

CRYOLITHOGENESIS

ICE COVER IN SHARAPOV SHAR LAGOON (THE KARA SEA) AND ITS IMPACT ON FREEZING OF BOTTOM SEDIMENTS

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The conditions of ice cover formation in the Sharapov Shar Lagoon (Bay) of the Kara Sea and its role in sediment freezing at the fast ice/bottom contact zone are considered. Based on field measurements, remote sensing data, and calculations, characteristic periods of the formation and destruction of the ice cover and its thickness over the past 46 years have been analyzed. It is shown that fast ice in the lagoon is observed for an average of 252 days a year; the ice thickness by the end of winter averages 139 cm and can exceed 160 cm in some winters. The base of sea ice is in contact with the bottom within a significant part of the lagoon: 49% of the area in mild winters and 60% of the area in severe winters. Numerical simulation indicates that at sea depths of more than 0.9 m, a seasonally frozen layer with a thickness of up to 0.8 m for loamy soils and 1.2 m for sandy soils is formed under the fast ice in winter and completely thaws in summer. Calculations have also shown that in the 20th century, there were conditions favorable for the formation of permafrost in the zone where sea ice is frozen to the bottom. The formation of permafrost was possible at depths of up to 90 cm. In the 21st century, rising air temperatures and increasing ice-free periods lead to permafrost degradation. Under modern conditions of global warming, sandy sediments can remain in the frozen state at sea depths of up to 0.7 m; clayey sediments – up to 0.3 m.

Keywords: frozen ground, permafrost zone, sea ice, fast ice, simulation of ground freezing.

Recommended citation: Godetskiy S.V., Bogatova D.M., Likutova O.A., Vergun A.P., Ogorodov S.A., Belova N.G., 2025. Ice cover in Sharapov Shar Lagoon (the Kara Sea) and its impact on freezing of bottom sediments. *Earth's Cryosphere* XXIX (1), 12–21.

INTRODUCTION

Significant areas of the coasts and shelves of Russia's Arctic seas are occupied by permafrost (including subsea permafrost) which is sensitive to climate changes. The shortening of the ice season and rising air and water temperatures affect the formation and preservation of permafrost and seasonally frozen sediments. Industrial development of the northern territories is impossible without knowledge of the characteristics of the soils composing the bottom and shores of the Arctic seas. Therefore, studies of the relationship between changes in the ice regime of the sea and the formation of permafrost are highly relevant. This issue is addressed in this paper.

The final stage of shelf permafrost degradation began 7–8 kyr ago and continues to this day [Romanovsky *et al.*, 1999]. Over the past 30 years, the subsea permafrost degradation in the Russian Arctic seas has accelerated significantly, reaching 18 cm/yr [Sergienko *et al.*, 2012; Semiletov *et al.*, 2020].

One of the factors of the formation of subsea seasonally frozen ground and permafrost is the ice cover. The presence of permafrost under beaches, coastal marshes, and areas, where sea ice freezes with bottom sediments, has been noted by many researchers [Gri-

goriev, 1987; Zhigarev, 1997], including observations in the area of Cape Kharasavei [Vasiliev *et al.*, 2011, 2017]. In addition, in the area of Cape Burunny (Baidaratskaya Bay of the Kara Sea), frozen sediments with a temperature of –9.9°C were found on an underwater spit (shoal) at the sea depth of 2–3 m; these sediments pinch out at a distance of 2.3 km from the shore [Buldovich, Danilov, 1998]. New formation of permafrost in some shallows of Cape Halkett (Alaska, Beaufort Sea) associated with the development of spit, is also mentioned in [Jones *et al.*, 2009].

According to simulation [Buldovich, Danilov, 1998], in the shallow waters of Baidaratskaya Bay, subsea permafrost with temperatures of –8 to –10°C is formed down to sea depths of 2–3 m, while at depths from 2–3 to 6–8 m, thawed or seasonally frozen sediments are common. Climate warming observed since the end of the 20th century and particularly pronounced in the Arctic [Ogorodov *et al.*, 2022] will obviously exert a negative impact on subsea permafrost, including its complete thawing.

Sharapov Shar Bay is located in the western part of the Kara Sea (Fig. 1). The predominant depth of the water area is 2–3 m. From the west, the bay is

protected from the direct impact of waves and ice by the aggradational Sharapovy Koshki Islands forming lagoon shoals. The eastern shore of the bay is characterized by thermoabrasion and abrasion-thermodenu-dation scarps in frozen sediments and a predominantly sandy beach. The bottom and shores of the bay are composed of fine-grained sands, silts, and clays [Motychko *et al.*, 2013].

The height of large waves in the bay does not exceed 110 cm for storms recurring once in 50 years. Tidal fluctuations are weak: the spring tide height is 23 cm, and tidal current velocities are about 5 cm/s. Total currents during storms do not exceed 50 cm/s [Makarov, Vyaly, 2020]. The ice cover is formed under calm conditions, when movement of young ice forms is insignificant, and the processes of ice hummocking and grounded hummock formation have a local character. As a consequence, the bay is almost completely covered with smooth first-year ice [Dumanskaya, 2014].

Most of the bay is located within the Kruzenshtern field, one of the key oil and gas development sites in the Arctic. The arrangement of wells on artificial islands is being discussed within the framework of development projects [Makarov, Vyaly, 2020; Solomatin, Kozlov, 2021]. To assess the stability of hydraulic structures, it is important to know the characteristics of bottom sediments and their state (frozen, unfrozen cryotic, thawed).

The purpose of this work is to evaluate the role of fast ice in the formation of frozen ground in the shelf zone using Sharapov Shar Bay as an example. No studies focused on the relationship between climate change, the timing and thickness of sea ice, and the formation of seasonally frozen sediments and permafrost have been conducted until now.

MATERIALS AND METHODS FOR MODELING ICE COVER AND FREEZING OF BOTTOM SEDIMENTS

The timing of *the ice regime phases* (stable ice formation, fast ice formation, breakup of fast ice, complete clearing of the water area from ice) in Sharapov Shar Bay was determined for the period of 2000–2023 based on the analysis of satellite images [https://worldview.earthdata.nasa.gov]:

Terra (MODIS) (October–November and May–July 2000–2023);

Sentinel-1a (October–November, April, June 2014–2023).

The thickness of sea ice in the bay was calculated on the basis of sums of frost degree days (SFDDs) according to data from the Marre-Sale weather station (Roshydromet network) for the period from 1977 to 2023, excluding the 1978/79, 1979/80, 1980/81 and 2001/02 winter seasons [https://rp5.ru, http://aisori-m.meteo.ru].

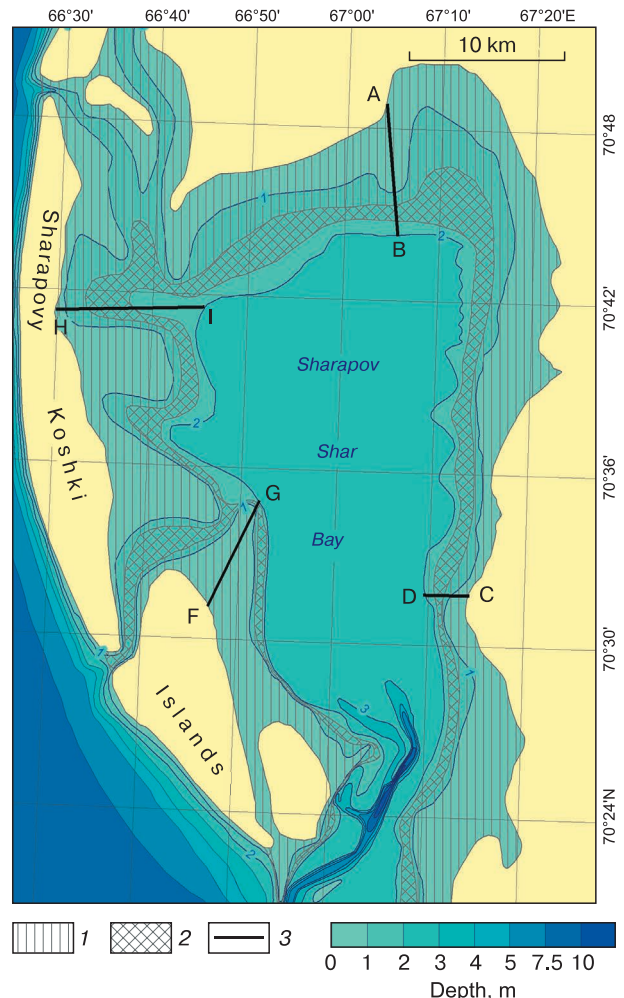


Fig. 1. Bathymetric map of Sharapov Shar Bay.

Hatching shows the boundaries of the maximum contact area of sea ice and seabed established on the basis of the calculated sea ice thickness for the conditions of (1) mild and (2) severe winter; lines (3) indicate the location of modeling profiles.

The SFDD was converted to ice thickness using the formula of N.N. Zubov [1956], which showed an adequate correlation with the in-situ data obtained during drilling in the period of the maximum ice cover development (March–April) in 2011–2023 (Fig. 2).

A bathymetric map of Sharapov Shar Bay was constructed to estimate the *position of the boundary of the fast ice–sea bottom contact area* (Fig. 1). The digital model of the seabed relief was obtained from the General Bathymetric Chart of the Oceans (GEBCO) data [https://www.gebco.net], marine navigation maps, and local surveys. All depths were converted to the 1977 Baltic Height System (BS-77) and then referenced to the mean annual sea level (MASL). According to the Kharasavei weather station (1977–1987; after 1987, this station was abolished), the MASL in the bay is 63 cm (BS-77).

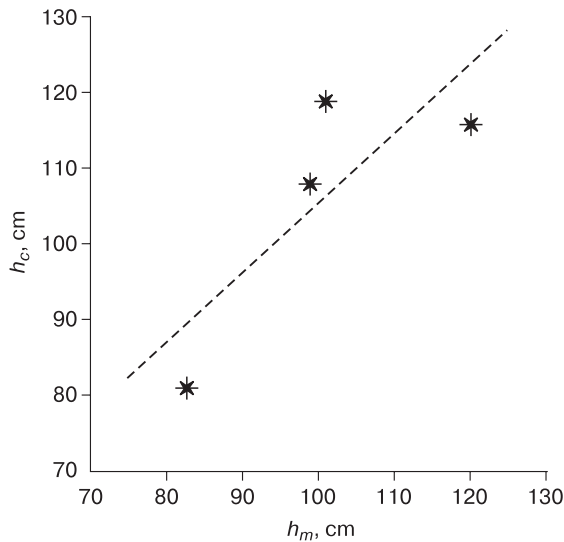


Fig. 2. Measured (h_m) versus calculated (h_c) ice thickness.

Numerical simulation of bottom sediments freezing under sea ice was carried out in the QFrost program [Ershov, 1999]. This work does not consider the history of the formation of the Sharapov Shar Bay sediments, their cryogenic structure, and the development of permafrost in the Late Pleistocene and Holocene, unlike other studies [Romanovsky, Tumskoy, 2011; Kotlyakov et al., 2015; Tumskoy, Kuznetsova, 2022]. Heat fluxes from the Earth's interior that are usually used in modeling shelf permafrost over long periods [Romanovsky et al., 1999, 2003] were not taken into account because of the much smaller modeled depths.

The thermal properties of the modeled sediments given in Table 1 [Aleksyutina, Motenko, 2017] are typical of the bottom sediments with the high water content (30–50%) and skeletal density (1.3–1.6 g/cm³). Because of the lack of actual data, a single-layer sediment section was considered. Bottom sediments of the Kara Sea shelf are saline, and their freezing temperature was taken equal to -1.5°C [Vasiliev et al., 2016]. The initial temperature distribution was derived from observation data at the Marre-Sale station [Dubrovin et al., 2015]. The temperature at the depth of zero annual amplitudes was -1.4°C . The calculations were carried out in two stages: first, the modeling was carried out for the last 30 years of the 20th

Table 1. Thermal properties of sediments used in modeling

Sedi- ment	λ_t	λ_f	C_t	C_f	Q_{phase} , MJ/m ³
	W/(m·K)		J/(m ³ ·K)		
Sandy	1.8	2.0	2800	2000	152.4
Loamy	1.45	1.55	2865	2250	289.3

Note: λ_t , λ_f – coefficients of thermal conductivity of sediment in the thawed and frozen states, respectively; C_t , C_f – volumetric heat capacity of sediment in the thawed and frozen states, respectively; Q_{phase} – heat of phase transition.

century, assuming that the sediments were in the unfrozen cryotic state at the time of the beginning of the calculations; the obtained results were then used as the initial conditions for modeling the state of the sediments in the 21st century. Due to the shallowness of the bay and the fact that the ice cover settles on the bottom, it was decided to calculate one-dimensional problems with varying boundary conditions at the surface.

To model the temperature regime of bottom sediments in the 20th century, mean monthly data on air temperature, snow cover depth, and sea ice thickness for the period of 1970–1999 were used (Table 2). Proskuryakov's formula [Osokin et al., 2017] was used to calculate the thermal conductivity of the snow; for simplification, a fixed value of snow density (250 kg/m³) was used. The coefficient of thermal conductivity of sea ice used in the calculations was constant and equal to 2.1 W/(m·K).

Ice cover in Sharapov Shar Bay develops gradually; fast ice is formed near the shore and grows during the entire cold season. Thus, in the winter season, there are some areas in the bay, where the ice lies on the bottom. Further from the shore, at greater depths, there is a layer of water between the ice and the bottom. While modeling, we took into account the presence of water and ice by setting different boundary conditions at the sediment surface. In the calculations, we assumed that fast ice formation starts from the shore. With increasing sea depth, the thickness of the fast ice increases; however, the time of contact with the bottom decreases. Boundary conditions of the third kind, which include temperature and the heat transfer coefficient, were assumed. Air temperature and the heat transfer coefficient were used for each month of each year. The heat transfer coefficient (α , W/(m²·K)) was calculated taking into account

Table 2. Sea ice and snow characteristics in Sharapov Shar Bay in 1970–1999

Characteristic	Month							
	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
Sea ice thickness, cm	30	60	87	106	114	124	132	122
Snow depth, cm	4.6	8.9	12.9	21.0	23.0	26.7	22.8	6.5
Snow thermal resistance, (m ² ·K)/W	0.17	0.32	0.47	0.77	0.84	0.98	0.84	0.24

Table 3. Boundary conditions for different sea depths at the initial modeling stage

h	Parameter	Month											
		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
30–135	T_{air}	–21.5	–22.4	–17.0	–13.6	–5.3	2.1	7.7	6.8	3.3	0	–13.0	–18.1
30	α	1.624	1.100	1.018	0.894	1.022	2.616	∞	∞	∞	∞	3.225	2.139
60	α	1.318	0.951	0.889	0.793	0.892	1.904	∞	∞	∞	∞	∞	1.638
90	α	1.109	0.837	0.789	0.712	0.791	1.497	∞	∞	∞	∞	∞	∞
105	α	∞	0.790	0.747	0.678	0.749	1.352	∞	∞	∞	∞	∞	∞
115	α	∞	∞	0.721	0.657	0.723	1.271	∞	∞	∞	∞	∞	∞
125	α	∞	∞	∞	0.637	0.699	1.198	∞	∞	∞	∞	∞	∞
135	α	∞	∞	∞	∞	0.676	1.133	∞	∞	∞	∞	∞	∞

Note: T_{air} – air temperature, °C; α – heat transfer coefficient, $\text{W}/(\text{m}^2 \cdot \text{K})$; h – sea depth, cm.

the ice thickness (assuming that it is equal to the depth of the bay). The heat transfer coefficient is inversely proportional to the thermal resistance ($\alpha = 1/\Sigma R$, where R is the thermal resistance), which is calculated as the ratio of the layer thickness to its thermal conductivity coefficient ($R = h_{\text{layer}}/\lambda_{\text{layer}}$).

In winter, there is no stratification of water under the ice, and the water temperature is close to the freezing point of -1.8°C . Mean monthly air temperatures (T_{air} , °C) from 1977 to 1999 according to data from the Marre-Sale weather station and heat transfer coefficients (α , $\text{W}/(\text{m}^2 \cdot \text{K})$) for different sea depths used as upper boundary conditions at the initial stage of modeling are given in Table 3. As the modeling was carried out for the first tens of meters of the section, the heat flux from the subsurface, as the lower boundary condition, was equated to $0 \text{ W}/\text{m}^2$.

For the period from 2001 to 2022, mean air temperatures and heat transfer coefficients for each month of each year were used as upper boundary conditions.

MODELING RESULTS AND DISCUSSION

Ice regime. An analysis of remote sensing data for 22 ice seasons in the 21st century demonstrated that, on average, stable ice formation in the bay begins in the second ten-day period of October. Fast ice in Sharapov Shar Bay usually begins to form one or two weeks after the onset of ice formation. Initially, a

200-m-wide stretch of fast ice is formed near the shore. The minimum number of days for the fast ice to form was observed in 2016 – three days; the maximum was 13 days in 2017 and 2021. On average, fast ice with the ice thickness of 10–15 cm is formed in the third ten-day period of October.

By the beginning of May, the ice cover reaches its maximum development. Melting and disintegration of the ice cover occurs under the influence of solar radiation and heat brought by currents and air masses. In early May, air temperature becomes positive and the formation of ice stops. The first signs of ice melting are the appearance of puddles on the ice surface, which gradually expand. Intensive ice melting occurs in June. Breakup of fast ice typically takes place in the third ten-day period of June.

Clearing of the Sharapov Shar Bay water area from ice begins in late June – early July and proceeds rather quickly, in a few days. Local ice hummocks and grounded ice hummocks are destroyed within one or two weeks after the fast ice breaks up. Full clearance of the water area from ice occurs in the first ten-day period of July.

Summary data on the timing of major ice phases in Sharapov Shar Bay are given in Table 4.

Sharapov Shar Bay is characterized by stable fast ice throughout the entire winter, from 217 to 271 days; on average, 252 days per year. Thus, the stationary ice cover is observed for 7.5–9 months per year. Taking into consideration drift ice, the ice sea-

Table 4. Dates of ice phases in Sharapov Shar Bay

Ice phase	Date		
	early	middle	late
Stable ice formation	1 st ten-day period of October (2013, 2014, 2015)	2 nd ten-day period of October	1 st ten-day period of November (2016, 2022)
Fast ice formation	2 nd ten-day period of October (2014, 2015)	3 rd ten-day period of October	1 st ten-day period of November (2016, 2022)
Fast ice breaking in	1 st ten-day period of June (2020)	3 rd ten-day period of June	1 st ten-day period of July (2019)
Complete sea ice clearance	3 rd ten-day period of June (2015, 2016, 2020, 2023)	1 st ten-day period of July	2 nd ten-day period of July (2014, 2017, 2019)

Table 5. Mean values of the sums of frost degree-days (SFDD) for severe, moderate and mild winters according to data from the Marre-Sale station, 1977–2023

Winter type		Number of winters	SFDD, °C
Severest		1	–4556
Severe	without the severest winter	8	–3968
	with the severest winter	9	–4042
Moderate		22	–3278
Mild	without the warmest winter	10	–2626
	with the warmest winter	11	–2588
Warmest		1	–2212

Table 6. Calculated values of sea ice thickness and sea ice – seabed contact area in Sharapov Shar Bay for mild and severe winters

Winer type	Sums of frost degree-days, °C	Ice thickness, cm	Sea ice – bottom contact area	
			km ²	% from the total area of the bay
Mild	–2588	121	582	49
Severe	–4042	157	716	60

son in Sharapov Shar Bay lasts from 232 to 283 days (on average, 263 days).

Ice thickness. According to the results of the SFDD calculations and typification of winter season based on them [Dumanskaya, 2014], for 42 ice seasons, the winter of 1998/99 (–4556°C) was the severest, while the warmest winter was in 2019/20 (–2212°C). Eight severe winters and ten mild winters were recorded. The 21st century accounts for only two severe winters and nine mild winters. Table 5 presents the SFDD typical values for moderate, severe, and mild winters.

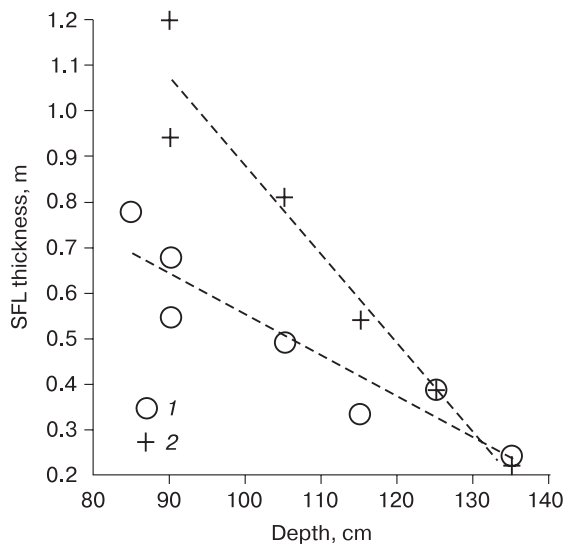


Fig. 3. Estimated thickness of the seasonally frozen layer (SFL) under the fast ice at different water depths for (1) clayey and (2) sandy bottom sediments.

The calculated ice thickness in the coldest season was 167 cm; in the warmest season, 110 cm. The bathymetric map of Sharapov Shar Bay (Fig. 1) shows the boundaries of the ice/seabed contact area for severe and mild winters. The maximum area of the contact in severe winter is 60% of the total bay area; in mild winter, it is about 49% (Table 6).

Results of the sediment freezing simulation.

The formation of a seasonally frozen layer (SFL) in the 20th century was possible at all ice cover thicknesses. The greater the ice thickness, and the later it settles on the seabed, the smaller the SFL thickness. The authors found that, provided fast ice forms in December, sandy bottom sediments do not transfer into the perennially frozen state at the ice thickness of more than 90 cm. For loamy sediments, this threshold is 80 cm because of the higher heat capacity. The SFL thickness varies from 0.2 to 1.2 m for sandy sediments and up to 0.8 m for clayey sediments (Fig. 3).

At the same ice thickness (90 cm), the seasonal freezing depth varies by 20% depending on the time of the ice formation (Fig. 3). At sea depths of up to 0.8–0.9 m, ice forms earlier and fast ice forms by November (ice thickness 30 cm) and December (more than 60 cm).

According to the modeling results, the formation of ice and its freezing with bottom sediments at the beginning of the cold season created favorable conditions for the formation of permafrost in the 20th century. The estimated permafrost thickness for the period of 1970–1999 was up to 3.5–6.6 m (Fig. 4). Sea ice forms throughout the entire winter period, and its thickness increases with increasing depth of the bay. As fast ice begins to form from the shore, some assumptions were made in the calculations. For example, in November, a 30-cm-thick ice layer lies directly

on the bottom at sea depths of less than 30 cm; at greater depths, fast ice is separated from the bottom by a layer of sea water, in our case with a temperature of -1.8°C . The presence or absence of ice contact with the bottom was considered in the model as different

boundary conditions. Table 3 presents averaged air temperatures from 1977 to 1999 and the heat transfer coefficients for different ice thicknesses.

According to previous studies [Vasiliev *et al.*, 2011], permafrost formation on the low shores of

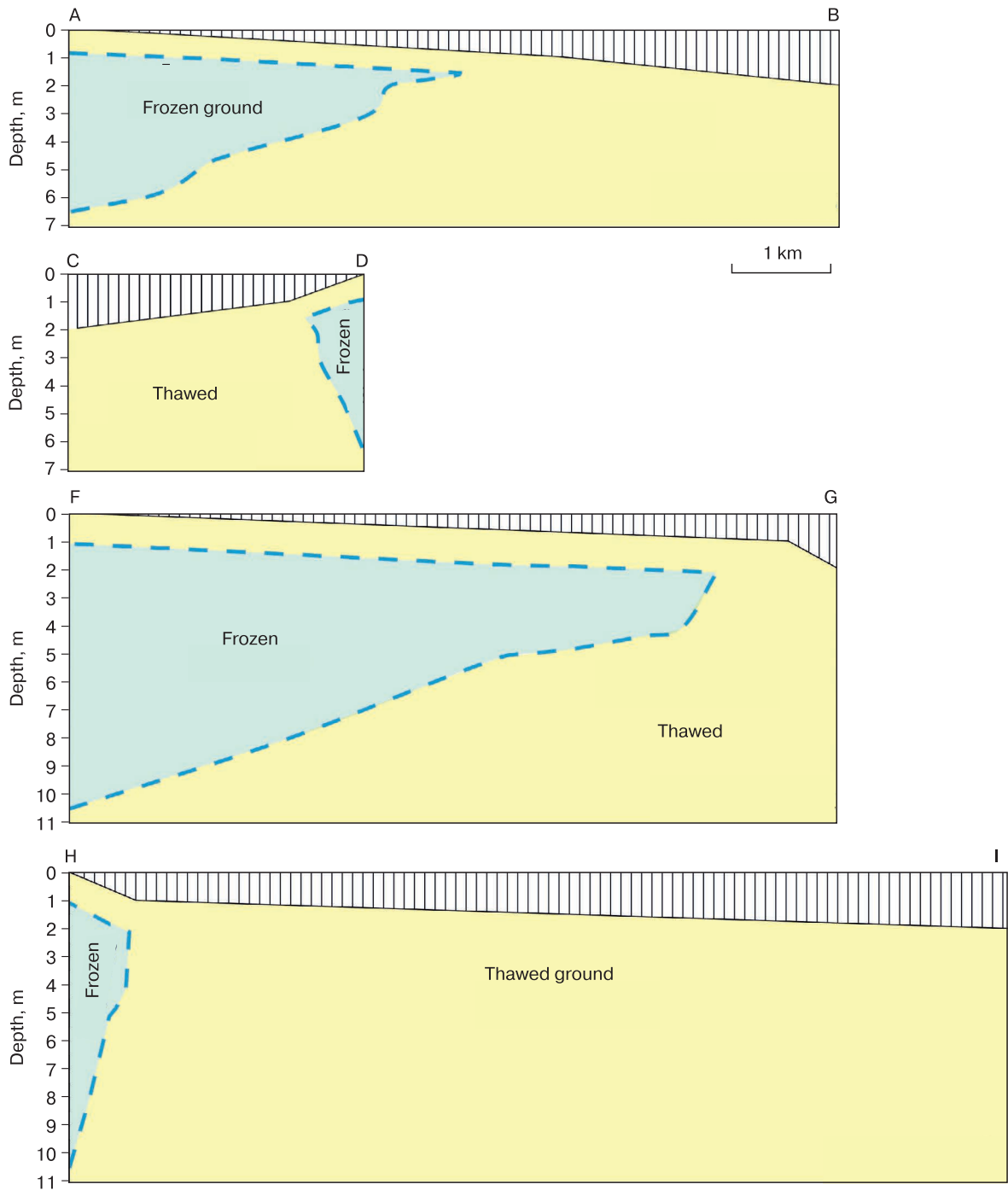


Fig. 4. Schematic sections reflecting the presence of permafrost from modeling data for the last 30 years of the 20th century.

Profiles A–B and C–D are for clayey sediments; sections F–G and H–I are for sandy sediments. The position of the sections is shown in Fig. 1. Hatching indicates sea ice.

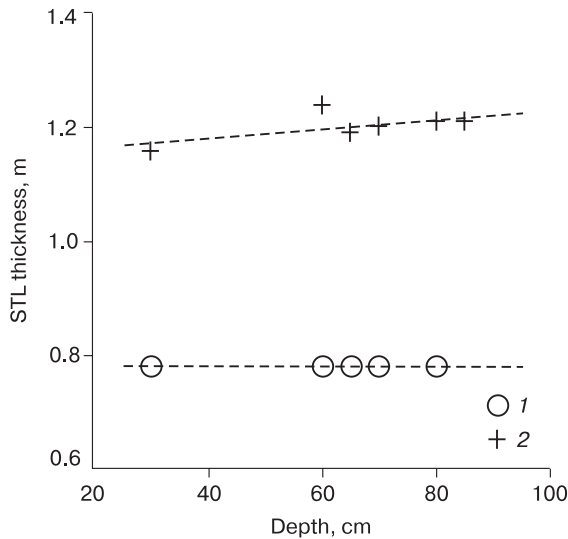


Fig. 5. Calculated thickness of the seasonally thawed layer (STL) in Sharapov Shar Bay at sea depths up to 90 cm for (1) clayey and (2) sandy sediments.

Western Yamal, including the area of Cape Kharasavei, was observed at sea depths of up to 1.5 m. In the area of Cape Burunny (Baidaratskaya Bay of the Kara Sea), frozen sediments were found on an underwater spit (shoal) at sea depths of 2–3 m; the frozen layer wedged out at a distance of 2.3 km from the shore [Buldovich, Danilov, 1998]. According to the modeling, the new formation of permafrost in

Sharapov Shar Bay is possible at shallower depths because of a higher salinity and lower freezing temperature of saline sediments.

In summer, the thickness of the thawed layer is up to 0.8 m for clayey sediments and 1.2 m for sandy sediments. Note that thawing depth does not depend on the ice thickness (Fig. 5).

Modeling of the second stage showed that permafrost, which could have formed over the last 30 years of the 20th century, begins to thaw from the top in the 21st century with an increase in the seasonal thawing depth (Fig. 6). The thickness of the seasonal thaw layer (STL) is greater in sandy soils than in clayey soils due to differences in their thermophysical properties. Complete degradation of the SFL and merging of the STL with the possible permafrost table was noted for 2022, when the permafrost table for sandy soils was at 407 cm at a water depth of 0.7 m, and for clayey soils at 220 cm at a water depth of 0.3 m.

The rates of permafrost degradation in the 21st century depend on sediment textures. In sandy sediments, permafrost can be preserved at sea depths up to 0.7 m; in clayey sediments, at sea depths up to 0.3 m. Since 2015, the STL thickness has increased significantly in comparison with that in 2001–2014. The differences in the STL and SFL thicknesses between 2006–2009 and 2012–2013 (Figs. 6, 7) indicate that bottom sediments subjected to freezing in winter do not have time to thaw completely in summer. That is, we observe non-stationary conditions, when the STL thickness is less than the SFL thick-

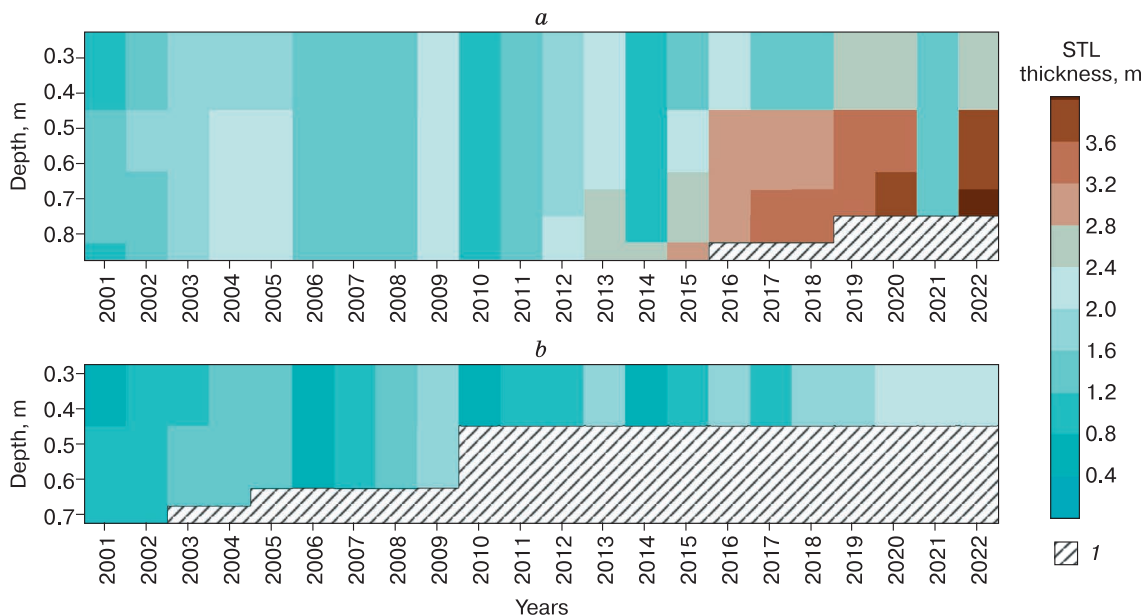


Fig. 6. Changes in the thickness of the seasonally thawed layer (STL) composed of (a) sandy and (b) clayey sediments at different sea depths in 2001–2022.

1 – complete thawing of soils.

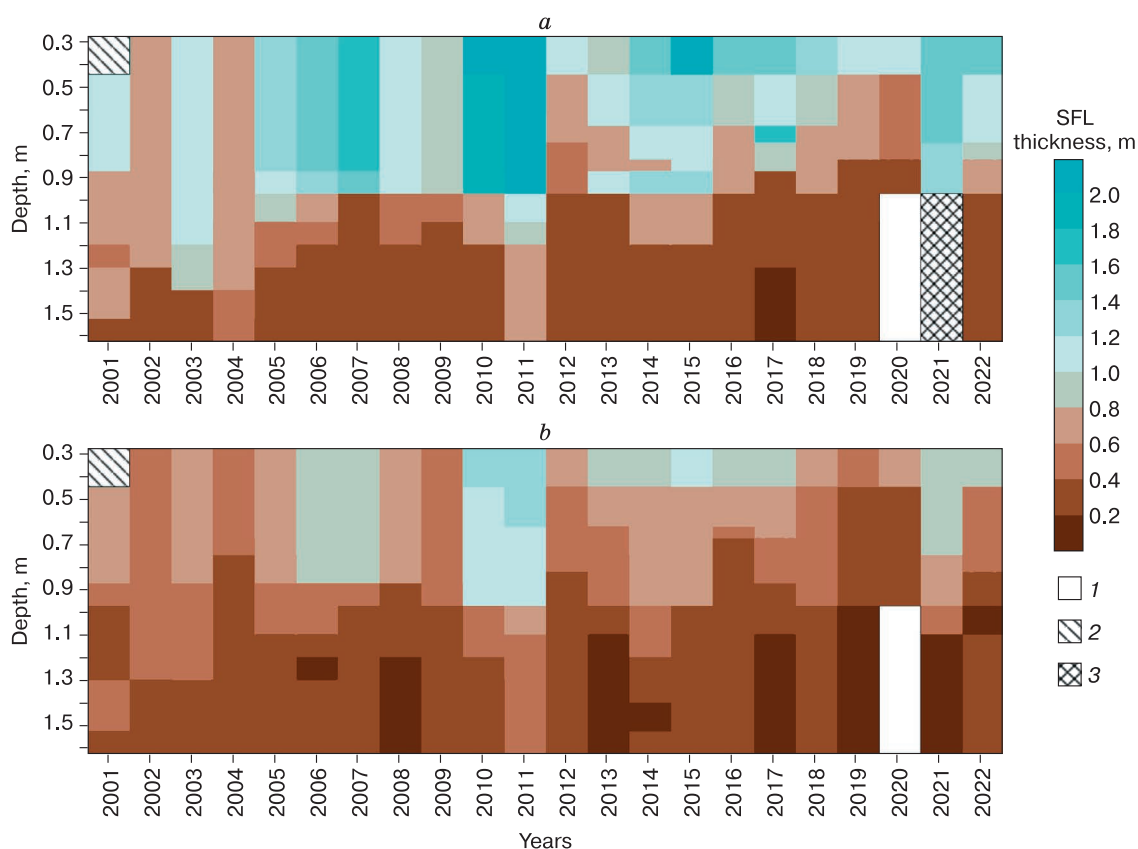


Fig. 7. Changes in the thickness of the seasonally frozen layer (SFL) composed of (a) sandy and (b) clayey sediments at different sea depths in 2001–2022.

1 – SFL is absent, 2 – SFL merged with permafrost, 3 – two-layered structure of the SFL.

ness, and permafrost formation takes place. In the 21st century, these conditions were only observed in 2006–2009 and 2012–2013. In the other periods, the conditions for the permafrost formation did not occur. Over the past decade, the STL thickness has always exceeded the SFL thickness.

M.N. Grigoriev [2006] provides data on the degradation of relict subsea permafrost on the shelf of Eastern Siberia. The degradation rate ranges from 1 to 10–15 cm/yr at contact of permafrost with seawater. New formation of permafrost in subaqueous conditions is possible at sea depths of up to 2.5 m and is observed in shallow-water areas of delta front and shallow bays, where active sedimentation takes place. Modeling indicates that in Sharapov Shar Bay, climatic conditions in the last decades of the 20th century were favorable for the preservation and even local new formation of permafrost. In the 21st century, the probability of permafrost development in Sharapov Shar Bay is absent, and local areas with permafrost that could have formed in the 20th century are degrading.

CONCLUSIONS

A schematic map of the ice cover of Sharapov Shar Bay with indication of the areas, where sea ice is in direct contact with seabed, is presented in this article. It is compiled on the basis of the analysis of long-term remote sensing data, available field observations, and calculated sea ice thicknesses. Modeling of the freezing and thawing of bottom sediments in Sharapov Shar Bay has been performed for a period from 1973 to 2022. The main conclusions of the research can be formulated as follows:

1. The ice season in Sharapov Shar Bay lasts on average from the 2nd ten-day period of October to the 2nd ten-day period of July. The stable fast ice in the bay is preserved for 252 days a year, from the end of October to the end of June.

2. The maximum annual sea ice thickness varies from ~120 cm in mild winters to ~160 cm in severe winters.

3. In winter, ice freezing with the bottom is observed on 50% of the bay water area, resulting in the formation of seasonally frozen sediments.

4. The thickness of the seasonally frozen layer depends on the properties of bottom sediments. At sea depths of more than 80–90 cm, the thickness of the seasonally frozen layer varies in a wide range from 0.2 to 1.2 m for sandy sediments and up to 0.8 m for clayey sediments. The seasonally frozen layer thaws completely during the summer period.

5. The thickness of the bottom sediment layer subjected to thawing in summer does not depend on the ice thickness and is controlled by the properties of the bottom sediment. For sandy sediments, it reaches 120 cm; for loamy sediments, it is about 80 cm.

6. According to modeling data, for the climatic conditions of the period 2001–2022, sediments, in which local development of permafrost took place in the 20th century, could have been preserved in the frozen state at sea depths of up to 0.7 m for sandy bottom sediments and up to 0.3 m for clayey bottom sediments.

Acknowledgements. *This work was supported by the State Budgetary Theme, project no. 126042920506-7.*

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Received May 20, 2024

Revised August 8, 2024

Accepted December 27, 2024

Translated by V.A. Krutikova