Regional Differences and General Patterns of Ice Ridges Morphometric Characteristics Distribution in the Kara and Laptev Seas

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ABSTRACT

The article describes the regional characteristics of the distribution of morphometric parameters of ice ridges in five local areas in the Kara and Laptev Seas. The article gives the main parameters of the morphometry of ice ridges of different water areas. The features of the consolidated layer distribution are shown depending on the study region and the ridge-building conditions. Averaged profiles of the cross-section of the ice ridge are shown, the nature of the change in the thickness of the consolidated layer concerning the sail and keel of the ice ridge is shown. Averaged vertical distributions of porosity are obtained. The article reveals regional differences and general patterns of distributions of the main morphometric characteristics of ice ridges.

KEYWORDS: ice ridge, morphometry, internal structure, consolidated layer, porosity

INTRODUCTION

Information about the morphometric characteristics of ice ridges and the patterns of their distribution are necessary to assess the possible ice load in the design of offshore structures (Alekseev et al., 2001). In different regions, the values of the morphometric characteristics of the ice ridges are different, which is mainly due to differences in meteorological and ice conditions.

Large-scale studies of AARI and Rosneft in 2013-2017 in the seas of the Russian Arctic have provided a large amount of information about the morphometry of large ice features. This article is a follow-up to "Morphometry and Internal Structure of Ice Ridges in the Kara and Laptev Seas" (Guzenko et al, 2019) with an emphasis on regional features of the distribution of morphometric characteristics. We carried out a comparative analysis of the main parameters of the internal structure of 104 first-year ice ridges studied in 2014-2017 in five local areas: southwest and northeast of the Kara Sea, southwest, northeast and Khatanga Bay of the Laptev Sea (Fig. 1). For the first four areas, the research data from 2014 and 2015 were used, for the Khatanga Bay - research data from 2017.

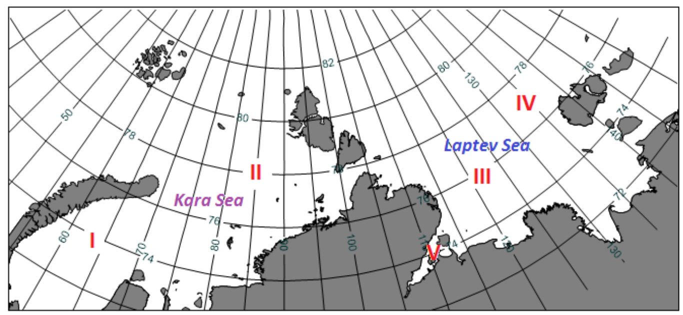

Fig. 1 – Study regions: I – southwestern Kara Sea, II – northeastern Kara Sea, III – southwestern Laptev Sea, IV – northeastern Laptev Sea and V – Khatanga Bay

The aim of this work is to identify regional differences and general patterns in the distribution of morphometric characteristics of the first-year ice ridges of the Kara and Laptev Seas based on the results of comparative analysis.

The results of the study will be useful to expand modern ideas about the role of physical processes that determine the ridge-building and their structure, as well as to clarify their morphometric parameters used in design.

RESEARCH METHOD AND INITIAL DATA

The technology of thermal drilling with a recording of the drilling speed on an electronic media developed at the AARI under the guidance of V. Morev (Mironov et al., 2003) was traditionally used as the main method for studying the morphometry and internal structure of large ice features. The main tool was the UVBL-2M water ice drilling system.

The basic idea of the technology is that the drilling speed is determined by the condition of the medium penetrated by the drill, which is divided into three types: hard ice, soft ice, and a void. When processing thermal drilling data, the freeboard and underwater part of the ice feature are determined, as well as the boundaries of voids and ice of various densities in the borehole with an accuracy of 1 cm. This technology allows to determine the basic morphometric parameters of the ice feature and study the internal structure. Empirically determined errors in measuring depth and drilling speed do not exceed 1%.

Initially, one of the largest ice ridges was selected in a particular area. Several profiles were laid perpendicular to the crest (from 2 to 5, depending on the length of the crest and the time available, most often 3). The distance between neighboring profiles was usually 15–20 m. Drilling points were marked along each profile every 2.5 or 5 m. The number of drilling points on the profile depended on the width of the crest. They tried to lay the profiles through the ice ridge crest so that their extreme points were on level ice. One of the profiles was always laid through the highest section of the sail so that one of the marked points corresponded to the highest point of the ice ridge sail. As a rule, a total survey of the upper surface of the ice ridge and video recording of the ridge keel using an underwater remotely operated vehicle (ROV) were carried out at the same time with thermal drilling, and since 2015, where possible, sonar survey of the ridge keel was also carried out (Guzenko et al, 2019, Mironov et al., 2019). Table 1 gives a description of the initial data on seas and research areas. Most ice ridges (28) were investigated in the southwest of the Kara Sea. And most of the boreholes were drilled in the ice ridges of the Khatanga Bay (1139). The northeast of the Kara Sea provided twice as less data as the other four regions. Two thirds of all the data were collected in the Laptev Sea, one third in the ice ridges of the Kara Sea. A total of 4444 boreholes were drilled, of which 571 were on level ice (at the ends of the profiles).

Table 1. The amount of initial data

Regions	Years of study	Number of ridges	Number of profiles	Number of boreholes
I	2014, 2015	28	84	954
II	2014, 2015	11	32	448
III	2014, 2015	23	72	972
IV	2014, 2015	20	70	931
V	2017	22	68	1139
Kara Sea	2014, 2015	39	116	1402
Laptev Sea	2014, 2015, 2017	65	210	3042
Total	2014, 2015, 2017	104	326	4444

Roman numerals designate regions similar to Fig. 1.

MAIN RESULTS OF DETERMINING MORPHOMETRIC CHARACTERISTICS OF ICE RIDGES

Basic morphometric parameters

Table 2 shows the main morphometric parameters of first-year ice ridges of different regions and seas. The ice ridges of the southwest and northeast of the Kara Sea had the largest average length of crests (97 m), the ice ridges of the Khatanga Bay had the smallest one (72 m). The average sail height from the maximum values for ice ridges was the highest in the northeast of the Kara Sea (3.6 m), and the lowest in the Khatanga Bay (2.4 m). The average height of the sail at all points of the sail was also the highest for the ice ridges of the northeast of the Kara Sea (2.3 m) and the ice ridges of the Khatanga Bay had the smallest one (1.2 m). The sail width averaged for the areas varied from 10 m (in the southwest of the Laptev Sea and in the Khatanga Bay) to 15 m (in the northeast of the Kara Sea). The average keel depth of the maximum values for ice ridges in different regions ranged from 7.2 to 12.2 m, the average keel depth at all points was from 4.4 to 6.6 m, the average keel width was from 41 to 57 m, the total ice thickness of the maximum values for ice ridges was from 9 to 14.3 m, and the total thickness at all points was from 4.9 to 7.4 m. All the maximum parameters belonged to ice ridges of the northeast of the Kara Sea, and the lower ones in the vast majority belonged to ice ridges of the Khatanga Bay, which were located on landfast ice, in relatively shallow water. The ice ridges in the southwest of the Kara Sea, southwest and northeast of the Laptev Sea had similar values of the main morphometric parameters. Due to relatively small ice ridges of the Khatanga Bay, the Laptev Sea had a larger number of studied objects, but all the presented average values of morphometric parameters of ice ridges of the Kara Sea were greater.

It should be noted that all morphometric characteristics in Table 2 are given according to thermal drilling data. However, the values of the maximum keel draft obtained from the drilling results are always underestimated relative to the real values. This is due to the fact that the deepest keel fragments are likely to be located between boreholes. Comparison of the maximum keel values determined by different methods (drilling, video filming with ROV and sonar survey) showed an underestimation of the maximum values of keel draft by 12 to 25% according to drilling data. An appropriate correction is also required to estimate the maximum total thickness of the ice ridge according to drilling data.

Thickness of the ice ridge consolidated layer

The thickness of the consolidated layer of ice ridges has major importance among the morphometric characteristics of ice ridges to determine the potential ice load on an offshore structure (Marchenko, 2002, Sudom and Timco, 2013). Consolidated layer (CL) is the part of the ridge in which the ice blocks were frozen into a monolith. CL was present in 98% of the drilled boreholes of first-year ice ridges. Fig. 2 shows the distribution of the CL thickness in the research areas, Fig. 3 shows the same in the seas. The red lines in the figures indicate the curves of theoretical laws that most closely approximate empirical data. For each empirical sample, we considered the approximation by five theoretical distributions: normal, log-normal, Weibull, gamma distribution and exponential. The quality of the approximation was estimated by two criteria: the square root of the root mean square error (RMSE) and the coefficient of determination (R^2). The lower the value of the first criterion is and the higher the second one, the better the theoretical law describes empirical data.

Table 3 shows the parameters of the most successful approximations for the seas and study areas, as well as the average values of the thickness, positions of the upper and lower boundaries of the CL. As we can see, the distributions of the CL thickness in most samples were better described by the Weibull distribution. The Weibull distribution was the best among other theoretical distributions in 3 of 7 samples, was the second-best in another 3 samples, and once it was the third-best in terms of approximation quality. The total sample was also better described by the Weibull distribution (Guzenko et al, 2019). The landfast ice ridges of the Khatanga Bay had the largest average thickness (2.55 m). The same ice ridges had the smallest dispersion of thickness (standard deviation – 0.53), which, apparently, is explained by the similar time of ridge-building (and CL in them) in this region. The average position of the upper and lower boundaries of the CL in all samples shows certain submergence of the CL, which is traditionally typical of the period of maximum snow accumulation at the end of the winter season. In the vast majority of samples, the above-water part of the CL was only 3-4% of the total thickness of the CL, the above-water part of CL for the ice ridges of the Khatanga Bay was 5%. Among the study areas, the largest range in the CL thickness (more than 8 m) was observed for the ice ridges of the northeast of the Laptev Sea. In three of five regions, the prevailing CL thickness ranged from 1.5 to 2 m; in the south-west of the Kara Sea, the prevailing range was 1-1.5 m, and in the Khatanga Bay it was 2.5-3 m.

Table 2. Averaged morphometric characteristics of the studied first-year ice ridges by region and sea

Regions	Ridge length, m	Sail height of the max values, m	Sail height by all sail points, m	Freeboard by all points, m	Sail width, m	Keel depth of the max values, m	Keel depth by all points, m	Keel width, m	Total thickness of the max values, m	Total thickness by all points, m
I	97	2.80	1.83	0.65	11	9.04	5.53	41	10.82	6.18
II	97	3.64	2.30	0.87	15	12.21	6.55	57	14.28	7.42
III	83	2.80	1.55	0.59	10	9.30	5.30	45	11.14	5.89
IV	93	3.13	1.80	0.61	11	9.68	5.16	47	11.51	5.77
V	72	2.38	1.18	0.52	10	7.18	4.40	41	8.98	4.92
Kara Sea	97	3.04	1.99	0.72	12	9.94	5.86	46	11.80	6.59
Laptev Sea	82	2.76	1.49	0.57	10	8.70	4.95	44	10.52	5.52

Roman numerals designate regions similar to Fig. 1

Table 3. Characteristics of the CL of first-year ice ridges of various samples and approximation parameters by theoretical distributions

Regions	Number of boreholes with CL	CL thickness (avg), m	CL standard deviation, m	CL boundaries, m		Distribution	Criteria RMSE/R^2	Distribution parameters	
				Top	Low			I (scale)	II (shape)
I	841	1.49	0.63	0.06	-1.43	Weibull	0.97/0.99	1.68	2.52
II	409	2.08	0.94	0.07	-2.01	Weibull	1.41/0.97	2.35	2.35
III	844	2.09	0.99	0.06	-2.02	Gamma	0.88/0.99	4.45	0.47
IV	851	2,32	1.21	0.10	-2.22	Weibull	0.75/0.99	2.62	2.01
V	861	2.55	0.53	0.13	-2.42	Normal	0.87/0.99	2.55	0.53
Kara Sea	1250	1.68	0.79	0.06	-1.62	Gamma	0.79/0.99	4.41	0.38
Laptev Sea	2556	2.32	0.97	0.10	-2.22	Normal	1.16/0.98	2.32	0.97

Roman numerals designate regions similar to Fig. 1.

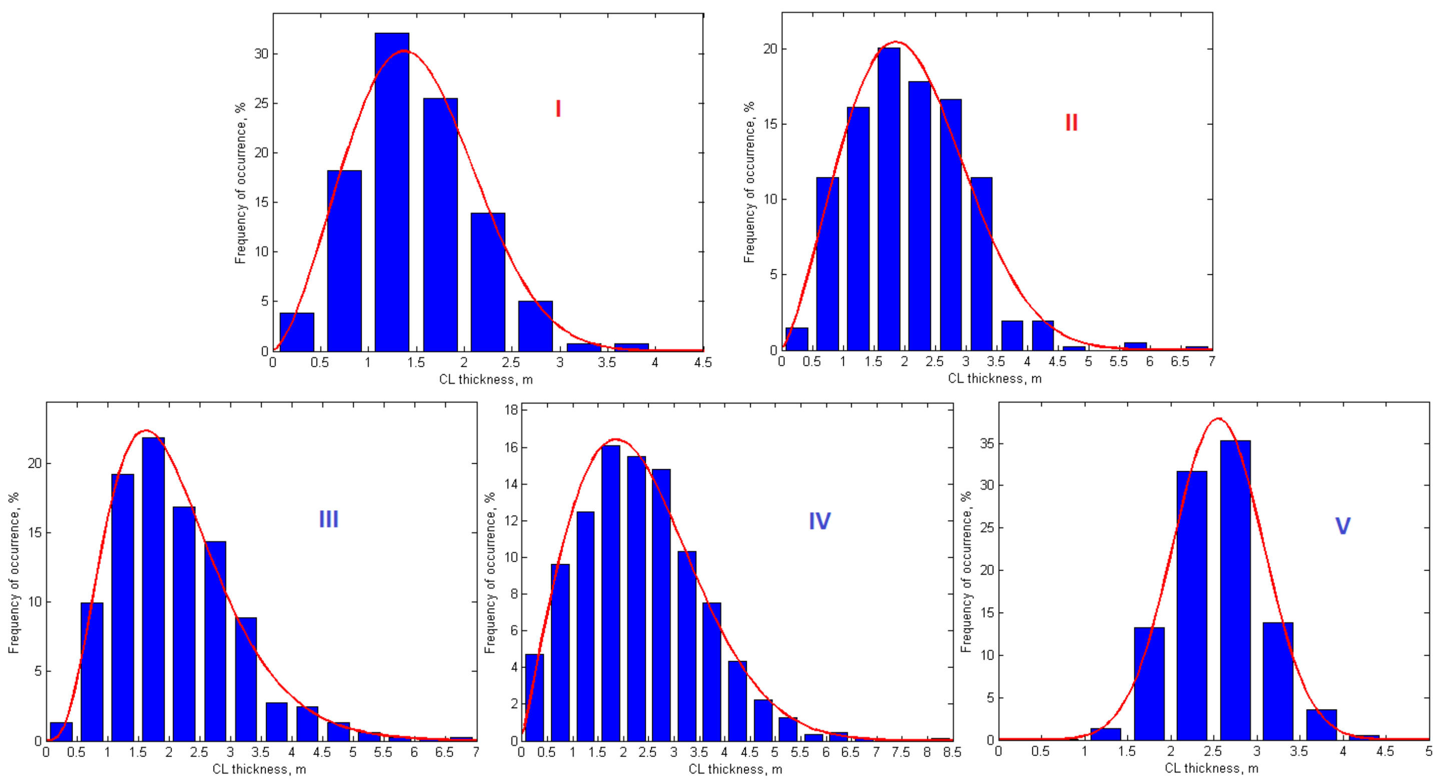

Fig. 2 – CL thickness distribution in different regions at the end of the winter period. Roman numerals designate regions similar to Fig. 1

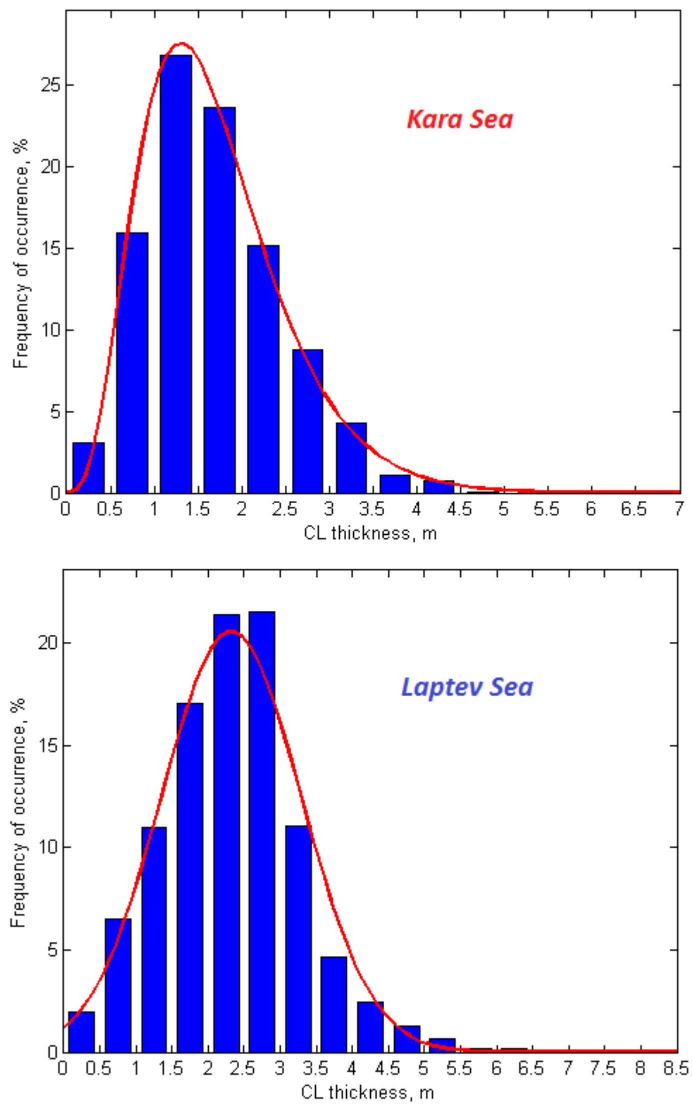

Fig. 3 – CL thickness distribution in the Kara and Laptev Seas

The ice ridges of the Laptev Sea generally had a significantly thicker CL (on average 2.32 m with a prevailing thickness range of 2-3 m) than ice ridges of the Kara Sea (on average 1.68 m with a prevailing thickness range of 1-1.5 m). This is primarily due to the harsher temperature conditions of the Laptev Sea regions. Table 4 shows the data for the sum of freezing degree-days (FDD) for the polar stations (p/s) closest to the study areas for the corresponding years. The temperature regime of the southwest of the Kara Sea was characterized by Popov p/s (Bely Island), and the northeast of the Kara Sea was characterized by Golomyanny p/s, southwest of the Laptev Sea by Tiksi p/s, northeast of the Laptev Sea by Kotelny Island p/s. The ice ridges of region V are divided into two groups: the western one, which relates to the Khatanga Bay with the nearest Khastyr p/s, and the eastern one, which belongs to the Nordvik and Anabar bays with the nearest Anabar p/s. Since the exact time of ridge-building and formation of CL in them is unknown, the date of steady transition of air temperature through zero was taken as the beginning of the FDD calculation, and the end of the FDD calculation corresponded to the middle of the ice ridges research period in a specific area. As we can see from the table, the FDD for the Laptev Sea regions is greater than for the Kara Sea stations.

Table 4. FDD at polar stations the closest to the study region

Year	Region	p/s	FDD (^oC)	Number of ridges
2014	I	Popov (Bely Is.)	3410	15
	II	Golomyanny Is.	3939	7
	III	Tiksi	4472	14
	IV	Kotelny Is.	4535	12
2015	I	Popov (Bely Is.)	3270	13
	II	Golomyanny Is.	4515	4
	III	Tiksi	4785	9
	IV	Kotelny Is.	4846	8
2017	V (west)	Khastyr	4642	13
	V(east)	Anabar	4569	9

Roman numerals designate regions similar to Fig. 1.

Distribution of the consolidated layer inside the ice ridge

Information on the typical distribution of the CL thickness inside the ice ridge relative to the sail and keel of the ice feature can be useful for a better understanding of the evolution of the CL and the relationships of this process with the parameters of the ice ridge morphometry.

The influence of ridge sail on the CL evolution was considered in some papers (Høyland and Løset, 1999, Salganik et al, 2020). The paper (Guzenko et al, 2019) presents data on a total sample of 105 ice ridges of the Kara and Laptev Seas, where it is shown that the average thickness of the CLunder sail is 28 cm or 14% greater than outside the sail. Table 5 shows the average values of the CL thickness for five regional samples depending on the location relative to the sail. For different samples, the percentage of points related to the sail ranged from 24 to 29%. In all five regions, the average CL thickness was greater under the ice ridge sail; the table shows the difference in average thicknesses in meters and percent (the average CL thickness outside the sail was taken as 100%). This, of course, does not cancel the possibility that the opposite results could be observed on individual ice ridges or drilling profiles, however, the general averaged pattern can be traced - in the vast majority of cases, the average CL thickness is greater under sail than outside of it. In the paper (Guzenko et al., 2018), an attempt was made to check this pattern on the largest amount of data available, as well as to catch the possible connection of this phenomenon with other morphometric characteristics of the ice ridge: the average height of the sail, the porosity of the sail, and the average size of voids in the sail. In total, 152 ice features (130 ice ridges and 22 stamukhi) were considered, which made up 14 regional-annual samples (12 ice ridge samples and 2 stamukhi samples). The same consistent pattern was obtained in 12 samples, but in two samples (one in the ice ridges and one in stamukhi) the average CL thickness under the sail was less than outside the sail. No relationships were found between the distribution of CL under the sail and outside of it with porosity or void sizes in the sail. However, in both cases, where the CL thickness under the sail was less than outside the sail, the average (at all points of the sail) sail height exceeded 2 m. For Region II, the average sail height at all points of the sail also exceeded 2 m (see Table 2), while the average CL thickness under the sail is still greater, however, the difference with the CL thickness outside the sail compared to other areas is minimal - only 2%. The largest difference in the CL thickness was observed in the northeast of the Laptev Sea - 48 cm (22%). The difference in the average CL thickness under and outside the sail is 25 cm larger in the ice ridges of the Laptev Sea than in the ice ridges of the Kara Sea, while the average height of the sail at all sail points is 50 cm greater in the ice ridges of the Kara Sea. Apparently, these figures can be an indirect demonstration of the heat-insulating properties of the sail relative to the CL. However, as the CL thickness under the sail is greater than its thickness outside the sail in all samples (see Table 5), the heat-insulating effect of the sail is not dominant in the formation of CL. In most cases, the sail, first of all, indicates the zone of the ice ridge where ice blocks have the densest packed structure in waterline area, which ultimately causes a thicker CL.

In the paper (Guzenko et al, 2019), the averaged values of the freeboard, keel depth and CL boundaries determined on the drilling profiles were carried out in two averaging options: from the maximum keel point and from the maximum sail point on each profile. For each averaging option, the same direction was taken from the maximum keel point to the maximum sail point on each profile. Figure 4 shows the results of such averaging for the studied seas. A total of 326 profiles of 104 ice ridges were used. Since measurements on real profiles were carried out with different resolution (more often 5 m, less often 2.5 m), the amount of data on distance marks of averaged profiles is also distributed unevenly. To smooth this effect a little, we used a moving average, determined from two neighboring values, taking into account the amount of data. As a result, we obtained the values of the main morphometric characteristics averaged to the middle of each 2.5-meter measuring range (i.e., for distance marks of 1.25, 3.75, 6.25 m, etc., in both directions relative to zero). Zero on the abscissa corresponds to either the maximum keel point (the first averaging option) or the maximum sail point (the second averaging option). The charts, in addition to the profile-averaged values of freeboard, keel and CL boundaries (along the left vertical axis), show a scaled-up change in the CL thickness (along the right vertical axis). Initially, there were over 2 times more data on the Laptev Sea than on the Kara Sea: 2556 versus 1250 drilling points. The averaged profiles show the areas most provided with data, where each 2.5-meter mark has at least 50 averaged values. As can be seen in Fig. 4, the averaged ice ridge profile of the Kara Sea shows a larger sail and keel, but a smaller CL thickness. The CL thickness in all the charts tends to increase towards the middle of the profile (mark 0 on the abscissa axis), and the CL thickness becomes maximum in the area of the maximum keel values, which is especially clearly seen in the charts related to the Laptev Sea. The maxima of the sail and keel on the averaged profiles are located close (on average, at a distance of 2.5 m from each other), so the sail zone mostly coincides with the thickened CL zone.

Table 5. The average thickness of the ice ridge CL in the sail area and outside of it for different regions and seas

Regions	Number of points with the CL		CL thickness (avg), m		Difference in CL thickness (a-b), m (%)	CL standard deviation, m	
	under the sail	outside the sail	under the sail (a)	outside the sail (b)		under the sail	outside the sail
I	217	624	1.58	1.46	0.12 (8)	0.68	0.61
II	112	297	2.11	2.07	0.04 (2)	1.00	0.92
III	224	620	2.37	1.98	0.39 (20)	1.09	0.93
IV	203	648	2.68	2.20	0.48 (22)	1.37	1.13
V	248	613	2.68	2.50	0.18 (7)	0.58	0.50
Kara Sea	329	921	1.76	1.66	0.10 (6)	0.84	0.78
Laptev Sea	675	1881	2.58	2.23	0.35 (16)	1.05	0.92

Roman numerals designate regions similar to Fig. 1.

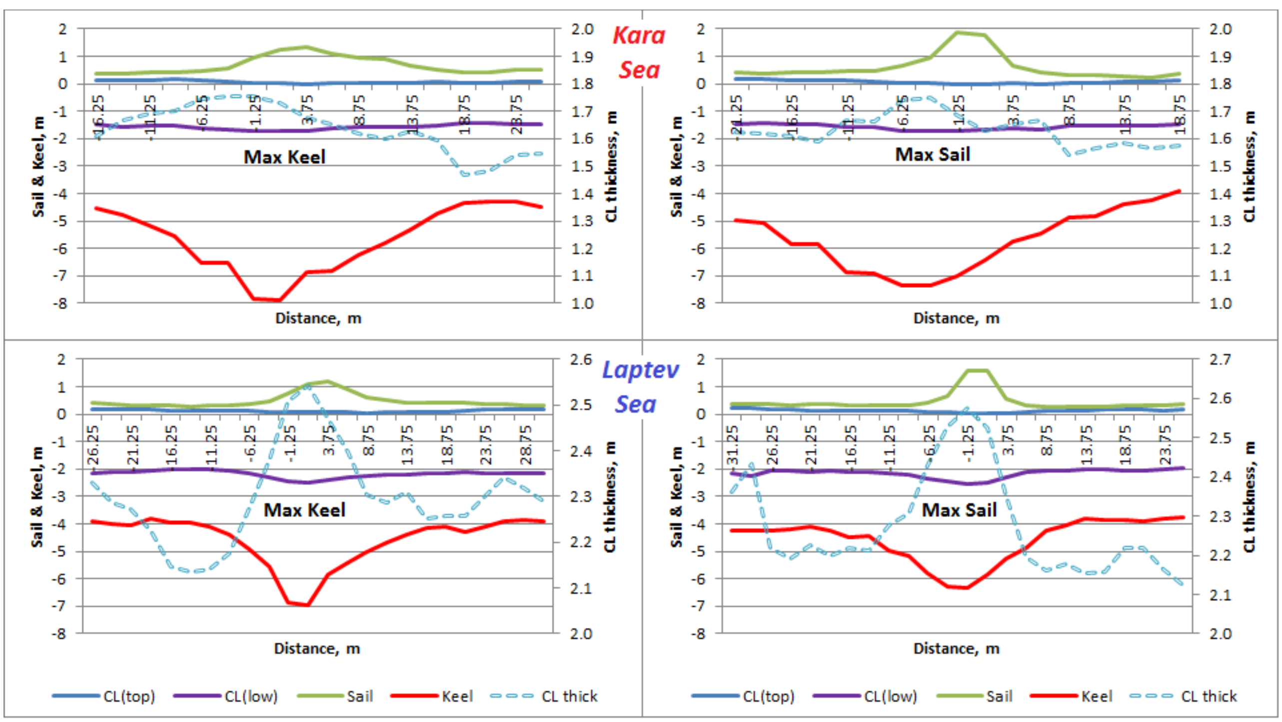

Fig. 4 – Averaged ridge profile from the maximum keel point (left) and maximum sail point (right) in different seas. Zero in the ordinate axis corresponds to the waterline.

Porosity Distribution by depth

Porosity (a relative content of voids in the ice feature; hereinafter: porosity is macroporosity) is a parameter of the internal structure of ice ridge directly related to the CL. Guzenko et al (2019) showed a vertical profile of porosity averaged with a resolution of 1 cm over the total set of measurement data. Figure 5 shows similar averaged profiles for five study areas (a total of 3873 boreholes were used to obtain data). The charts show 95% of all values; low-data sections of the curves corresponding to the extreme values of the sail and keel are filtered out. Most charts show that porosity tends to increase with sail height and keel depth. This tendency was previously noted in (Grishchenko, 1988, Surkov, 2001, Pavlov et al, 2016). However, in the keel of ice ridges of the Khatanga Bay (region V), a certain decrease in porosity is observed at a depth (compaction of ice blocks). Apparently, this is due to the fact that the ice ridges of region V were in a static state (landfast ice) in shallow water, which contributed to the filling of the space between the ice and the bottom with ice blocks during keel-building, their fixation there and subsequent compaction. The area of low porosity in all cases is observed below sea level in the area of the most likely location of the CL; the average value and the spread of the CL thickness for a particular study region determine the size and shape of this area. Table 6 shows the porosity of different parts of the ice ridge and the characteristics of the CL for different seas and regions. The average porosity values of the ice ridges of the Kara and Laptev seas are similar, while the average and relative CL thickness is much larger in the ice ridges of the Laptev Sea. In the ice ridges of the Kara Sea, the porosity of the sail is lower, and the porosity of the entire keel is higher than in the ice ridges of the Laptev Sea. Among the regions, the ice ridges of the Khatanga Bay had the minimum average porosity of the entire ice ridge and keel (13%). These ice ridges are characterized by the highest values of the average and relative thickness of the CL. The average porosity of the entire ice ridge in all samples does not differ from the porosity of the entire keel by more than 1%. The porosity of the rubble is lower in the ice ridges of the Kara Sea; among the regions, the smallest value (21%) refers to ice ridges in the northeast of the Kara Sea, and the largest (33%) value refers to ice ridges in the southwest of the Laptev Sea. The ice ridges of southwest regions of the Laptev Sea and the southwest of the Kara Sea had the highest porosity of the entire keel (21%) and the entire ice ridge (20%). The smallest porosity of the sail (13%) was detected in ice ridges of the northeast of the Kara Sea.

Table 6. Porosity of different parts of the ice ridge and the characteristics of the CL by region and sea

Region	Kara Sea	Lap. Sea	I	II	III	IV	V
Average porosity of ice ridge, %	18	17	20	15	20	17	13
Average sail porosity, %	14	17	14	13	17	15	18
Average keel porosity, %	19	17	21	15	21	17	13
Average porosity of the rubble, %	25	30	28	21	33	28	28
Average CL thickness, m	1.68	2.32	1.49	2.08	2.09	2.32	2.55
CL standard deviation, m	0.79	0.97	0.63	0.94	0.99	1.21	0.53
Relative CL thickness, %	25	42	23	27	35	40	52

Roman numerals designate regions similar to Fig. 1. Relative CL thickness is a ratio of CL thickness/total thickness.

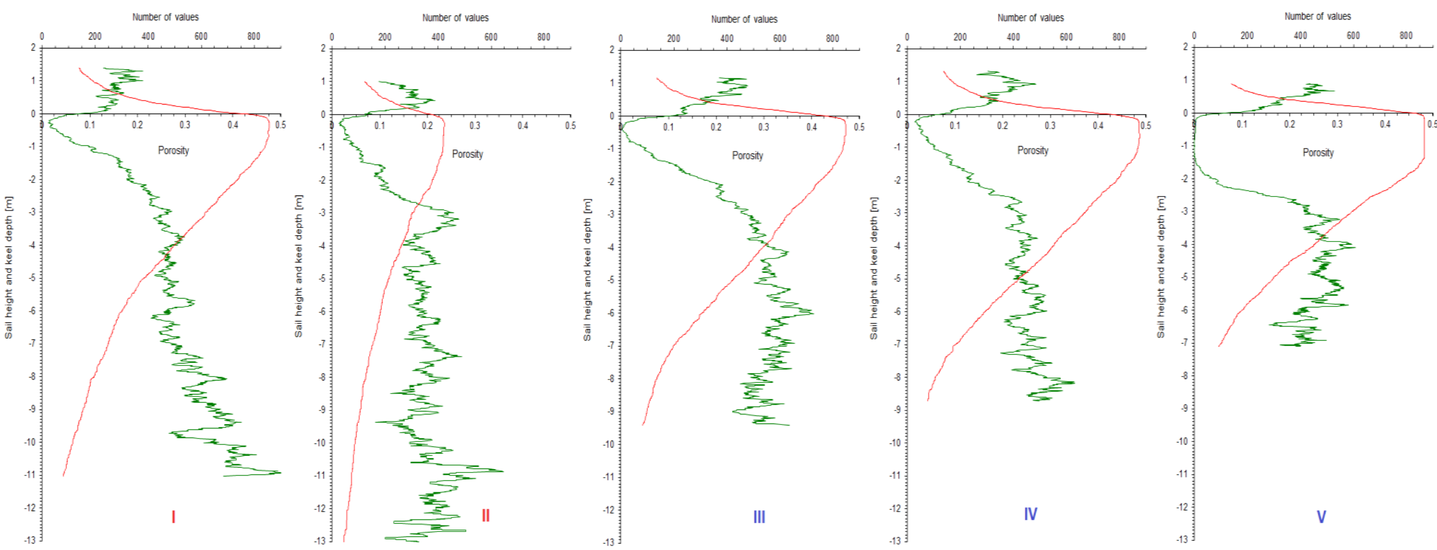

Fig. 5 – Averaged porosity (green line) distribution by vertical in different regions. The number of values (red line) is the number of averaged vertical porosity profiles obtained in the boreholes. Roman numerals designate regions similar to Fig. 1.

CONCLUSIONS

We performed a comparative analysis of the data on the morphometry and internal structure of 104 first-year ice ridges studied by the AARI and Rosneft Oil Company in various areas of the Kara and Laptev Seas in 2014-2017 using water thermal drilling.

It was revealed that the ice ridges of the Kara Sea generally had larger sizes than the ice ridges of the Laptev Sea, but the significantly smaller CL thickness, both average (1.7 versus 2.3 m) and relative (25 versus 42%). The areas of the Laptev Sea are characterized by more severe temperature conditions (which is confirmed by the data of the sum of freezing degree-days at polar stations); this, probably, determined the comparatively more intensive development of CL in the ice ridges of the Laptev Sea. The average porosity of ice ridges in the Kara Sea was slightly higher (18 versus 17%), and the porosity of the rubble was lower (25 versus 30%).

Each study area had its own particular nature. The ice ridges of the northeast of the Kara Sea exceeded the ice ridges of other regions in terms of their basic morphometric characteristics (sizes of sail and keel, total thickness). The ice ridges of the Khatanga Bay were investigated in landfast ice, in shallow water. They were characterized by the smallest size and the smallest porosity, but the largest average (2.55 m) and relative (52%) thickness of the CL. The small size and relatively low porosity of the keel of ice ridges in this region are related to their location at shallow depths, and the large CL thickness is determined by the harsh temperature conditions and probably relatively early formation times. The ice ridges of the southwest of the Kara Sea, with their considerable size, had the smallest average (1.5 m) and relative (23%) thickness of the CL. The ice ridges of the southwestern part of the Laptev Sea had the highest average porosity of the rubble (33%) and, along with ice ridges of the southwestern part of the Kara Sea, the highest porosity of the entire keel (21%) and ice ridge in general (20%). In most of the other morphometric parameters, ice ridges of this region took the middle position. The ice ridges of the northeastern part of the Laptev Sea were greater than the ice ridges of other areas of the Laptev Sea in most of the external parameters and as for the CL thickness (average - 2.3 m and relative - 40%), they took the second position after ice ridges of the Khatanga Bay among all areas of the two seas.

In addition to regional differences, we observed general patterns of distribution of the internal structure parameters of ice ridges. The average position of the CL in the ice ridges of all regions is characterized by some submergence (in most samples, the above-water part of the CL was only 3-4% relative to the total thickness of the CL). This position of the CL is typical of the period of maximum snow accumulation at the end of the winter season. The distributions of the CL thickness in most regions were better described by the Weibull function. For all samples, the average CL thickness was greater under the sail of the ice ridge than outside the sail (the difference in the average CL thickness under the sail and outside of it in different regions was from 2 to 22%). The CL thickness on averaged profiles tended to increase towards the middle of the profile, reaching maximum values in the area of the maximum keel. The maxima of the sail and keel on the averaged profiles are located slightly shifted from each other but the sail zone mostly coincides with the zone of the thickened CL. On the vertical profiles of averaged porosity, the porosity generally tends to increase with height in the sail and depth in the keel. The zone of minimum porosity was predictably located below the waterline in the area of the most probable CL position.

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