of the banks (from 1 to 5 m). Here and there, most likely where stamukhas regulary form, the top of the permafrost lies directly under the bottom surface. On lower surfaces, depending on the depths of the sea, the thickness of the cooled level varies from 5 to 15 m. Paleothermokarst basins composed of stratified cooled sediments are identified. Their appearance is related to lake thermokarst on drained parts of the shelf at the turn of the Late Neopleistocene and Holocene [*Romanovskii et al., 1999*]. Marine flooding led to the transformation of lake closed taliks into submarine ones. Within them the top of permafrost currently lies 30–60 m below the seafloor [*Rekant et al., 2009*]. Unlike frozen sediments cemented by ice, cooled sediments can be a source of material for the accumulation on the Vasil'evskaya and Semyonovskaya Banks.

DATA ON THE DYNAMICS OF ISLANDS AND BANKS

There are factual data on changes in the depth of the tops of shallows only from Semyonovskaya Bank, which is located within the eponymous shallow. In this shallow, besides the named bank, there also exists the Vasil'evskaya Bank (Fig. 4). The Vasil'evskaya and Semyonovskaya Banks formed at the location of eponymous islands, which were washed away in 1936 and 1951 [*Gakkel, 1957*]. There are also data on the cessation of the existence of Figurin Island around 1950 [*Gakkel, 1957*]. In 1952, a bank was discovered in its place using echolocation and named Figurin Bank [*Popov, 1987*].

Data on changes in sea depth within Semyonovskaya Bank. In 1955 the minimum depth of the sea within Semyonovskaya Bank was 0.1 m [*Klyuev et al., 1981; Are, 2012*]. In 1965 the top surface of Semyonovskaya Shallow was contoured with a 2 m isobath. The minimum depth of these banks was 0.8 m at the axis of the shallow [*Semenov, 1971; Klyuev et al., 1981*]. Thermal subsidence and the washing of Semyonovskaya Bank led to its deepening by 2–5 m in accordance with navigation maps from 1969–1971 [*Are, 2012*]. Detailed monitoring of changes in the depth of Semyonovskaya Bank (measurements from vessels with a small draft in 1999, 2000, 2003–2006)

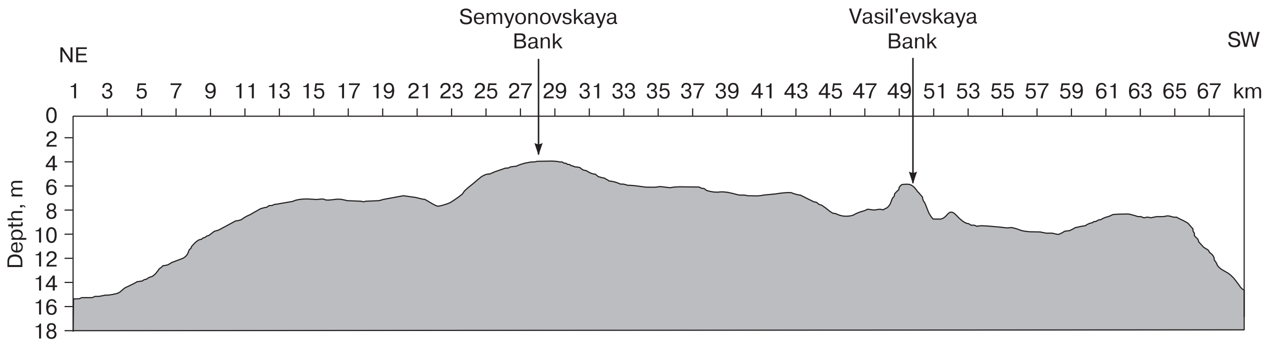

Fig. 4. Submeridianal section along the axis part of Semyonovskaya Shallow [*Charkin et al., 2007*].

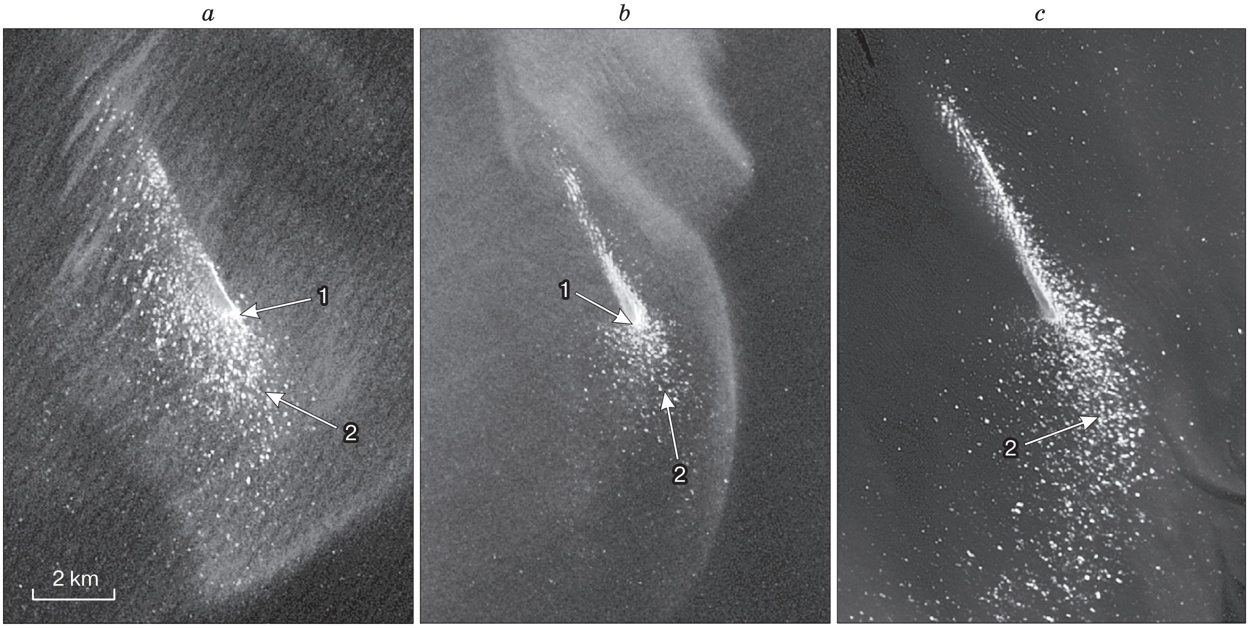

Fig. 5. Image of Vasil'evskaya Bank on Landsat-7, -8 SI, © USGS.

a – Landsat-7 (2007/08/12); *b* – Landsat-8 (2018/08/10); *c* – Landsat-8 (2020/07/19). 1 – stamukha remnants; 2 – breakers on shallows.

allowed for the description of the dynamic of its top surface in subsequent years [*Charkin et al., 2007*]. According to these data the smallest depth of Semyonovskaya Bank was 4.2 m in the beginning of the 2000s, compared to depths of 5.5 to 8.6 m within the shallow (Fig. 4). Significantly smaller minimum depths are provided in later publications [*Dudarev, 2016*] (0.8–1.0 m).

Data on shallow morphodynamics obtained using satellite images. Multitemporal satellite images (SI) provide important information about changes in shallows. Thus, based on Terra/MODIS data, the shallow at the top of Vasil'evskaya Bank was already first seen in 2003–2005 due to small breaking waves. From the end of October 2003 a stamukha forms almost yearly on this bank. Juxtaposition of Landsat-7 and -8 images from 2007, 2018 and 2020 allowed us to record the emergence of Yaya Island, the remains of stamukhas and breakers in shallows (Fig. 5). Using SI Landsat, Sentinel and MODIS from different seasons from 1973–2019 allowed us to identify a series of other banks. In periods of freeze-up and seasonal ice destruction they can be decoded based on stamukhas and hummocks' cooccurrence with them, while in the ice-free season they can be decoded by the presence of suspended matter fields above banks or breakers under wind conditions. Such are the Semyonovskaya and Nerpa Shallows, nameless shallows to the northeast and west of the Lena River delta, and the Opasnaya Bank [*Kucheiko et al., 2020*].

The rising surface of Semyonovskaya Bank on the eponymous shallow was first recorded on SI in 2004 based on the breakers above it. Later (2018) its location on SI was also determined using the breakers in the image. The results of the decoding allow us to conclude that sediments accumulate on Semyonovskaya Bank like on Vasil'evskaya, but more slowly. These facts explain the varying values of the depth of this bank in measurements from the beginning of the

Table 1. **Nanosnyy Island dynamics based on results of the measurements on Landsat -7, -8 SI**

Date of space imagery	Length of island, km	Width, km	Coastline length, km	Area, km^2
1999/07/13	2.9	0.23–0.34	6.0	0.75
2000/08/25	3.3	0.22–0.36	6.9	0.76
2002/08/20	3.2	0.18–0.49	7.1	0.84
2011/08/15	3.3	0.20–0.44	7.4	0.89
2014/08/13	3.6	0.20–0.63	8.7	1.22
2018/08/04 (upsurge)	3.5	0.16–0.35	7.7	0.76
2018/08/08	4.2	0.20–0.74	10.0	1.31
2018/08/11 (downsurge)	5.2	0.2–1.1	11.4	2.4
2019/07/19 (upsurge)	3.7	0.16–0.42	8.1	0.86
2019/08/04	4.3	0.16–0.90	10.6	1.46
2019/08/22 (downsurge)	4.8	0.2–0.9	11.0	2.0

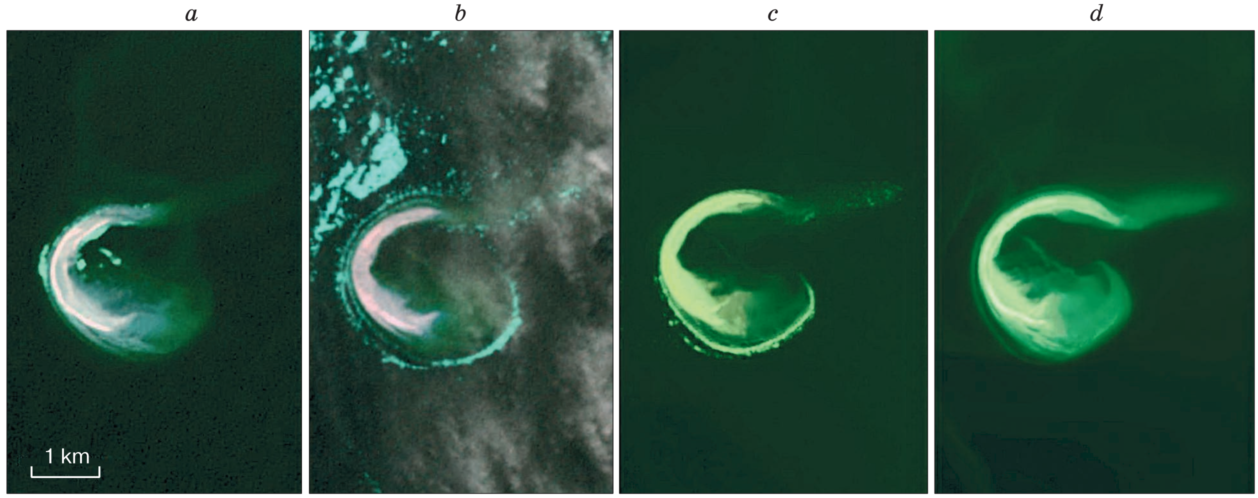

Fig. 6. Image of Nanosny Island on Landsat-7, -8 (Synthesis 543), © USGS.
a – Landsat-7 (2000/08/25); *b* – Landsat-7 (2002/08/20); *c* – Landsat-8 (2014/08/13); *d* – Landsat-8 (2018/08/08).

2000s – 4.2 m [*Charkin et al., 2007*] – and later – 0.8–1.0 m [*Dudarev, 2016*].

Banks can be exposed under wind-induced downsurges. Zatoplyaemyy Island on West Bank (117 km east of the Lena River delta) and Leykina Island (Osushnoy) (80 km northeast of Terpyai-Tumsa Peninsula) are also ascribed to formations that are exposed under downsurges and flooded under upsurges.

Newly formed islands are quite dynamic. Their configuration and surface area changes. Changes in their shapes and surface areas are recorded for Peschany, Leykina, Nanosnyy, Samoleta, Aerosyomski, Yaya Islands.

The existence of wind-driven phenomena, the amplitude of which can reach 2.0–2.5 m [*Mustafin, 1961*], complicates the precise determination of the configuration and parameters of low-lying islands. Nonetheless, for Nanosnyy Island, which had formed on Figurin Bank and is located on a shallow 33 km northeast of Cape Anisy of Kotelny Island, an increase in its length and surface area, particularly evident in recent years, has been established (Table 1, Fig. 6). The island represents a half-ring of the right shape, the convex part of which is oriented to the west, no more than 2 m in height. A shift in the island's coastline toward the east has been recorded. The products of washing from the western retreating coast are transported eastward, where they form spits which adjoin the island. From 2000 to 2014 retreat of a 1.5-km area of the western coast of Nanosnyy Island constituted 55 m on average, with a maximum of 86 m. As such, the average speed of movement from west to east was approximately 3 m/year. In the past five years the coast has retreated by the same amount, and the average speed over 18 years exceeded 5 m/year. The sea has washed away 0.21 km^2 of the western coast, and the increase in surface area in the southern and northern ends of the island has constituted 0.36 km^2.

CENTURIES-OLD CHANGES IN THE NATURAL ENVIRONMENT

Data on changes in climate and ice coverage can serve as the main indicators of centuries-old changes in the natural environment of Arctic seas. Reconstruction of the average annual air temperature (Fig. 7) demonstrates that in the 17th–beginning of 20th centuries, when the remnant islands formed by IC and the banks on their locations were washing away, the average annual air temperature was 1.5–2.0 °C lower than the contemporary temperature. The period from the warm early medieval times to the middle-end of the 19th century or a shorter interval (17th – middle of the 19th century) is called the Little Ice Age (LIA) (Fig. 7, 8).

Data on the distribution of microfossils in the surface sedimentary layer of the Laptev Sea shelf together with pollen data and data on the blockage of many-year sea ice of the coasts of Iceland can also serve as an indicator of fluctuations in climate and ice coverage of seas (Fig. 8). The coldest period (1400–1900, Fig. 8, *A*) is characterized by the disappearance of marine diatoms and minimum quantities of benthic foraminifera. Data on ice coverage near the coasts of Iceland are also quite descriptive (Fig. 8, *B*). They demonstrate that in the 17th–19th centuries it was particularly cold on the island. Migrants, of which there were already 25,000 by the year 900 (with a modern population of 150,000) – only 50 years after

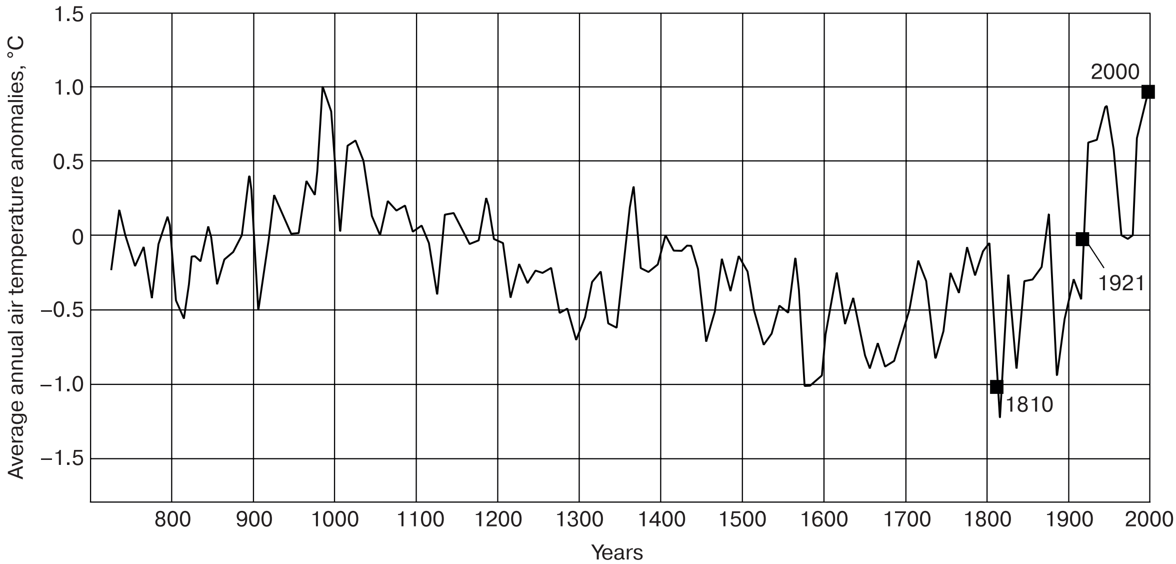

Fig. 7. Deviations of average annual air temperature in the western sector of the Russian Arctic from average values for 800–2000 as cited in [*Klimenko et al., 2013*], with simplifications.

The black squares indicate temperatures that were used to build the model of average annual temperature of bottom water in the beginning of the 1920s and 1800s.

the discovery of the island by Normans – leave the island or die [*Jones, 1964*]. Only in the beginning of the warming in 1930–1940 the sea around Iceland ceases to be icy.

Changes in ice coverage can be inferred from information about the possibility of navigation in the Arctic seas. In the warming of the Middle Ages (about 1000 years ago), the Normans reached 79° N in the strait between the Ellesmere and Greenland islands and travelled north of 80° N near Svalbard [*Jones, 1964*]. It is significant that Icelandic sagas barely mention sea ice as a barrier to sea travel.

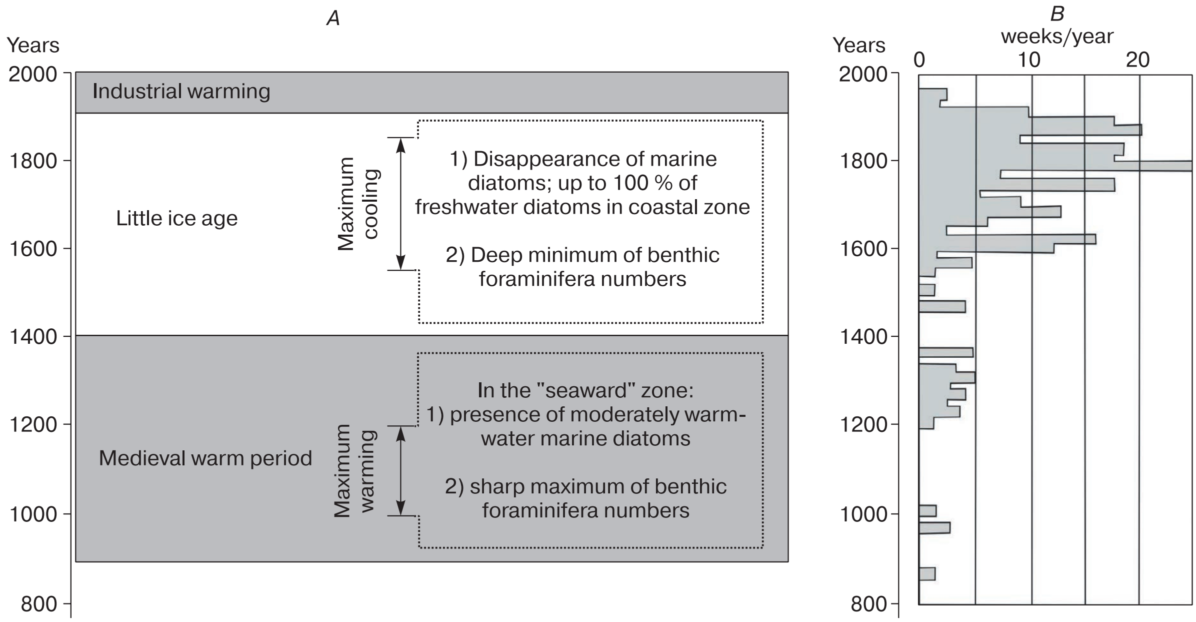

Fig. 8. Paleoclimatic reconstructions for 800–2000.

A – based on micropaleontological data on the Laptev Sea shelf [*Matul et al., 2007*]; *B* – based on the length (number of weeks per year) of blocking of the coasts of Iceland by Arctic pack ice [*Koch, 1945*].

Whale, seal and walrus hunters travelled to the coasts of Svalbard and Novaya Zemlya up to the year 1200. Expedition and fisherman travels on sea vessels among drifting ice was quite complicated in the eastern seas of the Arctic in the 17th – first half of the 19th centuries. For example, the Northeastern expedition directed by J. Billings (1787–1791) for the geographical study of the northeast with astronomical identification of geodesic control points was planned as a marine expedition, but had to be conducted on land. The study of the New Siberian Islands during this time (1770–1824) occurred exclusively by way of travel across ice [*The history..., 1954*]. In L.A. Zhigarev and V.A. Sovershaev's opinion [*1984*], sea fast ice could have been preserved or drifting ice could have existed throughout the entire summer around Semyonovskaya Shallow. Relief from ice occurred only in individual years. Based on the data in Fig. 7 and ice coverage values, the interval from the end of the 18th to the middle of the 19th centuries ought to be considered the pessimum of the LIA for the shelf part of the East Siberian seas.

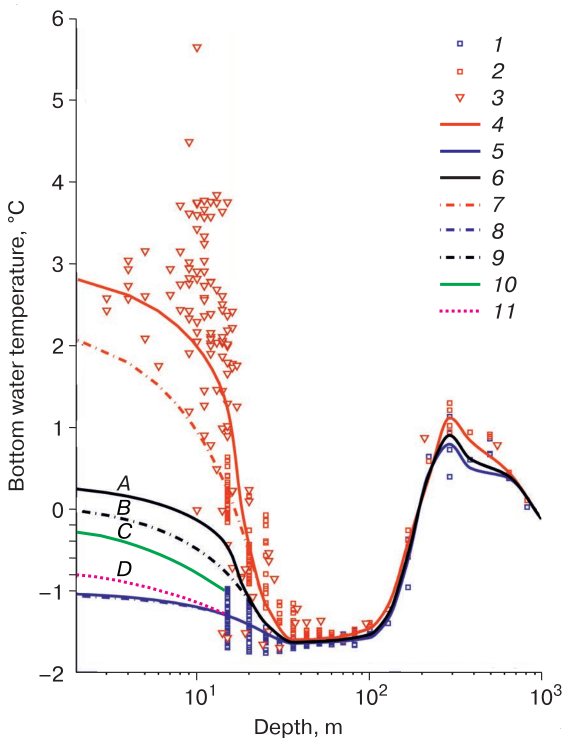

Fig. 9. Laptev and East Siberian Seas bottom water temperature data [*Nicolsky et al., 2012*] and model of century average bottom water temperature in the beginning of the 1920s and 1800s.

Average water temperature: *1* – winter temperature (AARI), *2* – summer temperature (AARI), *3* – summer temperature (International Siberian Shelf Study, ISSS). Average decadal water temperature curves for 1999–2009: *4* – summer temperature, *5* – winter temperature, *6* – average annual temperature. Average century water temperature curves for 1920–2009: *7* – summer temperature, *8* – winter temperature, *9* – average annual temperature. Model curves of medieval bottom water temperature: *10* – in the beginning of the 1920s, *11* – in the beginning of the 1800s.

The description of centuries-old dynamics of the natural environment will not be complete without the reconstruction of at least orientational values of average annual temperature of bottom water during the pessimum of the LIA. AARI has observed winter and summer bottom water temperature since 1921. For the reconstruction of its average annual values in the beginning of the 1920s the authors used the temperature data published in the work of [*Nicolsky et al., 2012*] (Fig. 9), where the temperatures of bottom water for the warmest decade (1999–2009) and its century values for the period from the beginning of the 1920s to 2009 are presented.

In order to understand what the minimum LIA temperature was in the 20th century, taking curve B (century average bottom water temperature) as the axis of symmetry we can graph a curve of minimum temperatures – curve C, symmetric to curve A, – and, using information about the amplitudes of air temperatures in the intervals 1921–2009 and 1800–1921 (Fig. 7), obtain an understanding of the minimum temperatures of bottom water in the 19th century (curve D) by creating graphs analogous to those described for the 20th century.

We will see that the average annual temperature in the beginning of the 1920s changed within the interval of the values: from −0.2...−0.3 °C near the shore to −0.8 °C at a sea depth of 10 m. During the pessimum of the LIA it changed from −0.8 °C near the shore to −1.2 °C at a depth of 10 m; in other words, it was almost identical to contemporary winter water temperature.

In conclusion to the considerations of the dynamics of the natural environment in the water area of the East Siberian Arctic it should be noted that a reconstruction (Fig. 7) based on data mainly for the western sector of the Arctic was used for the description of the average annual air temperature. It is currently higher than above the seas of the Eastern Arctic and was this way during the LIA. This is due to lesser climate continentality in the west. Because of this, the hydrodynamics, activity of cryogenic and ice processes on the shelf of Eastern Siberia in the Middle Ages was determined by even lower air and bottom water temperatures and especially greater ice coverage.

RESULTS OF THE ACTIVATION OF CRYOSPHERIC AND HYDRODYNAMIC PROCESSES INITIATED BY CLIMATE WARMING

The **climate warming** called the industrial warming and commencing in the beginning of the 20th century (Fig. 7) is most notable in 1990–2000. Warming in high latitudes (60–85° N) exceeds warming in the northern hemisphere by a factor of more than two. It is even more significant within the water areas of Arctic seas. Based on Roshydromet data the air temperature within the Laptev and East Siberian Seas in 2019 exceeded its average values in 1961–1990 by 3.9 °C and 3.3 °C, respectively. The rate of temperature increase relative to the indicated period of time exceeds that for the northern hemisphere (0.18 °C/10 years) [*The second assessment report..., 2014*] by a factor of 13 above Arctic seas (2.43 °C/10 years) [*Report..., 2020*]. In the authors' opinion, the reason for such an increase is the decrease in sea ice surface area and unabatingly decreasing surface albedo.

Decrease in ice coverage is expressed as decreasing sea ice surface area and is accompanied by an extending length of the ice-free season. The correlation coefficient of the decrease in ice surface area in September with summer air temperatures of the marine Arctic for 1979–2019 constitutes –0.92 [*Report..., 2020*]. If the degradation of sea ice in the 1980s and 1990s occurred owing to an Atlantic influence and was observed primarily only in the western sector of the Eurasian Arctic [*The second assessment report..., 2014*], in the 2000s it becomes rather palpable in the eastern sector, as well. The surface area of sea ice in the Laptev and East Siberian Seas has been steadily decreasing for the past two decades. In 2011–2020 it decreased by a factor of four compared to 1970–1989 (Fig. 10). According to AARI data, in August 2020 the Laptev Sea was entirely free of ice.

The increase in the length of the ice-free season on average for the Arctic seas of Russia in 2001–2011 relative to the cold years of 1965–1975 constituted 40 days [*The second assessment report..., 2014*]. According to data from Kigilyakh and Ayon stations it equates to 36 and 47 days, respectively. This length is significantly less only in bays (Tiksi Station – 7 days).

Hydrodynamic processes. An increase in the duration of the ice-free season means an increase in the dynamically active period, which was estimated at only 10–20 % of the year in the 1970s [*Sovershaev, 1981*], while in 2001–2011 it increased to 20–30 %. Seasonal ice boundaries retreating to the north and an increase in the duration of the dynamically active season significantly increase the length of wave fetch and wave activity in general. In the 1970s and 1980s the wave fetch length in the Laptev Sea varied from 90 km in July to 600 km in October, and the maximum wave height at the maximum fetch was 3 m [*Kaplin et al., 1991*]. Waves 3 m tall carry approximately 100 kW of energy per 1 m of the wave crest [*Safyanov, 1996, p. 17*]. Storm waves 5 m tall and 100 m long are now considered average. These waves are beginning to be recorded in seas where they were significantly smaller in the beginning of the 20th century: for example, in Beaufort Sea [*Thomson, Rogers, 2014*]. With such waves, for each square kilometer of the wave-covered water surface there are 3 billion kW of energy [*Safyanov, 1996*]. Even in the 1940s through 1960s waves affected the bottom in such a way during storms that sludge and sand were thrown onto the decks of vessels in the shallow Laptev and East Siberian Seas hundreds of kilometers from the coasts [*Klyuev, 1965*].

The presented quantitative data allow us to conclude that contemporary warming and decreasing sea ice coverage significantly increase the potential of morpholithogenesis. However, the specified potential is just a possibility of its manifestation. For the implementation of accumulation sediment material is necessary. Given its sufficient amount the energy of waves is spent on transport and accumulation of material, given its deficit it is spent on the washing of sediments. The formation of sediment material during contemporary warming is tightly related to the activation of cryogenic processes.

The activation of destructive cryogenic processes determines the annual arrival of 62 and 90 million tons of sediments to the bottom of the Laptev

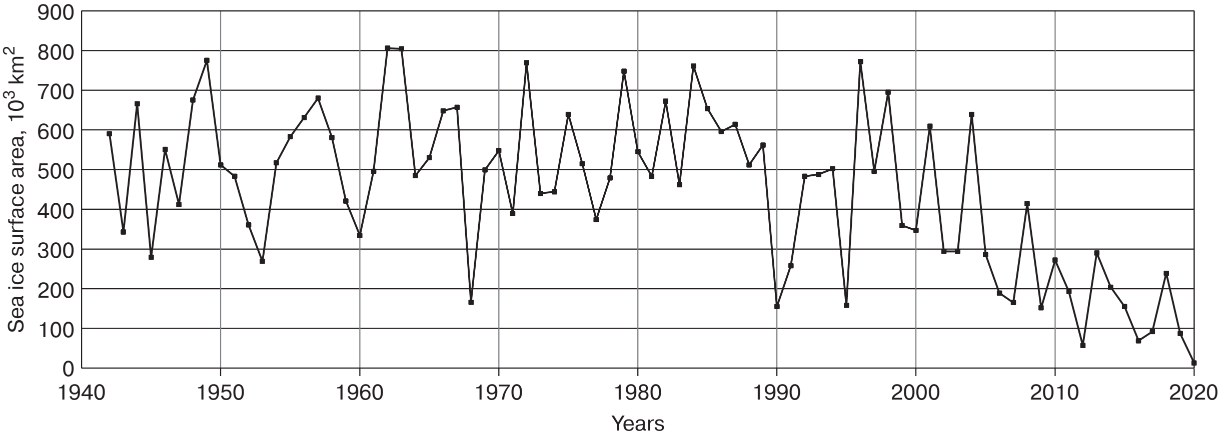

Fig. 10. Average sea ice area (ice coverage) in August in the Laptev Sea and the western part of the East Siberian Sea for 1940–2020 based on AARI data [http://www.aari.ru/projects/ECIMO/?im=100].

and East Siberian Seas, respectively [*Grigoriev, 2017*]. It occurs by way of the effect of these processes not only on coasts, but also on the bottom. The results of the juxtaposition of multitemporal different aerial and satellite images demonstrated that for Bolshoy Lyakhovsky Island and the southern coast of the Dmitry Laptev Strait 27 km^2 of the surface area of Bolshoy Lyakhovsky Island and 12.4 km^2 of the continental coast were washed away under the influence of thermal abrasion and thermal denudation from 1951 to 2000. In the period from 2000–2013 these values constituted 12.2 and 6.5 km^2, respectively. The rates of retreat of shores constituted 3.2 m/year for 1951–2000 and 6.4 m/year for 2000–2013 on average [*Pizhankova, Dobrynina, 2010; Pizhankova, 2016*]. A twofold increase in the rate of coastal retreat is a consequence of climate warming, which has particularly activated since the mid-1990s.

Thermal subsidence of the bottom is an equally widespread process. Widely known data from repeated (1940–1960) hydrographic imaging in the coastal zone 6–8 km wide along the 160-km Anabaro-Olenek coast composed of IC sediments [*Klyuev, 1970*] can serve as an example of their manifestation. Depression from subsidence of bottom sediments with high ice content constituted 0.4–1.0 m here. As a result, isobaths shifted 0.3–1.0 km toward the coast. According to F.E. Are's [*1998*] calculations 3.4 million tons of sediments entered the sea every year in the 1940s–1960s owing to thermal subsidence, as well as thermal abrasion and thermal denudation of these coasts. Currently, considering the scale of contemporary warming and shrinking ice coverage, the volume of sediments entering the sea should be even larger.

The degradation of permafrost in the Laptev and East Siberian Seas, as noted above, occurs not only from the bottom of the permafrost, but also from the surface, from their top. Unlike the LIA, during industrial warming it is actualized not only owing to sediment salinization, but, mainly, as a result of increasing bottom water temperature. It becomes particularly significant during periods of warming when the sum of summer positive temperatures of bottom water begins to exceed the sum of negative winter temperatures and its average annual temperature becomes positive.

In the first half of the 20th century published data on the existence of positive average annual temperature of bottom water based on data from instrumental observations were related only to the warming of the 1930s–1940s [*Geography..., 1949*]. In the 1970s the same temperatures, as well as bottom sediment temperatures above 0 °C, were recorded as a result of geocryological research completed near Muostakh Island [*Molochushkin, 1969*] and in Van'kina Bay [*Zhigarev, Plakht, 1974*]. Such temperatures were observed in the isobath interval from 2 to 7 m. In both cases they were related to the zone of heat influence of Lena River runoff. Temperatures above 0 °C were also known near mouths of large rivers and in numerous shallow bays. In other locations water temperatures in shallows were negative [*Are, 2012*].

Water temperature has been rising significantly since 1985 [*Dmitrenko et al., 2011; Nicolsky et al., 2012*]. Based on published data, the highest bottom water temperatures occurred in 1999–2009. It is quite significant that in surface area, up to 76° N, and in depth (up to depths of 9–10 m), the area of their distribution significantly expands. Positive water temperatures cause thawing of permafrost. Thawing eases the transport of sediments and their accumulation.

Newly formed above-surface and underwater landforms are currently freezing. The freezing of newly formed landforms occurs from the surface in the fast ice zone (isobath interval 0–2 m), where deep conductive cooling of bottom sediments occurs by way of ice freezing to the bottom. It is so significant that average annual temperatures of submarine permafrost near the water edge are characterized by values as low as in subaerial permafrost. In the 1970s they constituted –10...–12 °C in Van'kina Bay 72° N [*Katasonov, Pudov, 1972*]. Perennial freezing facilitates the conservation of newly formed landforms by complicating their erosion.

In conclusion it should be said that the activation of destructive cryogenic processes is first and foremost provided by shrinking ice coverage, an increase in the length of the dynamically active season and subsequently increasing power of hydrodynamic processes. During the LIA there were also areas where the permafrost layer was overlaid by a layer of cooled sediments. However, a small length of the wave fetch under conditions of widespread drifting ice and a short ice-free season did not contribute to the transport and accumulation of bottom sediments. The transport of the latter occurred mainly owing to ice processes.

The particle-size distribution of the sediments is quite an informative data for the identification of the conditions of sediment accumulation. The fraction composition of bottom sediments and its lateral variability within the area captured by sheets S-53; 54 of the geological map are shown in Fig. 11.

The contents of Fig. 11 show that contemporary sand-sized sediments are predominant near the coasts of the continent and the New Siberian Islands, as well as at the top parts of shallows. One such extensive shallow, which includes the Semyonovskaya Bank with Yaya Island, West Bank with Zatoplyaemyy Island and Nerpa Bank, is presented in Fig. 11, *a*. Monogranular sands transition into monogranular pure sands, where the sand fraction content exceeds 85 %, reaching 94 % in individual samples, in elevated areas of Semyonovskaya Shallow, West and Nerpa

Banks. It has equivalent values within two other sheets of the geological map (S-51; 52 and S-50) [*State… Map…, 2014, 2017*]. These are shallows, the tops of which are represented by Peschany, Leykina, Aerosyomki, Samolet Islands and nameless banks. In the authors' opinion, a similar process also occurs in the vicinity of Nanosnyy Island. In the location of the relict Figurin Bank the process of accumulation of modern sand sediments has been underway since the second half of the 20th century. This process is accompanied by their syncryogenesis.

The sand is of a local origin, it formed as a result of rewash of sands which were present as mixtures in the composition of primarily aleuritic IC ground blocks in the Late Neopleistocene. On the geological map [*State… Map…, 2014, 2016*] they are ascribed to palimpsest sediments. These are relict sediments which have been intensely reprocessed by contemporary hydrodynamic processes [*Geological Dictionary, 2011*]. In the modern genetic classification, they are ascribed to perluvium. Particles of the finer fraction are washed out and transported to deeper regions of the water area. Aleurites are predominant on the slopes of the banks, the role of sand particles in their composition decreases down the slope (Fig. 11, *b*). Pelite size particles accumulate in negative landforms of the bottom, including in the paleovalley of the eastern branch of the Yana River (Fig. 11, *c*).

In Semyonovskaya Shallow sands are not only rewashed but also used for sedimentation within Vasil'evskaya and Semyonovskaya Banks. On Vasil'evskaya Bank this process already became notice-

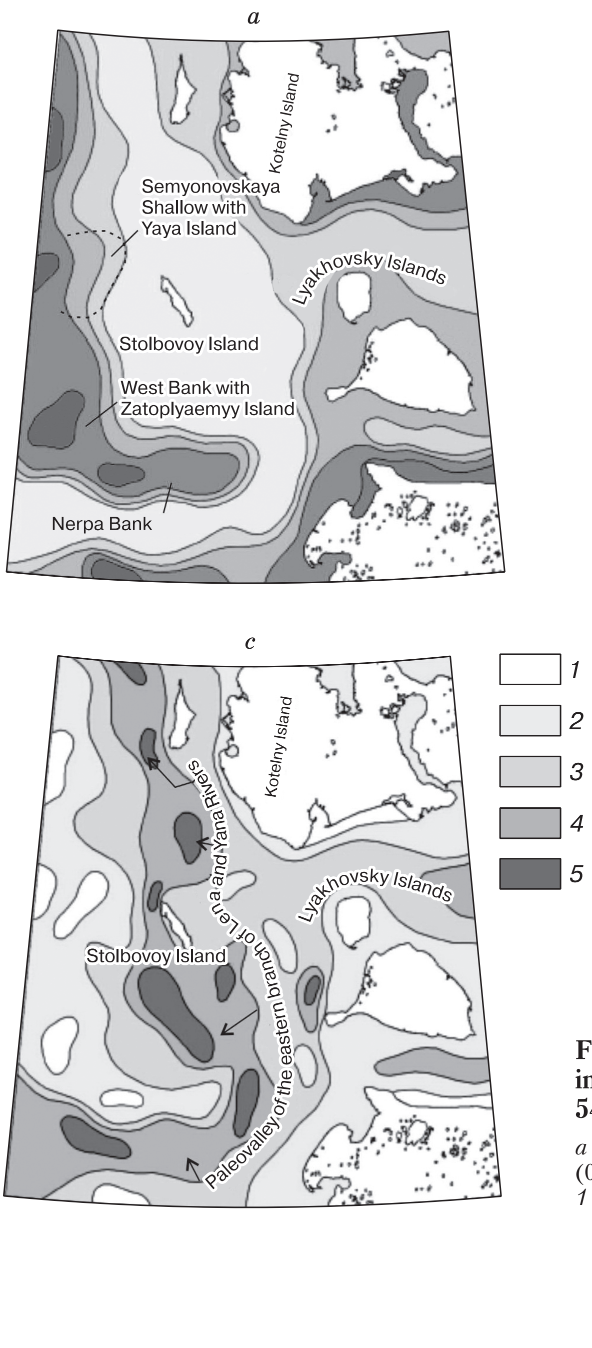

Fig. 11. Scheme of distribution of the main fractions in the sediments of the water area within sheet S-53; 54 [*State… Map…, 2016*].

a – sand (1.0–0.1 mm); *b* – aleurite (0.1–0.01 mm); *c* – pelite (0.01–0.001 mm). Particle-size distribution in the sediment (%): *1* – 0–10, *2* – 10–25, *3* – 25–50, *4* – 50–75, *5* – more than 75.

able from breaking waves in 2003–2005 and 2007, as mentioned above. Particle-size distribution of sediments within Semyonovskaya Shallow demonstrates that it currently represents an abrasion-accumulative form. Abrasion areas are mainly lower near-top parts of the shallow, while accumulative areas are the top surface of Vasil'evskaya Bank with Yaya Island, Semyonovskaya Bank and the underwater plain surrounding the shallow. Elevated parts of the shallow consist of fine- and, less commonly, medium-grained sands which formed as a result of the washing of IC sediments of the Late Neopleistocene. Currently they are reprocessed by the sea. Over the period of washing the particle-size composition of the IC, according to O.V. Dudarev's calculations [*Dudarev et al., 2015; Dudarev, 2016*], has been impoverished of its fraction of less than 0.01 mm by a factor of three, while there have become, on the contrary, approximately 70 times more particles of the sand fraction.

Despite the loss of fine-grained material as a result of washing, Semyonovskaya Shallow, according to O.V. Dudarev, still remains its source. The main ranges of suspended matter which are often recorded using SI are confined to this region. According to the data of marine monitoring expeditions its concentration reaches 26.3 mg/L during storms, while in the Vasil'evskaya Bank area it is 4–5 mg/L due to the increased content of the sand fraction in sediments (average content is 50.1 %) [*Dudarev et al., 2015*].

POI FEB RAS sea monitoring with sonar, bottom grab and CTD probe (which measures electrical conductivity, temperature and sea water density) application allowed us to obtain data on the spacial distribution of the particle-size composition of bottom sediments on the NE–SW profile, which is 140 km long (Table 2).

Drift current 35–50 cm/s was recorded during sea monitoring, which, according to V.V. Longinov [*1973*], is sufficient for detachment and transport of particles up to 0.5–1.0 mm in size. Thus, not only removal and transport into depressions of suspended particles are recorded, but also the possibility of sand particle transport. The latter demonstrates that even storms are not necessary for the accumulation of sands on Vasil'evskaya and Semyonovskaya Banks and the formation of Yaya Island.

Normal, as well as stronger, sea roughness forms poorly sorted sediments (for example, aleuritic mictite (Table 2)) by tranforming the lithodynamic regime. On the slope of Vasil'evskaya Bank with a sea depth of 7–9 m there are moderately sorted fine-grained sands with an average 69.1 % modal fraction group content (63.0 % median subfraction). The sediment belt of Semyonovskaya Bank with a 69 % sand fraction content does not descend lower than a 15-meter depth. Near the foot of the shallow at sea depths of 17 m the zone of pelitic aleurite accumulation begins (Table 2).

In summary, it should be noted that the particle-size distribution of bottom sediments corresponds to the contemporary hydrodynamic regime. The latter, in turn, is justified by the expansion of the sea ice-free water area, an extension by a factor of 1.5 of the dynamically active time and the existence of a large volume of thawed sediments which are available for transport and accumulation.

However, why is sediment accumulation is observed primarily on Semyonovskaya Shallow and Figurin Bank (Nanosnyy Island)? To answer this question we must look to data on the contemporary rise in the sea level and the vertical movement of Earth's crust.

Contemporary vertical movement of Earth's crust. The formation in the second half of the 20th and beginning of the 21st centuries of Nanosnyy and Yaya Islands and a rise in the surface of Semyonovskaya Bank occur despite a rise in the sea level. In the second half of the 20th century it was estimated to be 1.7 mm/year, in 1993–2010 it was estimated to be 3.2 mm/year [*IPCC, 2014*]. In relation to this the estimate of contemporary vertical tectonic movements is deemed absolutely essential. Among these are movements which currently take place or took place several hundred years ago, which are identified based on quantitative data [*Nikonov, 2006*], specifically geodesical, level measuring, historical, archaeological, geophysical, as well as data obtained with the help of measurements by multitemporal satellite images and maps using space geodesy methods. The rate of vertical movements within platform plains varies from 0.1 to 4 mm/year [*Nikonov, 2006; Zakharov, 2006*].

Table 2. **Particle-size composition of the deposits of the NE–SW profile through Semyonovskaya Shallow [*Dudarev et al., 2015*]**

Region	Depth, m	Fraction content, %			Lithological type of sediment
		1–0.1 mm	0.1–0.01 mm	<0.01 mm	
Vasil'evskaya Bank slope	7–9	69.1	27.5	3.4	Fine-grained sand
Middle part of the shallow	7	43.5	47.0	9.5	Aleuritic mictite
Semyonovskaya Bank slope	10	37.9	56.9	5.2	Sandy aleurite
Foot of the shallow	17	15.2	67.8	17.0	Pelitic aleurite
Accumulative plain north of the shallow	27	4.2	28.6	67.2	Aleuritic pelite
Accumulative plain south of the shallow	25	0.0	6.5	93.5	Pelite

The authors attempted to identify and estimate the rate of vertical movements in the region. For the Nanosnyy Island area, which is ascribed to the Eastern-Laptev uplift zone (regional morphostructure B), such an estimate was made based on an analysis of the results of observations of perennial sea level dynamics (Table 3). It was completed using data from the polar stations Kigilyakh and Sannikov Strait. The former is located on Cape Kigilyakh of Bolshoy Lyakhovsky Island; the latter is located in the southwestern end of Kotelny Island. Given the aforementioned trends of rise in the sea level (+1.7 mm/year during 1950s–1980s and +3.2 mm/year during 1993–2010) the change in level in the Dmitry Laptev Strait based on average readings from Kigilyakh Station was characterized by the following values for the same periods: –0.85 mm/year during the first of the indicated periods and –1.38 mm/year during the second (Table 3). Negative values of the readings indicate that not only does the sea level rise, but also the coast where the station is located, and the rise of the coast precedes the rise of the sea level. Data on Sannikov Strait Station demonstrate that during 1950s–1980s the rate of the rise of the southwestern coast of Kotelny Island exceeded the rate of the rise of the level of the ocean by 0.33 mm/year and was 0.20 mm/year behind it during 1993–2010.

Contemporary uplift is established for Semyonovskaya Shallow and Yaya Island based on the results of juxtaposition of seismological data and data on contemporary movements of Earth's crust [*Avetisov, 2004*]. The shallow is located within the submeridianal zone of earthquakes, which stretches through the entire shelf (Fig. 3). The rate of vertical movements as compared to other Arctic seismically active sites can be estimated to be no less than 2–3 mm/year.

The obtained data allow us to conclude that both positive structures of the Eastern-Laptev zone and the earthquake epicenter zone stand out in the similarity or slight exceeding of their rate of vertical movements as compared to that of the sea level rise. Data on the formation of Yaya and Nanosnyy Islands and measurements from SI allow us to quantitatively characterize the sedimentation (Table 1). Nanosnyy Island, which is composed of contemporary sediments, is already marked on the topographic map of 1986, which records the condition of the region in 1973. Yaya Island was first recorded only in 2013. The sedimentation rates of Nanosnyy and Yaya Islands can be characterized as rather fast, considering that it occurs upward on the underwater slope, against the pull of gravity. Such transport of sediments occurs as a result of the transformation of the thermal abrasion profile of the underwater slope into an accumulative one. The transformation is justified by increased power of hydrodynamic processes which, in turn, is provided by an early cleansing of the water area of ice and an increase in the length of the dynamically active period.

Other islands (Leykina, Zatoplyaemyy, Aerosyomki, Samoleta) and banks are characterized using SI only by changes in their shapes. Their surface areas remain almost unchanged. Sedimentation on elevated areas of the sea bottom are a very rare occurrence. In East Siberian seas, like in all seas, it is mainly related to negative structures, the bulk of sediments is directed specifically there. This is pelite-sized material (Fig. 11). However, the presence of palimpsest sands on the indicated islands and banks [*State... Map..., 2014, 2016*] indicates their replacement of sandy sediments, which had formed as a result of IC thermal abrasion in these areas: i.e., sedimentation. Here, however, as in Semyonovskaya Shallow and the vicinity of Nanosnyy Island, sand fraction particles accumulate in elevated areas of the shallows, while finer particles are carried to negative bottom landforms. We will note again that this is indicative of an accumulative profile of equilibrium on the underwater slope of shallows. The rate of sedimentation under conditions of sea level rise is apparently insufficient for its identification using SI.

The question about Peschany Island stands on its own. It is marked on the geological map [*State... Map..., 2017*] as consisting of Late Holocene sea wave sediments. The pedestal of the island in the diameter exceeds its size by a factor of 2–2.5. The top of the pedestal with the island, the height of which constitutes 1 m, rises more than 10–15 m above the surrounding underwater plain [*State... Map..., 2017*]. This height can apparently be attributed to the existence of its significantly more ancient formation. Ring-shaped bars, which are the location of stamukha concentration, deciphered by the ice remains on SI,

Table 3. **The magnitude of the linear trend of sea level change based on observation data at Kigilyakh and Sannikov Strait stations for the periods 1950–1980 and 1980–2016 [*Merkulov et al., 2017*] and its correlation with the rate of contemporary coast rise in the region of observation stations**

Stations	Observation period	Trend magnitude (mm/year)		Coast rise rate in relation to the sea level trend
		Before 1980s	After 1980s	
Kigilyakh	1951–2016	–0.85	–1.38	Over the trend
Sannikov Strait	1950–2016	–0.33	+0.20	Almost identical

Note. A minus signifies a lowering of the sea level in relation to the coast, a plus signifies its rise.

Fig. 12. Gravel-pebble material and drift-wood, pushed by drifting ice onto the coast of Kotelny Island [*Are, 2012*].

reliably protect it from erosion and determine the long existence of the island in a little-changing form.

Ice processes. Even if litho- and morphogenetic sea ice activity changed in shallows in the contemporary warming, it changed quite insignificantly. The role of ice in sedimentation occurs in several ways. This is accumulation as a result of transport activity of frazil and cloudy ice, i.e. containing a large amount of mineral and organic inclusions. Bulldozing of bottom sediments up the underwater slope by drifting ice under pressure from onsetting wind plays a rather significant morphogenetic role [*Barnes et al., 1988; Kempema et al., 1989*]. It is thought that bulldozing is one of the main processes which contributed to the formation of barrier islands near Alaska's coasts. During warming it occurs closer to the coast [*Ogorodov, 2011*] and continues to be an efficient geomorphological factor in the water area of the Laptev and East Siberian Seas (Fig. 12). In many cases sedimentation can occur in the wave or wind shadow of stamukhas, as well as around the latter during storms, which, according to A.Yu. Gukov [*2014*], happened during the formation of Yaya Island.

In cold periods or years burial of surface ice (remains of fast ice, stamukhas, icebergs) by marine sediments also apparently takes place. Their subsequent thawing may be the cause of the formation of arc-like spits and bars which form lagoons adjoined to pre-existing islands. There are particularly many of them in the northern part of the Kara Sea, where the connection between lagoons with icebergs buried earlier is especially likely.

Shallows are the location of concentration of stamukhas which freeze to the bottom. As mentioned above, they protect newly formed landforms, assuming storm-caused unrest and ice loads from the sea. The formation of thick grounded hummocked many-rowed barriers at sea depths of 4–5 m along the fast ice border takes place each year in the autumn and spring during its formation and destruction [*Ogorodov, 2011*].

On hummocked areas, after thawing of stamukhas, sediments can be desalinized, which eases their freezing, if they were not frozen. Within areas of their regular yearly formation this circumstance contributes to the stabilization of the frozen condition of the ground, which, inarguably, facilitates sedimentation.

CONCLUSIONS

1. Within the Laptev and East Siberian Seas, during the course of the 17th–20th centuries, island-remnants of the Late Neopleistocene Ice Complex were washed, as later were the shallows and banks which had formed in their place. At the turn of the 20th and 21st centuries sedimentation with island formation begins in these shallows.

2. Shallows are attributed to positive morphostructures which correspond to raised tectonic blocks in the rift system of the Laptev Sea. Sedimentation in shallows occurs together with sedimentation in negative morphostructures and river paleovalleys.

3. The main reason for contemporary sedimentation in shallows is a decrease in the surface area of sea ice in East Siberian seas and an increase by a factor of 1.5–2 (compared to the 1970s) of the length of the ice-free season in relation to climate warming.

The priority role of sedimentation in shallows currently belongs to hydrodynamic processes, while earlier it occurred mainly by way of sea ice.

4. A deficit of sedimentary material in the 17th–20th centuries is replaced by its excess at the turn of the 20th and 21st centuries in relation to the activation of cryogenic processes – thermal abrasion and thermal denudation of coasts, thermal subsidence and bottom thermal abrasion, degradation of permafrost from the top. As a result, the thermal abrasion profile of the underwater coastal slope in shallows transforms into an accumulative one. Coarser material (sandy) is given the opportunity to move upward, forming and growing banks and islands, finer material is carried into the deep into paleovalleys and negative morphostructures.

5. Sedimentation in shallows occurs under conditions of a rising sea level, which takes place at a rate of 3 mm/year. Because of this it becomes noticeable and is seen in satellite images for morphostructures subjected to tectonic uplift, the rate of which is commensurable with or beyond the rate of the rising sea level. This is the Nanosnyy Island region in the East Siberian uplift zone and Semyonovskaya Shallow, which is ascribed to the seismically active zone of the Laptev Sea.

6. Ice processes also play an important role. They stimulate sedimentation owing to transport of bottom sediments by drifting ice, contribute to freezing

by desalinating sediments in locations of stamukha formation and provide protection from storms for newly formed islands and banks.

7. Archives of satellite images and modern technologies for their processing play a significant role in the study of morphogenesis on the shallows of Arctic Seas.

Acknowledgements. *The authors express their gratitude to A.A. Kucheiko for useful information obtained from Sentinel and Terra/MODIS satellite images, for the suggestions and advice, to V.E. Tumskoy for the remarks that made it possible to substantially improve the original version of the article.*

References

Are, F.E., 1998. The thermoabrasion of Laptev Sea shores and its input into sediment balance of the sea. Kriosfera Zemli [Earth's Cryosphere], II (1), 55–61 (in Russian).

Are, F.E., 2012. Coastal Erosion of the Arctic Lowlands. Academic Publishing House "Geo", Novosibirsk, 291 pp. (in Russian).

Avetisov, G.P., 2004. Seismicity of the Russian Arctic continental margin. Geology and mineral resources of Russia. Six volumes. Volume 5. Arctic and Far East Seas. Book 1. Arctic seas. VSEGEI, St. Petersburg, pp. 31–43 (in Russian).

Barnes, P.W., Rawlinson, S.E., Reimnitz, E., 1988. Coastal geomorphology of Arctic Alaska. In: Arctic Coastal Processes and Slope Protection Design. A.T. Chen, C.B. Leidersdorf (Eds.). American Society of Civil Engineers, New York, pp. 3–30.

Burguto, A.G., Dorofeev, V.K., Rekant, P.V., et al., 2016. State Geological Map of the Russian Federation. Scale of 1:1 000 000 (third generation). Laptev-Siberian Sea series. Sheet S-53. Stolbovoy Island; S-54 Lyakhovsky Islands. Explanatory letter. Cartographic factory VSEGEI, St. Petersburg, 300 pp. + 9 tabs. (in Russian).

Charkin, A.N., Dudarev, O.V., Semiletov, I.P., Shilo, I.N., 2007. The Current State of Relict Banks on the shelf of the East Siberian Seas. In: Cryogenic Resources of Polar Regions. Materials of the International Conf. (Salekhard, June 2007). ONTI of the Pushchino Scientific Center of the Russian Academy of Sciences, Pushchino, vol. 1, pp. 184–186 (in Russian).

Dmitrenko, I.A., Kirillov, S.A., Tremblay, B., et al., 2011. Recent changes in shelf hydrography in the Siberian Arctic: potential for subsea permafrost instability. J. Geophysical Research, vol. 116, C10027, DOI: 10.1029/2011JC007218.

Dudarev, O.V., 2016. Recent lithomorphogenesis on the East Arctic shelf of Russia. Abstract... doc. g-m. n., Vladivostok, 49 pp. (in Russian).

Dudarev, O.V., Charkin, A.N., Semiletov, I.P., et al., 2015. Peculiarities of the present-day morpholithogenesis on the Laptev Sea Shelf: Semenovskaya Shoal (Vasema Land). In: Proceedings of the Academy of Sciences, 462 (1), 510–516 (in Russian).

Fartyshev, A.I., 1993. Features of the Coastal Shelf Cryolithozone of the Laptev Sea. Nauka, Novosibirsk, 136 pp. (in Russian).

Gakkel, Ya.Ya., 1957. Science and development of the Arctic. Morskoy transport, Leningrad, 132 pp. (in Russian).

Gavrilov, A.V., Romanovskii, N.N., Hubberten, H.-W., Romanovsky, V.E., 2013. Distribution of islands – ice complex remnants on the East Siberian arctic shelf. Kriosfera Zemli [Earth's Cryosphere], VII (1), 18–32 (in Russian).

Geography of the Soviet Arctic Seas, 1949. Proceedings of the AARI, vol. 8. No. 2. The Laptev Sea. Glavsevmorput, Moscow; Leningrad, 484 pp. (in Russian).

Geological Dictionary, 2011. In three volumes. Third edition, revised and additional. O.V. Petrov (Ed.). Vol. 2, VSEGEI, St. Petersburg, 446 pp. (in Russian).

Grigoriev, M.N., 2017. Study of permafrost formations degradation in East Siberia coastal zone (subsequent to the results of expeditions of 2014–2016). Arctic and Antarctic Research, issue 1, 89–96 (in Russian).

Gukov, A.Yu., 2014. Revival of Vasilievsky Island. Priroda [Nature], No. 5, 70–73 (in Russian).

IPCC, 2014: Climate Change, 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [main group of authors, R.K. Pachauri and L.A. Meyer (Eds.)]. Geneva, Switzerland, IPCC, 163 pp.

Ivanov, V.L., Kim, B.I., Kos'ko, M.K., Ivanova, N.M., 2004. Geological structure and development history of the basin. Laptev sedimentary basin. In: Geology and mineral resources of Russia. Six volumes. Vol. 5. Arctic and Far East Seas. Book 1. Arctic seas. VSEGEI, St. Petersburg, pp. 274–310 (in Russian).

Jones, G., 1964. The Norse Atlantic Saga. Being the Norse Voyages of Discovery and Seetlement to Iceland, Greenland, America. Oxford University Press, London, 246 pp.

Kaplin, P.A., Leontiev, O.K., Lukyanova, S.A., Nikiforov, L.G., 1991. Shores (Nature of the World). Mysl, Moscow, 479 pp. (in Russian).

Katasonov, E.M., Pudov, G.G., 1972. Cryolithological studies in the area of Vankina Bay of the Laptev Sea. In: Permafrost research, vol. XII. Moscow State University Publishing House, Moscow, pp. 130–136 (in Russian).

Kempema, E.W., Reimnitz, E., Barnes, P.W., 1989. Sea ice sediment entrainment and rafting in the Arctic. J. Sediment. Petrol. 59 (2), 308–317.

Klimenko, V.V., Matskovsky, V.V., Dalmann, D., 2013. Comprehesive reconstruction of the temperature of the Russian Arctic over the past two millennia. Arktika: ekologiya i ekonomika [Arctic: Ecology and Economy], No. 4 (12), 84–95 (in Russian).

Klyuev, E.V., 1965. The role of permafrost factors in the dynamics of the bottom topography of the polar seas. Okeanologiya [Oceanology], 5 (5), 863–869 (in Russian).

Klyuev, E.V., 1970. Thermal abrasion of the polar seas coastal strip. Izvestiya VGO, 102 (2), 129–135 (in Russian).

Klyuev, E.V., Kotyukh, A.A., Olenina, N.V., 1981. Cartographic and hydrographic interpretation of the disappearance of Semyonovsky and Vasilievsky Islands in the Laptev Sea. Izvestiya VGO, 113 (6), pp. 485–492 (in Russian).

Koch, L., 1945. The East Greenland Ice. Meddelelser om Grőnland, Copenhagen, Bd. 130, No. 3, 373 pp.

Kucheiko, A.A., Ivanov, A.Yu., Ainov, K.V., Lisachenko, E.S., 2020. Detection of shallows and small islands in the southern part of the Laptev Sea using satellite data. Earth from Space, issue 27, 50–60 (in Russian).

Longinov, V.V., 1973. Sketches of Oceanic Lithodynamics. Nauka, Moscow, 244 pp. (in Russian).

Lukina, N.V., Patyk-Kara, N.G., Sokolov, S.Yu., 2003. Russian Arctic Seas. Neotectonic structures and active faults. In: Atlas: Geology and mineral resources of the Russian shelf areas. M.N. Alekseev (Ed.). Scientific World, Moscow, sheet 3–4 (in Russian).

Matul, A.G., Khusid, T.A., Mukhina, V.V., et al., 2007. Recent and Late Holocene environments on the southeastern shelf of the Laptev Sea as inferred from microfossil data. Oceanology 47 (1), 90–101 (in Russian).

Merkulov, V.A., Ashik, I.M., Timokhov, L.A., 2017. Tendencies of multi-year variability of the sea level at the coastal stations of the Arctic Ocean. Arctic and Antarctic Research, No. 3 (113), 51–65 (in Russian).

Molochushkin, E.N., 1969. On the nature of heat transfer between water and bottom sediments in the coastal zone of the Laptev Sea. In: Questions of the geography of Yakutia. Yakut book Publishing House, Yakutsk, issue 5, pp. 121–126 (in Russian).

Mustafin, N.F., 1961. On catastrophic surges in the southeastern part of the Laptev Sea. Arctic and Antarctic Research, No. 7, 59–65 (in Russian).

Nicolsky, D.J., Romanovsky, V.E., Romanovskii, N.N., et al., 2012. Modeling sub-sea permafrost in the East Siberian Arctic Shelf: The Laptev Sea region. J. Geophysical Research, vol. 117, F03028.

Nikonov, A.A., 2006. Modern movements of the Earth's crust. Ed. 2nd, sup., Editorial URSS, Moscow, 192 pp. (in Russian).

Ogorodov, S.A., 2011. The Role of Sea Ice in Coastal Dynamics. Publishing House MSU, Moscow, 173 pp. (in Russian).

Patyk-Kara, N.G., Arkhangelov, A.A., Plakht, I.R., 1989. Regional geomorphological benchmarks in the Cenozoic history of the Eastern Arctic. Geomorphology, No. 4, 96–104 (in Russian).

Pizhankova, E.I., 2016. Modern climate change at high latitudes and its influence on the coastal dynamics of the Dmitriy Laptev Strait area. Earth's Cryosphere XX (1), 46–59.

Pizhankova, E.I., Dobrynina, M.S., 2010. The dynamics of the Lyakhovsky Islands coastline (results of aerospace image interpretation). Kriosfera Zemli [Earth's Cryosphere], XVI (4), 66–79 (in Russian).

Popov, S.V., 1987. Marine names of Yakutia. Essays on the toponymy of the Laptev and East Siberian Seas. Book Publishing House, Yakutsk, 163 pp. (in Russian).

Rekant, P.V., Tumskoy, V.E., Gusev, E.A., et al., 2009. Distribution and peculiarity of bedding of the sub-sea permafrost near Semenovskoe and Vasilievskoe Shallows (Laptev Sea) revealed by high-resolution seismic profiling. In: System of the Laptev Sea and the Adjacent Arctic Seas: Modern and Past Environments. Moscow University Press, Moscow, pp. 332–348 (in Russian).

Report on the peculiarities of the climate in the territory of the Russian Federation for 2019, 2020. Roshydromet, Moscow, 97 pp. – http://www.meteorf.ru/press/news/20626/

Romanovskii, N.N., Gavrilov, A.V., Tumskoy, V.E., et al., 1999. Thermokarst and its role in the formation of the near shore zone of the Laptev Sea shelf. Kriosfera Zemli [Earth's Cryosphere], III (3), 79–91 (in Russian)

Romanovskii, N.N., Hubberten, H.-W., Gavrilov, A.V., et al., 2003. Permafrost and gas hydrate stability zone evolution on the eastern part of the Eurasia Arctic Sea shelf in the Middle Pleistocene–Holocene. Kriosfera Zemli [Earth's Cryosphere], VII (4), 51–64 (in Russian)

Safyanov, G.A., 1996. Coastal Geomorphology. Moscow University Press, Moscow, 400 pp. (in Russian).

Semenov, Yu.P., 1971. Conditions for the formation of bottom sediments in the Laptev Sea. In: Sea Geology. Publishing house of Research Institute of Arctic Geology, Leningrad, vol. 1, p. 47–53 (in Russian).

Sovershaev, V.A., 1981. Influence of Sea Ice on the Development of the Arctic Shelf Permafrost Zone (on the example of the Eastern Arctic Seas). In: Permafrost zone of the Arctic Shelf. Publishing House of the Institute of Permafrost Science of the Siberian Branch of the USSR Academy of Sciences, Yakutsk, pp. 70–83 (in Russian).

State Geological Map of the Russian Federation, 2014. Scale of 1:1 000 000 (third generation). Sheet S-51. Olenek Bay. S-52 Lena River Delta. Lithological map of the water area bottom surface. Cartographic factory VSEGEI, St. Petersburg (in Russian).

State Geological Map of the Russian Federation, 2016. Scale of 1:1 000 000 (third generation). Sheet S-53, 54 – Stolbovoy Island – Lyakhovsky Islands. Lithological map of the water area bottom surface. Cartographic factory VSEGEI, St. Petersburg (in Russian).

State Geological Map of the Russian Federation, 2017. Scale of 1:1 000 000 (third generation). Sheet S-50 – Ust-Olenek. Lithological map of the water area bottom surface. Cartographic factory VSEGEI, St. Petersburg (in Russian).

The history of the discovery and development of the northern sea route, 1954. Vol. 1. Morskoy transport, Moscow, 475 pp. (in Russian).

The second assessment report of Roshydromet on climate changes and their consequences on the Russian Federation territory. General summary, 2014. Roshydromet, Moscow. – URL: https://cc.voeikovmgo.ru/images/dokumenty/2016/od2/od2.pdf

Thomson, J., Rogers, W.E., 2014. Swell and sea in the emerging Arctic Ocean. Geophysical Research Letters, No. 41, 3136–3140.

Zakharov, V.S., 2006. Modern vertical movements of the Earth's crust. In: Modern global changes in the natural environment. In 2 volumes. Vol. 1. Scientific World, Moscow, pp. 626–643 (in Russian).

Zhigarev, L.A., Plakht, I.R., 1974. Features of the structure, distribution and formation of subaqueous cryogenic strata. In: Problems of Cryolithology. Moscow State University, Moscow, vol. IV, pp. 115–124 (in Russian).

Zhigarev, L.A., Sovershaev, V.A., 1984. Thermoabrasive destruction of the Arctic islands. In: Coastal Processes in Cryolithozone. Nauka, Novosibirsk, pp. 31–38 (in Russian).

URL: https://ru.wikipedia.org/wiki/Яя_(остров) (last visited: 12.11.2019).

URL: https://ru.wikipedia.org/wiki/Коч (last visited: 05.02.2020).

URL: http://www.aari.ru/projects/ECIMO/?im=100 (last visited: 23.12.2020).

Received March 27, 2021
Revised version received January 17, 2021
Accepted February 3, 2021