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CRYOGENIC PHENOMENA IN SEAS AND OCEANS

ON THE DIFFERENCES BETWEEN DRIFTING ICE RIDGES AND ICE RIDGES IN THE LANDFAST ICE

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The analysis of differences in the structure of drifting ice ridges and ice ridges in the landfast ice was carried out on the basis of information obtained during research work done by the Arctic and Antarctic Research Institute in 2007–2019 in the Kara and Laptev seas. The studies were carried out using thermal water drilling with logger recording of the penetration rate. The main attention was focused on the distribution of ice ridge porosity and the thickness of the consolidated layer. The unconsolidated part of the ice ridge keel and its compaction in the process of ice ridge formation under the action of the Archimedes force were considered. It was revealed that the ice ridges in the landfast ice differed from drifting ice ridges in their somewhat smaller geometric dimensions, but in steeper sail and keel slopes, as well as in a different keel/sail ratio (3.1 versus 3.6). In the landfast ice ridges, the porosity of the unconsolidated part of the keel was lower than in drifting ice ridges (by 6% on average). It was confirmed that the gradual decrease in the porosity of the unconsolidated part of the keel of the ice ridges in the landfast ice was caused by the under-ice currents.

Keywords: *ice ridge, drifting ice, landfast ice, thermal drilling, sail, keel, consolidated layer, porosity.*

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INTRODUCTION

According to the nomenclature of the World Meteorological Organization [*WMO..., 1970–2017*], landfast ice is a type of sea ice that forms and remains motionless along a coast, where it is attached to a coastline, to an ice wall or an ice barrier between shallows and icebergs grounded on the shallow sea floor.

It may form naturally from salt water or by adfreezing to the coast or to the already existing floating landfast ice of any age range. It can extend to a distance of only a few meters or to several hundred kilometers from the coast. The term drifting ice is used in a broad sense and includes any kind of ice, except for the motionless landfast ice.

An ice ridge is a chaotic pile-up of ice blocks, which occur in a sail under the force of gravity, and in a keel under the force of gravity and Archimedes' force. The ice ridges are the intrinsic part of the ice cover of the Earth's polar regions and are subdivided into drifting and motionless (landfast) types. In terms of the formation, the drifting ice ridges and the landfast ice ridges are almost the same, because in both cases they are the result of the ice piling up during compression of ice floes. At the initial stage of the ice ridge development, the pile-up of ice blocks is formed, and most of them become submerged in the water. This leads to strong local thermal gradients between the cold ice blocks and the surrounding water. Therefore, at the initial point of time, the vertical distribution of the temperature in the ice ridge keel will look like a sawtooth line with "teeth" unequal in height and shape. As the consolidated layer (CL)* grows, the sawtooth line will transform into the piecewise linear line, which, later, will be smoothed and deviated towards low temperatures in the upper part of the keel.

The end of the initial phase of the ice ridge formation can be defined as the moment, when the unconsolidated keel becomes isothermal and comes to the state of thermodynamic equilibrium. The initial phase of the ice ridge life is rather short (16–96 h [*Høyland, Liferov, 2005*]) and proceeds equally for both drifting ice ridges and ice ridges in landfast ice. Then the main phase begins, and the breakpoint on the temperature profile, located between the sloping section in the CL and the isothermal section (in the unconsolidated keel), determines position of the CL lower boundary [*Høyland, 2002*].

The consolidated layer isolates the underlying keel from cold air. This results in continuous degrada-

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* A consolidated layer of the ice ridge is a layer of dense (solid) ice with an upper boundary near a waterline. This layer is formed by the action of cold and water freezing in the space between blocks of ridged ice. It includes these blocks and is characterized by the strength close to that of level ice.

tion of the unconsolidated keel and leads to the transformation of the ice ridge into the second-year ice ridge or to the melting/decay of the ice ridge. At this stage, the living conditions of the ice ridges are already different, because under-ice currents strongly affect the keel of the ice ridges in landfast ice. Drifting ice ridges move (in the absence of wind load) directly under the action of currents. Therefore, the relative movement of water masses and keels of the drifting ice ridges is insignificant or absent at all.

The purpose of this work is to discuss the results of the comparative analysis of the main morphometric characteristics and the internal structure of the drifting ice ridges and the ice ridges in landfast ice. Our study is based on data obtained during the works of the Arctic and Antarctic Research Institute in 2007–2019 in the Kara and Laptev seas.

The work [*Guzenko et al., 2021*] is one of the recent works on this topic in the studied region. Morphometry of the ice ridges in the Spitsbergen fjords, in the central part of the Barents Sea, and in the Fram Strait was considered in the works [*Strub-Klein, Høyland, 2011; Sand et al., 2013*]. Much attention was paid to the impact of ocean currents on keel erosion. It was noted that small ice ridges in landfast ice are more affected by keel erosion than large ice ridges. The currently accepted theory considering the flow through consolidated layers states that up to 20% of the boundary flow falling on the keel can seep through it [*Amundrud et al., 2006*]. The extremely interesting results, which are not yet confirmed by other researchers, are given in [*Shestov, Marchenko, 2014*]. These data indicate that inside the unconsolidated part of the keel, a velocity of sea water flows in voids can be up to three times higher than the flow velocity under the level ice surrounding the ice ridge. Subsequent studies [S*hestov, Marchenko, 2016a,b*] give reasons for the ice growing and decreasing macroporosity of the unconsolidated keel over time owing to the keel permeability for seawater and changes in water salinity.

METHODS

The ice ridge structure was studied with the use of thermal water drilling with logger recording of the penetration rate. The description, scheme, and technical characteristics of the system are given in [*Mironov et al., 2003*]. The drilling was generally carried out along the profiles routed across the ice ridge crest. The distance from the top of the snow cover (ice) to the sea level was additionally measured at each drilling point. The morphometric characteristics of the ice ridges and their internal structure were determined on the basis of the subsequent processing of the rates of a thermal drill [*Morev et al., 2000*]. The penetration rate depends on the thermal power supplied to the thermal drill as well as on ice porosity and (to a small extent) on ice temperature. Therefore, the location of voids, consolidated and unconsolidated ice in the borehole sections was determined directly from the drilling rate. The movement of the thermal drill is dramatically accelerated in the areas of porous ice (especially in voids filled with snow, slush, water, or air). The necessary condition for validity of the determination of voids is the drilling at the constant thermal power (if thermal power is not constant, accurate registration of the changes in the power during drilling is required). The values of the above-water and underwater parts of the ice cover, CL boundaries of the ice ridges, boundaries of voids, and zones of ice with different porosity were determined during the subsequent processing of the obtained thermal drilling data.

An important characteristic of the internal structure of ice ridges is their porosity. K. Høyland [*2002*] distinguishes two levels of this parameter: macroporosity and total porosity. The macroporosity is defined as the ratio of the volume of voids in the selected area of the ice ridge to the total volume of this area. The total porosity also includes the porosity of the level ice, from which the ice ridge is composed. In other words, the total porosity also includes micropores located directly in ice blocks. The boundaries and sizes of the voids are recorded on the basis of the thermal drilling rate. In this work, the porosity θ is defined as the following value:

$\theta(x, y, z) = 0$, with ice in the point with coordinates (x, y, z),

$\theta(x, y, z) = 1$, without ice.

The linear porosity is obtained by averaging this function vertically, over the given depth interval, while the volumetric porosity is obtained by averaging over the given volume. The distribution of porosity by depth at each drilling point is determined by the step function, where zero corresponds to ice and unity corresponds to void. Air bubbles and cells with brine in the ice blocks are not taken into consideration. It is impossible to determine the volumetric porosity in detail by the point drilling due to the complicated internal structure of the ice ridge.

However, it can be estimated using the obtained distributions of the linear porosity at different points. It is believed that the volumetric porosity is equal to the average value of the infinite number of linear (in this case, vertical) porosities. Currently, it is considered that the volumetric porosity of the ice ridge corresponds to the averaged values of its linear porosity [*Høyland, 2002*].

When calculating ice loads on hydraulic structures, an ice ridge is often considered as a special case of loose medium with the wide range of fractions [*Alekseev et al., 2001; Bolgov et al., 2007*]. Consolidation of the loose medium under gravity was considered in [*Oleinikov, Skachkov, 2011*]; the proposed models were compared with experimental data on

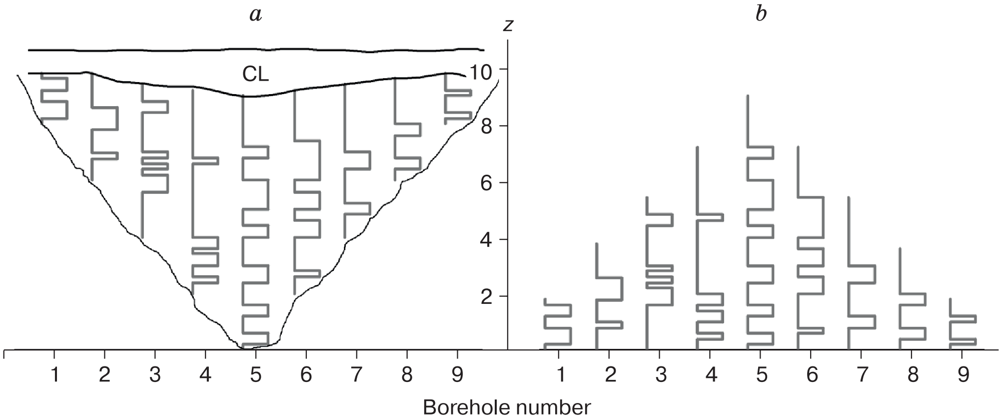

Fig. 1. The distribution of porosity of the unconsolidated part of the keel of the ice ridge in individual boreholes (*a*) and in the case of the shift to the depth of the maximum keel draft (*b*).

CL – consolidated layer; *z* – distance from the lower edge of the keel.

rocks and snow. According to the model [*Oleinikov, Skachkov, 2011*], the decrease in porosity of the loose medium with depth occurs due to an increase in pressure. The authors believe that the similar process may be quite important at the initial stage of the ice ridge formation. Thus, the possible manifestations of the process were given in more detail.

According to these authors, the keel of the ice ridge can also be considered as the turned over pile of ice blocks, which, during the process of the ice ridge formation, may be affected by consolidation not only under the action of gravity but also under the action of the Archimedean force. In this case, the zone directly bordering the lower surface of the keel will be the zone, where compression stress is absent. With distance upward from the lower edge of the keel, the porosity will decrease under pressure of ice block piles. Due to the fact that the CL porosity, in most cases, is equal to zero, let us consider only the unconsolidated part of the ice ridge keels. To establish the nature of the porosity distribution of this part, we will average individual distributions of the unconsolidated keel porosity at all points of ice ridge drilling, grouping them according to regions. The averaging procedure will be as follows. In M.N. Skachkov's model, the loose medium is condensed in depth. The zero depth corresponds to the medium surface, and then it grows downward. In our case, the ice ridge keel is the turned over loose medium; therefore, the depth will grow upwards, and the zero depth now corresponds to the lower surface of the keel. Due to the fact that the bottom surface of the keel is not a plane, and all individual distributions of porosity are in different depth intervals, it is necessary to level them by depth before averaging. This can be done, for example, by shifting the distributions down to the depth of the maximum keel draft.

Figure 1 schematically demonstrates this process. The lines indicate the distributions of the unconsolidated keel porosities in individual boreholes. The height of the curves corresponds to the borehole length in the unconsolidated keel. After the levelling, all individual distributions at the depth of the maximum keel draft, it is necessary to consider all depths (from the maximum keel depth to the lower CL boundary) consistently and to average the step curves on the basis of those boreholes that exceed the considered horizon. Let us use this technique to assess possible differences in the distribution of porosity of the unconsolidated keel for the ice ridges formed on drifting ice and in landfast ice.

DISCUSSION

This work was based on the data obtained from the Sea of Okhotsk, the Kara Sea, and the Laptev Sea in 1998–2019. The drifting ice ridges studied in these seas were combined into one group. The second group included the ice ridges of Baidaratskaya Bay of the Kara Sea, Khatanga Bay of the Laptev Sea, and the ice ridges of Shokalsky Strait, which were in the landfast ice at the time of the study. We considered 134 drifting ice ridges and 56 ice ridges in the landfast ice. Table 1 demonstrates the main features of the ice ridges from the first and second groups.

In terms of morphometric parameters (size), the landfast ice ridges are slightly smaller than the drifting ice ridges. They have steeper slopes of the sail and keel; CL is significantly thicker, the ratio of the CL thickness to the average thickness of ice blocks in the sail is twice as large. The latter parameter is an indirect indicator of a more significant age of the ice ridges in the landfast ice, which was confirmed in [*Guzenko et al., 2021*]. A somewhat lower value of the keel/sail ratio for the ice ridges in the landfast ice (3.1 vs. 3.6 for drifting ice ridges) is probably due to more intensive thawing and subsequent decay of ice blocks at the lower edge of the keel.

Table 1. **Averaged characteristics of drifting ice ridges and ice ridges in the landfast ice**

Characteristics	Ice ridges	
	drifting	in landfast ice
Number of ice ridges	134	56
Average sail height, m	3.1	2.5
Average keel draft, m	11.0	7.6
Ratio keel/sail	3.6	3.1
Average CL thickness, m	1.9	2.5
Average porosity of the unconsolidated part of a sail	0.20	0.22
Average porosity of the unconsolidated part of a keel	0.27	0.21
Average vertical size of voids in a sail, m	0.24	0.14
Average vertical size of voids in a keel, m	0.39	0.20
Average ratio of CL thickness to the total ice thickness	0.32	0.54
Average thickness of ice blocks in the ice ridge sail, m	0.50	0.35
Average thickness of level ice nearby the ice ridge, m	1.2	1.7
Average ratio of CL thickness to the block thickness in the ice ridge sail	4.4	8.4
Average sail slope angle, degrees	26	33
Average keel slope angle, degrees	25	29

In [*Naumov et al., 2019*], the morphometric parameters of the Baidaratskaya Bay ice ridges, which were in the landfast ice at the time of the study, were considered and the results of the studies for the period 2005–2017 were summarized. According to these data, the average height of a sail in different years was 0.9–2.7 m, and keel draft was 4.4–8.0 m. These values agree well with the data from Table 1: 2.5-m-high sail and 7.6-m keel draft for ice ridges in the landfast ice. In reference to the CL thickness, the data from the paper do not clearly demonstrate the increased CL thickness in the landfast ice. The studies have been carried out for 10 years, and the range of the average CL thicknesses (1.5–2.4) is quite evenly distributed over the years of the study. The porosity of the unconsolidated part of the keel also varies in the wide range, from 0.13 to 0.44; however, the most frequent porosities range from 0.32 to 0.36, which is also much higher than the values in Table 1. The porosity value of 0.74 for 2013 reported in [*Naumov et al., 2019*] is probably a random value or a typing mistake. This value slightly reduces representativeness and confidence for the represented data.

Høyland's formula [*Høyland, 2002*] gives a straight correlation between the porosity of the unconsolidated part of the keel, the thickness of the ice surrounding the ice ridge, and the CL thickness. Assuming that the CL is absent at the moment of the ice ridge formation and its thickness is zero, the formula looks like

$$H_{CL} = \sqrt{\frac{H_{LI}^2 - H_{LI0}^2}{\theta_{\text{av}}}},$$

where H_{CL} is the CL thickness, m; H_{LI0}, H_{LI} are the ice thickness in the ridging moment and the thickness of the ice surrounding the ice ridge, respectively, m; θ_{av} is the average porosity of the unconsolidated part of the keel.

Taking the average thickness of ice blocks in the ice ridge sail as the ice thickness at the moment of ridging and using the data from Table 1, we can calculate the expected CL thickness of the drifting ice ridge. It turns out to be 2.01 m, which is close enough to the CL average thickness of 1.90 m from Table 1. At the same time, for the ice ridges in the landfast ice, the same calculation gives a significantly overestimated CL thickness equal to 3.65 m. The value of 2.4 m (Table 1) is obtained only if the value of 0.45 is taken as the porosity of the unconsolidated keel. Such porosity for fresh ice ridges in the landfast ice is unlikely, especially if we consider that the resulting porosity of the ice ridge sails in both groups is almost the same, 0.20 and 0.22 (Table 1). Therefore, it follows that the keel porosity of the fresh ice ridges should also be in the range of 0.24–0.30. In this case, theoretically, there should be a factor limiting the CL growth. According to [*Naumov et al., 2019*], the most important factor affecting the CL thickness is the presence of the significant snow cover. The thickness of the snow cover for the considered ice ridges in the landfast ice ranged from 0.2 to 0.8 m. The average thickness of the snow cover in the Khatanga Bay was about 0.3 m; in the Shokalsky Strait, it ranged within 0.2–0.8 m (although at some points it was up to 2.3 m). Therefore, the role of the snow cover in the CL growth for different types of ice ridges does not seem to be unambiguous. Alternatively, we can suggest that the slowing down of the consolidation of the landfast ice ridges is affected by the increased geothermal flux.

Figure 2 demonstrates the smoothed distributions of porosity of the unconsolidated keel for drifting ice ridges and for the ice ridges in the landfast ice. These data were obtained using the averaging procedure described above. Figure 2 also represents the relative amount of data averaged in this process. The smoothing was performed by moving average with 2-m width. The zero of the ordinate axis corresponds to the zero distance from the bottom edge of the keel. Line *5* shows the boundary distance, beyond which the number of averaged data does not exceed 5% of the total number. It can be seen that curve *1* of the porosity of ice ridges in the landfast ice at a distance of about 9 m is shifted towards the lower values in relation to the drifting ice ridges (curve *2*). Figure 2 also illustrates the difference in the values of the average porosity of the drifting ice ridges and the ice ridges in the landfast ice (curve *3*) in the most informative range. It follows that the porosity of the unconsolidated keel of the ice ridges in the landfast ice is, on average, 8.5% lower than that of the drifting ice ridges (at the maximum difference of 12.7%). The average porosity of the unconsolidated keel of the landfast ice ridges is 6% lower than that of the drifting ice ridges (Table 1). It should be taken into account that the average values of porosity are given for the entire thickness of the unconsolidated part of the keel, and the above value of 8.5% was obtained only for distances (from the lower edge of the keel) in the range of 2–8 m.

The obtained difference can be related to the size of the ice ridges. The rate of water filtration through a porous medium depends on the size of the pores, in our case, on the unconsolidated keel voids. The size of the voids depends on the size of ice blocks composing the keel. This was shown in [*Amundrud et al., 2006*]. Voids in the landfast ice ridges are smaller (Table 1); therefore, when the current affects the unconsolidated keel of such ice ridge, it turns out that under-ice water hardly penetrates inside the keel, but leads to melting of the keel from its external edge (generally, from the bottom of the ice ridge, where the current is stronger [*Schramm et al., 2000*]). Thus, macroporosity θ_{av} of the unconsolidated part of the keel of the landfast ice ridge decreases, because the most porous lower part thaws or is decayed due to erosion.

To verify this assumption, the computer simulation of decay of the lower parts of the keel under the action of the currents was additionally carried out.

The porosity distribution according to [*Oleinikov, Skachkov, 2011*] was simulated for 16 unconsolidated keels with 15-m draft each. Then, the lower parts of the keels, ranging in size from 0.3 to 4.5 m, were randomly removed. The remaining fragments of the porosity distributions were shifted and averaged using the procedure described above. As a result, the averaged porosity curve was shifted toward the lower values by about 10% at the maximum value, which agrees well with the difference in Fig. 2.

According to field observations, in the Shokalsky Strait (directly in the area of the studies of landfast ice ridges), there are daily tidal currents with the average velocity of 0.04 m/s at a depth of 10 m and the maximum velocity of 0.23 m/s [*Kharitonov, Borodkin, 2020*]. These data indirectly indicate that the main reason for the decreased porosity of the keels of the landfast ice ridges is the action of under-ice currents.

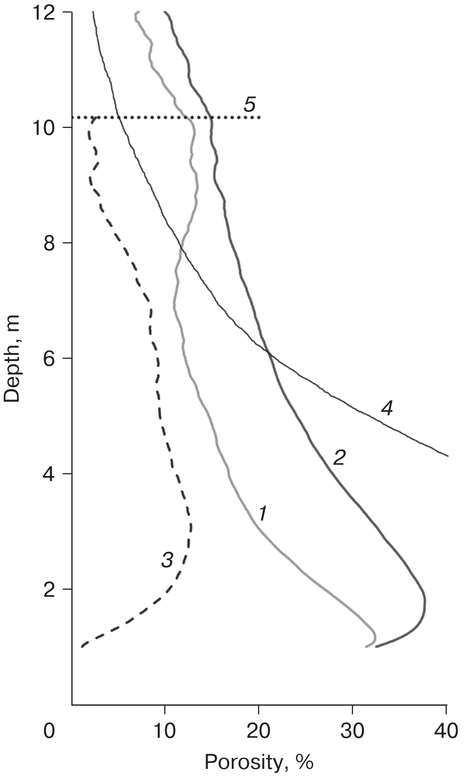

Fig. 2. The smoothed averaged porosity of the unconsolidated part of the keel of the drifting ice ridges and the ice ridges in landfast ice and the relative number of the averaged data.

1 – landfast ice; *2* – drifting ice; *3* – difference in values; *4* – relative number of the averaged values; *5* – the depth, above which the amount of the averaged data does not exceed 5% of the total.

In [*Shestov, Marchenko, 2016a,b*], the mathematic and laboratory simulations, as well as the results of in situ experiments were considered. These data confirm the impact of seawater penetrating into the ice ridge keels on the decrease in porosity of the unconsolidated part of the keel. The generalized porosity plots in Fig. 2 and the comparison of the average vertical sizes of voids in the sail and keel for the ice ridges of both groups (Table 1) support this effect.

The authors of [*Ervik et al., 2018*] note that macroporosity of the keel decreased during the period of staying under the conditions of heat transfer from the ocean to the atmosphere. This may be due to the double effect on the unconsolidated part of the keel from the above-described under-ice current and from the growth of the CL thickness due to its thermodynamic evolution. This is confirmed by the data of field measurements (Table 1), according to which the ice ridges in the landfast ice generally were formed earlier than the ice ridges on the drifting ice. This is indicated by the CL thickness and the size of ice blocks (i.e., a lower thickness of the level ice, from which the ice ridges were formed).

Therefore, the ice ridges in the landfast ice at the time of measurements (April–May) on average should be somewhat smaller in size (due to thawing the lower part of the keel) and should have lower porosity of the unconsolidated keel than the ice ridges on drifting ice.

CONCLUSIONS

After the analysis of the data, it is possible to draw the following conclusions:

– The ice ridges in the landfast ice differed from the drifting ice ridges in their smaller geometric size and the keel/sail ratio (3.1 vs. 3.6), but in steeper slopes of the sail and keel;

– The CL thickness of the studied drifting ice ridges on average was 1.9 m; for the ice ridges in the landfast ice, it was 2.5 m;

– The average degree of consolidation of the studied ice ridges, i.e., the ratio of CL thickness to the total ice thickness in ice ridges was 32% for the drifting ice ridges and 54% for ice ridges in the landfast ice;

– Porosity of the nonconsolidated part of the keel of the ice ridges in the landfast ice was on average 6% lower than that of the drifting ice ridges; in the keel zone, at distances less than 8 m from the keel edge, this difference averaged 8.5%;

– Our data confirm the conclusion by other researchers that macroporosity of the unconsolidated part of the ice ridge keel gradually decreases under the impact of under-ice currents.

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