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Relationship between the consolidated layer thickness and other morphometric characteristics of first-year ice ridges

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ABSTRACT

The paper considers the morphometric particularities of 129 first-year ice ridges studied in different regions of the Kara and Laptev Seas in the period 2007-2017. The dependence of the consolidated layer thickness of the ice ridges on the temperature conditions of the local region is shown, taking into account the average age of ice ridges in the region. Differences in the morphometry of ice ridges studied on landfast ice and drifting ice are considered. The morphometric characteristics of ice ridges in different regions are given, averaged over the gradations of the average consolidated layer thickness. A general pattern is shown that connects the consolidated layer thickness with the external parameters of the ice ridges.

KEYWORDS: One-years ice ridge; Consolidated layer; Morphometry; Fast ridge.

INTRODUCTION

The increase in economic activity on the shelf of the freezing seas in the 21st century requires developing knowledge about the properties of the ice cover, in general, and large ice features, in particular. First-year ice ridges are ice features typical for all freezing water areas. Their morphometric properties must be taken into account for calculating ice loads on the designed shelf structure. The key morphometric characteristic for taking into account the possible impact of the ridge on the marine infrastructure is the consolidated layer (CL) inside the ice feature (Astafiev et al., 1997, Frederking, 1999, Sudom and Timco, 2013). Fig. 1 shows a diagram of an idealistic cross-section form of an ice ridge with the main morphometric parameters (in practice, different configurations of sails and keels may occur).

This paper is based on the results of complex studies of 129 first-year ice ridges carried out in different regions of the Kara and Laptev seas in the spring periods of 2007-2017. Fig. 2. demonstrates the study regions. Work on ice ridges in regions I-IV was carried out on drifting ice in 2014-2015 the team landed on the ice from an icebreaker, in regions V (2017) and VI (2007, 2010) the team landed from a helicopter. Ice ridges in region V were studied on fast ice, and ice ridges in region VI were studied both on drifting ice (2007) and fast ice (2010).

Considering that, from a practical point of view, ice ridges with the largest average CL thickness are of particular interest, the purpose of this study is to identify the morphometric qualities that characterize such ice ridges and to consider the factors that determine the development of a heavy CL.

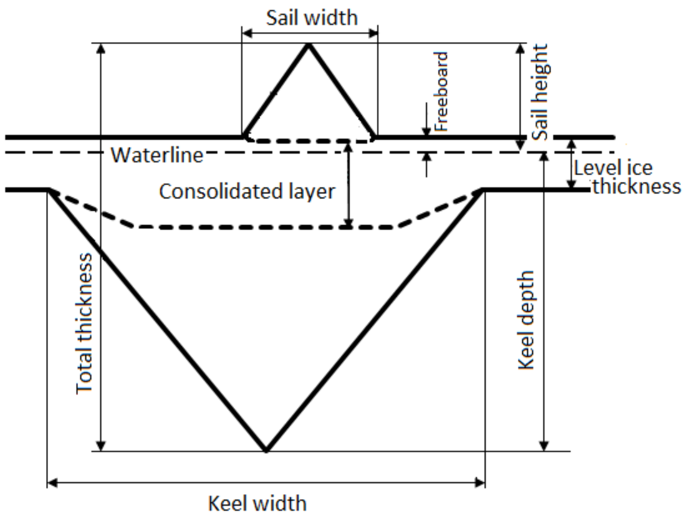

Figure 1. Diagram of an ice ridge cross-section

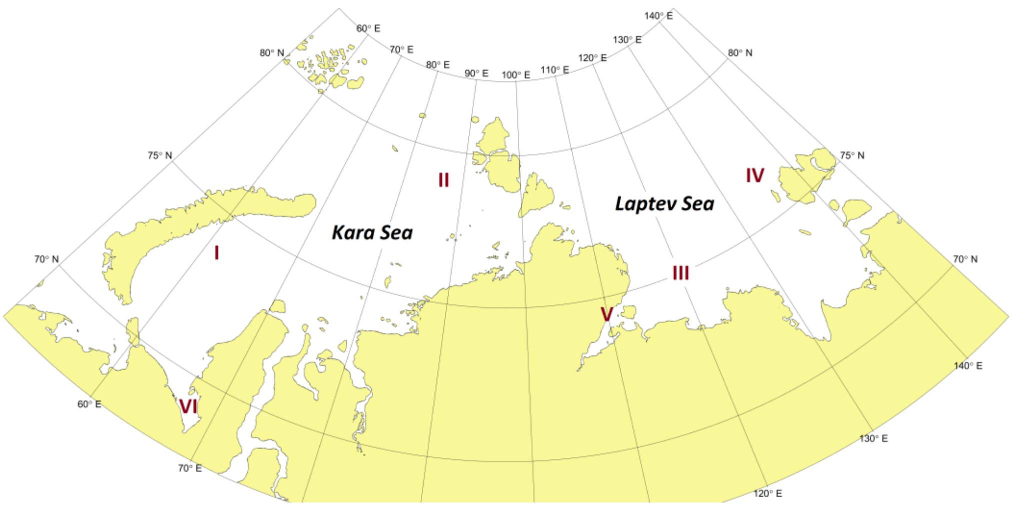

Figure 2. Study regions: I – southwestern Kara Sea, II – northeastern Kara Sea, III – southwestern Laptev Sea, IV – northeastern Laptev Sea, V – Khatanga Bay (with N ordvik and Anabar Bays), and VI – Baydarata Bay

RESEARCH METHOD AND DATA VOLUME

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 (Morev et al., 2000) is the main method for studying the morphometry and internal structure of large ice features. This technology has two modifications: electric drilling and water drilling. In the first case, ice melting occurs due to an electrically heated drill bit, in the second - with the help of heated seawater. Both modifications have the key principle in common - the depth and speed of the drill's immersion in ice with a step of several millimeters are automatically recorded to the logger. The drill operator controls if the recording is correct with the help of a marked cable (for electric drilling) or a hose (for water drilling) - at certain moments corresponding to the immersion of the marks on the cable (or hose) into the borehole, the drill operator presses the special button, making a mark in the record. These marks during the analysis of the record were compared with the automatically recorded values of the drilling depth. The average error did not exceed 1%. The processing of the obtained records makes it possible, with an accuracy of 1 cm, to identify the boundaries of voids and ice of different densities for each borehole. With the help of a special electronic probe, the excess of ice over the waterline in the borehole is determined. After identifying the internal structure in each borehole, the CL is selected on the drilling profile using a special algorithm. Electric drilling is a more mobile option than water drilling, which requires fairly heavy equipment. However, water thermal drilling provides significantly higher productivity, therefore, over the past decade, if logistic conditions permit, this modification has been used more often. In more detail, the particularities of the application of the water drilling technology with speed recording are described in (Guzenko et al., 2019). The data used in this article were obtained through both electric drilling (2007-2010, ice ridges of Baydarata Bay, region VI) and water drilling (2014-2017, ice ridges of regions I-V). Simultaneously with drilling, the parameters of ice blocks (length, width, thickness, and shape) were measured on ice ridges. Since 2014, total station survey was used to study the morphometry of the ice ridge sails, and underwater remotely operated vehicle and sonar were used to study the keels. The ice ridges were drilled on cross-sections (on average, there were 3 profiles per ridge), laid perpendicular to the crest. Drilling on the profiles was carried out with a step of 5 and 2.5 m. On the undeformed area closest to the ridge, polygons were located to measure the thickness of the level ice.

Table 1 shows the amount of data on the investigated first-year ice ridges in 2007-2017. A total of 5121 boreholes were drilled at 394 profiles. On average, 40 drills were carried out on each ice ridge. Some of the boreholes belonged to level ice since they tried to start and finish drilling on undeformed ice to cover the entire width of the ridge if possible. About one-third of ice ridges were investigated on fast ice. In general, about twice as many measurements were made on drift ice as on fast ice. With respect to the seas, the number of studied ice ridges was similar: 64 ice ridges in the Kara Sea, 65 ice ridges in the Laptev Sea. The largest number of ice ridges (28) was studied in the southwest of the Kara Sea, and the largest number of boreholes was drilled in the Khatanga Bay. The smallest number of the studied ice ridges (11) and the performed drilling (448) refers to the northeast of the Kara Sea.

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
VI	2007, 2010	25	68	677
Drift ice	2007, 2014, 2015	88	269	3409
Fast ice	2010, 2017	41	125	1712
Total	2007-2017	129	394	5121

Roman numerals designate regions similar to Fig. 2.

PARTICULARITIES OF DEVELOPMENT OF THE CONSOLIDATED LAYER

Basic morphometric characteristics of ice ridges

Table 2 shows the basic morphometric characteristics by regions and years of study. The arithmetic means of the mean or maximum values of the morphometric parameters of individual ridges for the corresponding samples are given.

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

Regions	Year of study (number of ridges)	Ridge length, m	Sail height of the max values, m	Sail height by all sail 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	CL thickness, m	Block thickness, m	Level ice, m
I	2014 (15)	86	2.73	1.64	12.0	8.98	5.12	44.5	10.72	5.70	1.54	0.46	0,85
	2015 (13)	109	3.07	1.72	10.0	9.40	4.88	43.0	11.32	5.62	1.32	0.52	0.94
II	2014 (7)	86	3.46	2.02	15.1	11.91	6.21	45.1	13.76	7.07	1.91	0.72	1.45
	2015 (4)	116	3.96	2.30	16.0	12.74	6.80	78.0	15.21	7.63	2.18	0.63	1.38
III	2014 (14)	78	2.76	1.64	10.9	9.56	5.52	48.7	11.32	6.16	2.16	0.49	0.98
	2015 (9)	90	2.86	1.47	9.0	8.90	5.21	40.2	10.86	5.79	2.05	0.43	0.99
IV	2014 (12)	90	2.67	1.69	9.9	8.50	4.76	45.1	10.33	5.27	2.28	0.50	0.97
	2015 (8)	97	3.82	1.94	12.0	11.44	5.92	48.9	13.27	6.68	2.50	0.50	1.44
V	**2017 (22)**	**72**	**2.38**	**1.25**	**10.2**	**7.18**	**4.33**	**40.8**	**8.98**	**4.85**	**2.51**	**0.36**	**1.76**
VI	2007 (6)	75	2.27	0.96	21.9	9.42	5.66	42.8	10.79	6.25	1.71	0.37	0.91
	2010 (19)	**57**	**3.63**	**1.90**	**14.9**	**12.27**	**8.69**	**38.0**	**14.38**	**9.81**	**2.70**	**0.45**	**1.40**
Tot. (129) avg		82	2.97	1.64	12.2	9.66	5.69	44.3	11.53	6.40	2.13	0.47	1.22
Tot. max		230	5.43	3.15	41	21.67	12.92	112	25.91	14.28	4.00	1.00	2.24
Tot. min		24	1.43	0.63	4	3.47	1.98	14	3.68	1.90	0.64	0.16	0.47
Drift (88) avg		91	2.97	1.68	12.1	9.72	5.38	46.5	11.55	6.04	1.92	0.51	1.05
Fast (41) avg		65	2.96	1.55	12.4	9.54	6.35	39.5	11.48	7.15	2.59	0.40	1.59

Roman numerals designate regions similar to Fig. 2. The rows with the data of ridges on the fast ice are highlighted.

According to most of the averaged morphometric parameters – the average crest length (116 m), average (2.3 m) and maximum (4 m) sail height, maximum depth (12.7 m) and average keel width (78 m), maximum total thickness (15.2 m) – the largest ridges were investigated in the northeast of the Kara Sea (region II) in 2015. Quite large ridges were investigated in the same region in 2014 (these ice ridges had the largest average block thickness - 0.72 m), in the northeast of the Laptev Sea (IV) in 2015, and Baydarata Bay (VI) in 2010. The ice ridges of the Baydarata Bay in 2010 are distinguished by the highest average keel depth (8.7 m), total thickness (9.8 m), and CL thickness (2.7 m), but the smallest average value of the crest length (57 m). In the northeast of the Kara Sea, the maximum values of sail height (5.4 m) in 2015, keel depth (21.7 m), and total thickness (25.9 m) in 2014 were recorded. The ridges studied in Khatanga Bay (V) and Baydarata Bay in 2007 are the least large in terms of most morphometric parameters. The ice ridges of Khatanga Bay are characterized by the smallest average and maximum values of the keel depth and total thickness, the smallest average block thickness (0.36 m), but the largest average thickness of the surrounding level ice (1.76 m), and the second-largest average CL thickness (2.51 m). The ice ridges of the Baydarata Bay, investigated in 2007, are distinguished by the smallest average (1 m) and maximum (2.3 m) sail heights, but the largest average sail width (22 m). The smallest average sail width (9 m) and keel width (40 m) were recorded on ridges in the southwest of the Laptev Sea (III) in 2015. The ice ridges of the southwest of the Kara Sea (region I) correspond to the smallest CL thickness (1.3 m in 2015) and the surrounding level ice (0.85 m in 2014). The table also shows the average values for a combined sample and separately for the samples of ridges on drift ice and fast ice. According to the data in the table, the main morphometric differences between fast ice and drift ice ridges are as follows: ice ridges on drift ice have significantly longer crests (1.4 times), and ice ridges on fast ice noticeably exceed the average CL thickness (1.4 times) and surrounding level ice (in 1.5 times). If fast ice ridges are located in relatively shallow water, then it can be seen in small values of the keel depth and, accordingly, total thickness, as in the ice ridges of Khatanga Bay, where the prevailing depths were 8-10 m. The limiting influence of the bottom did not affect the morphometry of the fast ridges of the Baydarata Bay (2010) - the depths in the region of their study, as a rule, exceeded 15 m.

Distribution of the thickness of the ice ridges CL

Figure 3 shows the distributions of the CL thickness over points on the drift ice ridges (3025 values) and over points on fast ridges (1396 values). The red lines in the histograms indicate the curves of theoretical laws that most closely approximate empirical data. For each sample, an approximation by four two-parameter distributions (normal, log-normal, Weibull, gamma distribution) was considered. 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 (Guzenko et al., 2020 b). Both empirical distributions are best approximated by the gamma distribution. The maximum recorded value of the CL thickness at the point was 8.08 m on the drift ridges (maximum at the point of the fast ridges was 6.54 m). According to the points on the drift ice ridges, the average value of the CL thickness was 1.98 m (the standard deviation σ=1.02 m), and 2.6 m along the points of fast ridges (σ=0.7 m). The highest repeatability of CL thicknesses on drift ridges ranged 1-2 m, and on fast ice – ranged 2-3 m. Histograms of the distribution of average values of CL thickness over ridges over the entire sample (129 ridges) and samples along drift (88 ridges) and fast ridges (41 ridges) can be seen in Fig. 4. In general, ridges on fast ice, in comparison with drift ridges, correspond to a more heavy CL with a smaller total spread of thicknesses.

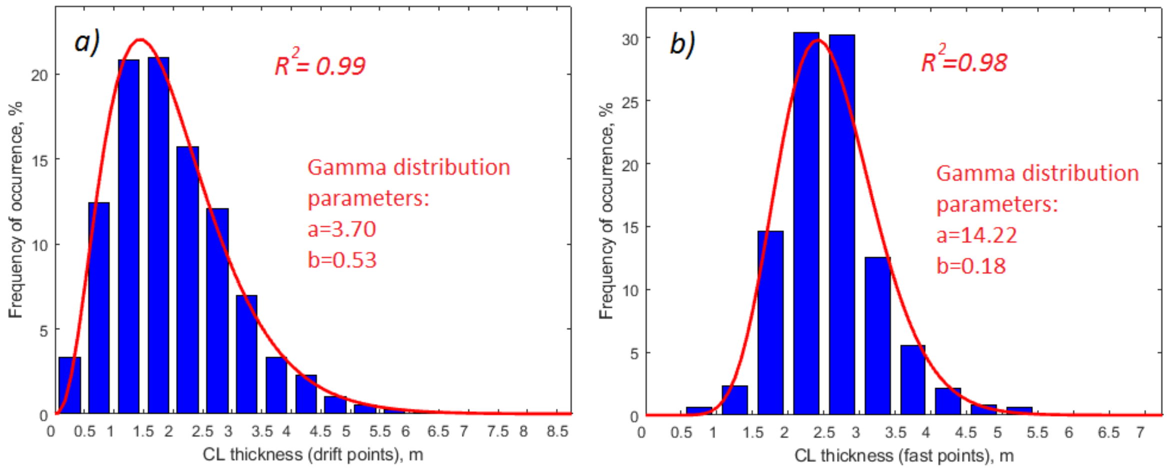

Figure 3. The distribution of the CL thickness over points on drift ice ridges (a), and over points on fast ice ridges (b)

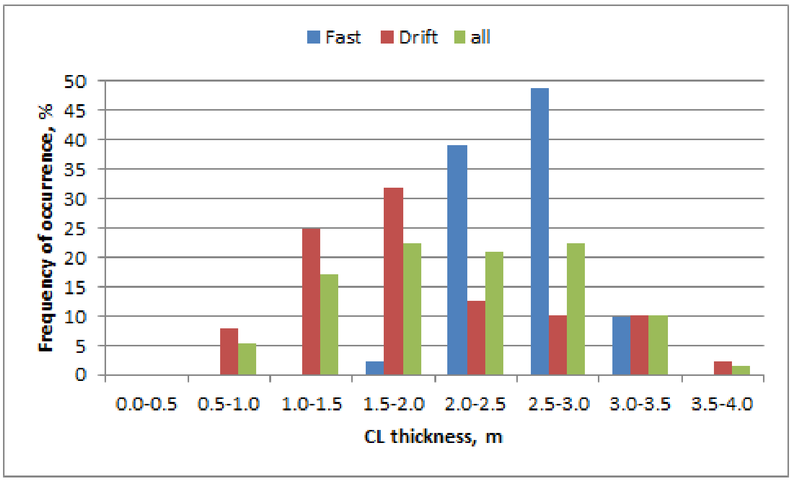

Figure 4. Distribution of CL thickness by average values on ice ridges

Relationship between the thickness of the ice ridge CL and the temperature regime of the region

The CL thickness of ice ridges depends on regional particularities associated, first of all, with the temperature regime of the local region. The influence of heat fluxes from water on the morphometric characteristics of ridges is not taken into account in this study, although for some condisions the influence of this factor may be significant (Marchenko, 2018). The relationship between the region-averaged CL thicknesses with the sums of freezing degree-days (FDD) calculated from the data of polar stations was previously considered for regions I-V without taking into account the age of ice ridges (Guzenko et al., 2020 a). In this work, we attempted to estimate the average age of the ice ridges in the region, starting from the average values of the level ice thickness and the thickness of the blocks. In (Mironov and Porubaev, 2019) it is noted that to determine the age of the ice ridge, it is better to use not the average, but the modal value of the block thickness since the latter characteristic better reflects the thickness of the ice floe at the moment of ridge-building. The relationship between ice thickness (H, cm) and FDD was determined by the classical formula of Zubov (1945):

$$H^2 + 50H = 8FDD \qquad (1)$$

First, using formula (1), the date of ice floe formation was determined from the average thickness of level ice and the data on the air temperature from the polar station. Then, using the same formula, the average date for the formation of ice ridges was determined from the modal value of the thickness of the ice ridge blocks. The difference between the dates of the middle of the study period and the date of formation of ice ridges in the region corresponds to the average age of ice ridges. This methodology involves several assumptions. First, the FDD is calculated based on data from one polar station closest to the study region. This approach is more valid for fast ice ridges, whereas ice floes with drift ice ridges by the time of the study could have time to visit regions with different temperature conditions. Estimation of the age of ice ridges using meteorological re-analysis and drift reconstruction is described in (Bonath et al., 2018). The second assumption is that the blocks that make up the sail originated from level ice near the crest on which the measurements were made. It is known that ice ridges are often formed from the interaction of two ice floes of different thicknesses, and the blocks that form the sail, in the overwhelming majority, are fragments of a thinner ice floe. And since measurements on the level ice polygon near the ice ridge were carried out only on one side of the crest, it is difficult to say with certainty that these measurements characterize a thinner ice floe, the fragments of which formed the ridge sail. The third assumption comes down to the fact that we operate not with the parameters of individual ice ridges, but with the average values for the region, obtained as a result of averaging these parameters. Table 3 shows the results of our calculations for the study regions. We can see that more often (in 5 cases) ice ridges formed on drift ice in February, twice in January, and once at the end of December and the beginning of March. The average age of ice ridges on drift ice at the time of the study was 3.3 months. Ice ridges on fast ice formed in November and December; at the time of the study, they were about 5.5 months old. Apparently, the large age of the fast ice ridges, first of all, explains their large average CL thickness.

In Baydarata Bay (region VI), the region of study of ice ridges on drift ice in 2007 was located near the region of work on fast ice in 2010. The average date of the study of ice ridges in 2010 was 12 days later. The meteorological conditions of 2006/2007 winter were classified as mild and 2009/2010 winter was classified as moderate. However, such a serious difference (about 1 m) in the average values of the CL thickness of the ice ridges for two years is primarily since the estimated average age of the ice ridges in 2007 was 2 months less than that of the ice ridges in 2010. The fast ice region of Khatanga Bay (V) is geographically adjacent to the study region on drift ice in the southwest of the Laptev Sea (III). Even though the time of the study of ice ridges in region III fell on average one month later, the average age of ice ridges in this region over 2 years at the time of the study was more than 2.5 months less than that of fast ice ridges in region V. As a result, the superiority of ice ridges of the Khatanga Bay in the average CL thickness and the relative CL thickness (the ratio of the CL thickness to the total thickness), which was 55% for fast ice ridges in region V and 36% for drift ice ridges in region III.

Table 3. Average age of ice ridges by study region

Regions, polar station	Year of study (number of ridges)	Date S	Level ice, m	Block thickness (mode),m	Date F	Age of ridges, mos.	FDD from date F to date S	CL thick.,m	k
I, Popov (Bely Is.)	2014 (15)	18.04	0.85	0.41	18.02.14	2	986	1.54	0.049
	2015 (13)	19.04	0.94	0.41	03.02.15	2.5	1255	1.32	0.038
II,Golomyanny Is.	2014 (7)	05.05	1.45	0.63	31.12.13	4.2	2670	1.91	0.037
	2015 (4)	03.06	1.38	0.45	11.01.15	4.7	2740	2.18	0.042
III, Ust-Olenyok	2014 (14)	16.05	0.98	0.48	20.02.14	2.8	1435	2.16	0.057
	2015 (9)	27.05	0.99	0.44	25.02.14	3	1624	2.05	0.050
IV, Kotelny Is.	2014 (12)	23.05	0.97	0.45	2.03.14	2.7	1352	2.28	0.062
	2015 (8)	10.05	1.44	0.51	10.01.14	4	2898	2.50	0.046
V, Khastyr	**2017 (22)**	**24.04**	**1.76**	**0.31**	**10.11.16**	**5.5**	**4241**	**2.51**	**0.039**
VI, Marresale	2007 (6)	16.05	0.91	0.26	05.02.07	3.4	1375	1.71	0.046
	2010 (19)	**28.05**	**1.40**	**0.38**	**15.12.09**	**5.4**	**2925**	**2.70**	**0.050**

Roman numerals designate regions similar to Fig. 2. Date S is the date of the middle of the study; Date F is the date of the ridge formation; k is the ratio of CL thickness to the square root of FDD from date F to date S. The rows with the data of ice ridges on the fast ice are highlighted.

Beketsky et al. (1996) noted that the size of the consolidated part of the ice ridges being in the fast ice for a long time, can be from 50 to 60% of the total thickness of the ice ridges. This leads to an increase in the design load from the impact of such an ice ridge on the legs of ice-resistant platforms. Thus, the authors conclude, fast ice ridges and stamukhas are considered very important objects of research. The paper (Mironov et al., 2019) provides drift data for 5 stamukhas in the fast ice region of the southwest of the Laptev Sea according to satellite buoys in 2017. In the summer months, after the fast ice breaks up, as a result of sea level fluctuations, the stamukhas get afloat and begin to drift. The maximum recorded drift speed of the stamukha was 102 cm/s, the average speed was 29 cm/s. The daily distance covered by the drifting stamukha reached 57 km, and the weekly distance is 284 km. The recorded duration of the stamukha drift reached 30 days. Obviously, fast ice ridges have no less potential mobility, and a high degree of their consolidation allows them to pose a threat to the marine infrastructure for a long time.

In (Guzenko et al., 2020 a) FDD were calculated from the date of a stable transition of air temperature through 0 degrees in a specific region. The result of this connection was an estimate of the average CL thickness in the region during the period of maximum development of the ice cover without estimating the age of the ice ridges. Here we propose the dependence of the thickness of the ice ridge CL on the FDD, taking into account the estimate of the age of the ice ridges in the regions, given in Table 3. Traditionally, the formulas connecting the ice thickness (H) and the air temperature are based on Stefan's law and represent the dependence of the form:

$$H = k\sqrt{FDD} \quad (2)$$

Here, k is the empirical coefficient, which we obtained for each region as the ratio of the average CL thickness to the square root of FDD, calculated from the average date of ice ridge formation to the middle of the period of their study. The k-values are given in the rightmost column of Tab. 3. The average k value by the region was 0.047. Timco and Goodrich (1988) proposed an expression relating the CL thickness (H_{CL}) in cm to the sum of degree hours. If their expression is normalized to meters and FDD, then it will be as follows:

$$H_{CL} = 0.029\sqrt{FDD} \quad (3)$$

Leppäranta and Hakala (1992) suggest the expression:

$$H_{CL} = a\sqrt{\frac{FDD}{p}} \ , \quad (4)$$

where a is a semi-empirical coefficient, usually ranging 0.02-0.025 m (ºC day)$^{-1/2}$, p is the porosity of the rubble in fractions of a unit.

If we substitute the average porosity value rubble p = 0.28 into formula (4), then the value of the coefficient k connecting H_{CL} and the square root of the FDD, depending on the value of a, will be in the range 0.038-0.047. The maximum limit of values of this range (at a = 0.025) corresponds to the value of k obtained by us on the average over the regions.

Relationship between the CL thickness and the external parameters of ice ridges

According to the data of 129 ridges, it was not possible to reveal a noticeable correlation between the average CL thickness and other morphometric parameters of the ice ridges. A moderate positive correlation was recorded between the CL thickness and the freeboard (0.36), the average total thickness (0.36), and the average keel depth (0.35). For a sample of drift ice ridges, the largest correlation values of the CL thickness were with the average total thickness (0.38), average values of the sail height, freeboard, keel depth (0.37 each), maximum sail height (0.35), and average block thickness (0.32). According to a sample of fast ice ridges, the highest correlation was recorded between the CL thickness and the average thickness of blocks (0.51). The relatively low values of the correlation coefficients are understandable: the CL thickness is primarily determined by the thermal conditions and the duration of their impact (the age of the ridge), and the external morphometric parameters are mainly associated with the dynamic processes and ice thickness at the moment of formation of the ridge. However, the positive values of the correlation between the CL and all the external parameters of ridges in different samples indicate a general trend.

Table 4. Morphometric characteristics of ice ridges averaged over gradations of CL thickness

Regions (number of ridges)	Ranges of CL thickness, m	Number of ridges	CL thickness, m	Sail height of the max values, m	Sail height by all sail points, m	Freeboard, 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	Ridge length, m	Block thickness, m
I (28)	< 1	3	0.82	2.36	1.31	0.54	10	6.33	3.27	30	8.26	3.79	**112**	0.35
	1-1.5	13	1.26	2.83	1.70	0.54	9	9.18	4.85	40	11.11	5.56	89	0.50
	1.5-2	10	1.74	2.95	1.67	0.67	13	9.51	5.42	51	10.97	5.95	104	0.50
	2-2.5	2	2,04	**3.68**	**2.04**	**1.02**	**15**	**11.62**	**6.59**	**52**	**14.43**	**7.75**	85	**0.56**
II (11)	1-1.5	1*												
	1.5-2	5+	1.70	3.54	2.11	0.79	13	**12.38**	6.31	51	**14.43**	7.10	81	0.65
	2-2.5	4+	2.38	**3.75**	**2.13**	**0.92**	**18**	12.01	**6.56**	**65**	14.11	**7.48**	**116**	**0.73**
	2.5-3	1*												
III (23)	< 1	2	0.97	2.34	1.38	0.41	7	7.73	2.93	33	8.19	3.34	59	0.49
	1-1.5	5	1.33	2.37	1.28	0.40	8	7.40	4.33	39	9.05	4.73	74	0.40
	1.5-2	4	1.61	2.69	1.41	0.60	12	9.12	5.30	56	11.68	5.91	65	0.32
	2-2.5	5	2.43	2.75	1.52	0.64	11	9.30	5.45	**58**	10.93	6.09	101	0.52
	2.5-3	2	2.55	2.89	1.90	0.52	6	8.86	4.66	39	10.29	5.18	**120**	0.55
	> 3	5	3.27	**3.51**	**2.00**	**0.95**	**14**	**12.15**	**7.76**	39	**14.52**	**8.70**	82	**0.59**
IV (20)	< 1	2	0.71	2.27	1.40	0.42	11	7.96	4.15	49	9.74	4.56	45	0.30
	1-1.5	1*												
	1.5-2	5+	1.66	2.60	1.57	0.40	8	8.48	4.16	33	10.24	4.56	93	0.39
	2-2.5	-												
	2.5-3	6	2.68	3.33	1.76	0.66	11	**11.18**	5.72	45	**12.46**	6.38	92	0.58
	> 3	6	3.31	**3.75**	**2.18**	**0.84**	**14**	9.94	**6.15**	**61**	12.42	**6.99**	**110**	**0.59**
V (22)	1.5-2	1*												
	2-2.5	9+	2,32	2.28	1.23	0.51	**12**	6.85	4.17	38	8.87	4.68	64	0.31
	2.5-3	12	2.66	**2.46**	**1.26**	**0.52**	9	**7.45**	**4.46**	**43**	**9.07**	**4.98**	**79**	**0.39**
VI (25)	1-1.5	2	1.25	***2.72***	***1.03***	***0.66***	**23.75**	9.07	5.17	41.25	***11.79***	5.83	62.50	***0.47***
	1.5-2	4	1.94	2.05	0.92	0.56	21.04	***9.60***	***5.90***	**43.54**	10.28	***6.46***	**81.25**	0.34
	2-2.5	7	2.36	3.58	1.79	1.12	13.93	11.96	8.68	34.52	13.93	9.80	57.14	0.41
	2.5-3	8	2.71	3.64	1.88	1.11	***16.41***	12.26	**8.77**	39.38	14.50	**9.87**	***58.00***	0.45
	> 3	4	3.26	**3.70**	**2.11**	**1.16**	13.54	**12.81**	8.56	***41.46***	**14.92**	9.72	53.75	**0.52**

Roman numerals designate regions similar to Fig. 2; Freeboard is the average elevation of the ice ridge above the waterline, including the sail area; * the data of a single ice ridge are assigned to the neighboring gradation marked with +. The maximum values for the region are highlighted. For region VI, the maximums by year are shown in italics (2 top rows - 2007, 3 bottom rows - 2010).

Table 4 shows the basic morphometric characteristics by 6 regions, averaged over the gradations of the average CL thickness. Averaging was carried out when at least two ice ridges fell within the gradation. If only one ice ridge fell into any gradation, then for averaging it was joined to the ridges of the nearest gradation (such cases are marked in the table with footnotes). As you can see from the Table, the largest CL thickness gradation for all six regions corresponds to the highest sail heights (maximum and averaged over the crest), freeboard, which includes both the sail area and the area outside of the sail, as well as the largest values of the thickness of the sail blocks. In five regions out of six, the largest gradation of the CL thickness corresponds to the largest values of the average keel depth and the average total ice thickness. The highest values for the maximum keel, maximum total thickness, sail, and keel widths are in the highest CL gradations in four out of the six regions. And only the largest values of the ice ridge length correspond to the largest gradation of the CL thickness in half of the cases. In general, we can see a general pattern: ice ridges with the largest CL thickness, as a rule, are characterized by the largest dimensions.

In (Beketsky et al., 1997), an expression is proposed for the ice ridges of the Sea of Okhotsk, which connects the CL thickness with the maximum sail height (H_s):

$$H_{CL} = 1.15H_S \tag{5}$$

Apparently, the studied ice ridges of the Sea of Okhotsk had a relatively heavy CL and a small sail. In our case, the coefficient expressing the ratio of the average CL thickness to the maximum sail height is on average 0.77 (0.69 - for drifting, 0.94 - for fast ridges), and the maximum value in the regions (1.09) corresponds to fast ridges of Khatanga Bay. But the direct relationship between the CL thickness and the parameter of the external morphometry of the ice ridge, expressed in formula (5) is more important than quantitative estimates. Our data, given in Table 4, give reason to believe that this pattern is typical not only for the Sea of Okhotsk. Except for the first two rows for region VI, corresponding to the ice ridges of 2007 in the Baydarata Bay, in all regions we can see an increase in the maximum sail height with an increase in the average CL thickness. And given that, other external parameters of the ice ridge (keel depth, sail and keel width, total thickness, block sizes) are traditionally associated with the sail height in the form of direct linear or power-law dependences, it is not surprising that the general pattern in most cases also manifests itself for them, too.

CONCLUSIONS

Based on the results of the analysis of the CL thickness of 129 first-year ice ridges in the Kara and Laptev seas, the following conclusions can be drawn.

From the point of view of determining the maximum ice load made by ice ridge, the ice features located in the fast ice deserve priority attention. The age and, accordingly, the thickness of the fast ice ridges, as a rule, is significantly greater than that of the ridges studied on drift ice at the same time in the same or nearby region. After the landfast ice breaks up, ice ridges can drift over long distances, and their high degree of consolidation allows them to maintain their solidity for a long time.

The dependence of the average thickness of the ice ridge CL on the temperature conditions of the region is shown, taking into account the estimate of the average age of the ice ridges. The average value of the empirical coefficient showing the ratio of the CL thickness to the square root of the FDD was 0.047.

The general regularity of the relationship between the CL thickness and the parameters of the external morphometry of ice ridges within a particular region is manifested in a direct relationship: ice ridges with the heaviest CL, as a rule, have the largest external dimensions. Revealing and clarifying the relationships between external morphometric parameters, on the one hand, and characteristics of the internal structure of ice ridges, on the other hand, deserves to be the subject of future research.

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REFERENCES

Astafiev, V.N., Surkov, G.A., Truskov, P.A.,1997. *Hummocks and stamukhas of the Okhotsk Sea*. Progress-Pogoda: St.Petersburg.

Beketsky, S.P., Astafiev, V.N. and Truskov, P.A., 1996. Structure of Hummocks Offshore of Northern Sakhalin, *Proceedings of the 6th International Offshore and Polar Engineering Conference*, Los Angeles, USA, May 26-31, 1996, Vol. II, pp. 398-400.

Beketsky, S.P., Astafiev, V.N., Truskov, P.A., 1997. Design Parameters for Hummocks and Grounded Hummocks in the Sea of Okhotsk. Proceedings 7th International Offshore and Polar Engineering Conference, Honolulu, USA, May 25-30,1997, II, pp. 487-493.

Bonath, V., Petrich, C., Sand, B., Fransson, L., Cwirzen, A., 2018. Morphology, internal structure, and formation of ice ridges in the sea around Svalbard, *Cold Regions Science and Technology*, 155, pp. 263-279. https://doi.org/10.1016/j.coldregions.2018.08.011

Guzenko, R.B. et al., 2019. Morphometry and Internal Structure of Ice Ridges in the Kara and Laptev Seas, *Proc. 29th Int. Ocean and Polar Engineering Conf.*, Honolulu, HI, USA, ISOPE, 1, pp. 647–654.

Guzenko, R.B., Mironov, Y.U., May, R.I., Porubaev, V.S., Kharitonov, V.V., Khotchenkov, S.V., Kornishin, K.A., Efimov, Y.O., Tarasov, P.A., 2020. Morphometry and Internal Structure of Ice Ridges in the Kara and Laptev Seas, *International Journal of Offshore and Polar Engineering*, 30, 2, pp. 194–201. https://doi.org/10.17736/ijope.2020.jc784

Guzenko, R.B. et al., 2020. Regional Differences and General Patterns of Ice Ridges Morphometric Characteristics Distribution in the Kara and Laptev Seas, *Proc. of the 30th Int. Ocean and Polar Engineering Conf.*, Shanghai, China, ISOPE, pp. 789-795.

Frederking, R., Timco, G.W., Kamesaki, K., Tada, H., 1999. Review of first-year ridge geometries and properties in Sakhalin region. *Proc. of the Int. Workshop on Rational Evaluation of Ice Forces on Structures*, Mombetsu, Japan, February 2-4, 1999, pp. 21-33.

Leppäranta, M. and Hakala, R., 1992. The Structure and Strength of First-year Ice Ridges in the Baltic Sea, *Cold Regions Science and Technology*, 20(3), pp. 295–311. https://doi.org/10.1016/0165-232X(92)90036-T.

Marchenko, A., 2018. Influence of the Water Temperature on Thermodynamic Consolidation of Ice Rubble. *Proc. 24th IAHR Int. Symposium on Ice*, Vladivostok, Russia, 2018, pp. 53-61.

Mironov, Y.U., Guzenko, R.B., Porubaev, V.S., Kharitonov, V.V., Khotchenkov, S.V., Nesterov, A.V., Kornishin, K.A., Efimov, Y.O., 2019. Morphometric Parameters of

Stamukhas in the Laptev Sea. *International Journal of Offshore and Polar Engineering*, 29, 4, pp. 383–390; https://doi.org/10.17736/ijope.2019.jc771

Mironov, Y.U., Porubaev, V.S., 2019. Estimation of the age of ice hummocks in the freezing seas. *Ice and Snow*, 59 (3), 355–362. https://doi.org/10.15356/2076-6734-2019-3-385.

Morev, V.A, Morev, A.V, and Kharitonov, V.V, 2000. *Method of Determination of the Structure of Ice Ridges and Stamukhi, Ice Properties and Ice and Soil Boundaries*, Patent No 2153070, Russia, issued July 20, 2000.

Sudom, D. & Timco, G., 2013. Knowledge Gaps in Sea Ice Ridge Properties. *Proc. of the 22nd Int. Conference on Port and Ocean Engineering under Arctic Conditions*, Espoo, Finland, POAC, 11 pp.

Timco, G. & Goodrich, L., 1988. Ice Rubble Consolidation. *Proc Int. Assoc. Hydraul. Res. Ice Symp*., Sapporo, Japan, IAHR, I, pp. 427–438.

Zubov, N.N., 1945. *L'dy Arktiki (Arctic Ice)*. Izdatel'stvo Glavsevmorputi: Moscow.