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Evolution of internal structure of ice ridge investigated at «North Pole - 38» and «North Pole - 39» drifting stations

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ABSTRACT

The paper presents the investigation results of morphometric characteristics of an ice ridge conducted in May-June 2011 and in April 2012 at «North Pole - 38» and «North Pole - 39» drifting stations. These studies were conducted using electric thermal drilling with computer recording of the penetration rate. Boreholes were drilled along the cross-section of the ridge crest at 0.5 m intervals. Cross-sectional profiles of ice ridge as well depth-wise distributions of volume content of solid ice phase are illustrated. Structural changes of ice ridge occurred during the year from its first investigation are observed. As expected, due to the summer melting and sea currents, the keel depth of ice ridge decreased from 17.1 m to 13.9 m, the sail height of ice ridge decreased from 6.1 m to 3.8 m. Average thickness of consolidated layer of ice ridge increased from 2 to 2.4 m. Sail porosity decreased from 0.04 to 0.01, while keel porosity increased from 0.04 to 0.06 owing to the wash-out of small ice blocks from lateral keel edges.

INTRODUCTION

One of the key factors of the safety of structures and efficiency of marine operations is the impact of ice ridges. Special attention was given to their studies lately. Ice ridge is a hill-like chaotic conglomeration of broken sea/freshwater ice (afloat and partly or totally frozen) formed as a result of compression. Information about the structure of these ice formations acquires a great importance in connection with development of natural resources on the Arctic shelf including exploration and production of hydrocarbons.

The sources of such data are field observations on the evolution of ridged formations. A disadvantage of such studies is significant work duration, complexity of controlling various parameters such as air temperature, solar radiation intensity, etc.

Researchers of various countries have performed the study of consolidated layer (CL) growth of separately selected ice ridge (e.g. Hoyland and Loset, 1999; Gordienko, 2003). Observations of model ridges consolidation process were conducted during three months in the ice basin of the Arctic and Antarctic Research Institute (AARI). Complete consolidation of the ridge keel along with a rapid thawing of the keel parts lying below and most remote from the total ridge mass were recorded (Stepanov et al., 2004).

In 1991 all-winter monitoring of the structure and temperature of one sea ice ridge in the northern Baltic Sea was studied (Lepparanta et al., 1995). The ridge experienced substantial structural evolution: the consolidated layer grew, average porosity decreased, keel thickness decreased, and the ridge geometry became smoother. In spring the ice blocks throughout the keel beneath the consolidated layer melted uniformly.

Trisha Amundrud (2004) did an excellent review of the sources devoted this problem. She concluded that both ridging and ridge melt are found to be dependent on the geometric properties of ice pack. Floe size, keel shape, and internal keel geometries will influence the evolutions of ridged ice throughout the year.

This work presents information on annual evolution of the morphometric characteristics and internal structure of first-year ice ridge investigated in May-June 2011 and in April 2012 on «North Pole» drifting station by means of electric thermal drilling.

METHOD

Investigation of the structure of ice ridges carried out by means of electric thermal drilling device of AARI comprising electric thermodrill ETI-3M2 and equipment for penetration rate recording on a laptop. Power was supplied by a 5 kW generator. Schemes and detailed descriptions of the thermal drilling plants can be seen in the paper (Morev and Kharitonov, 2001). An example of recording the penetration rate of ice ridge drilling and reconstruction of its structure is presented in Fig. 1. Methods of determination of the hard ice, porous ice and void zones can be seen in the paper (Kharitonov, 2005).

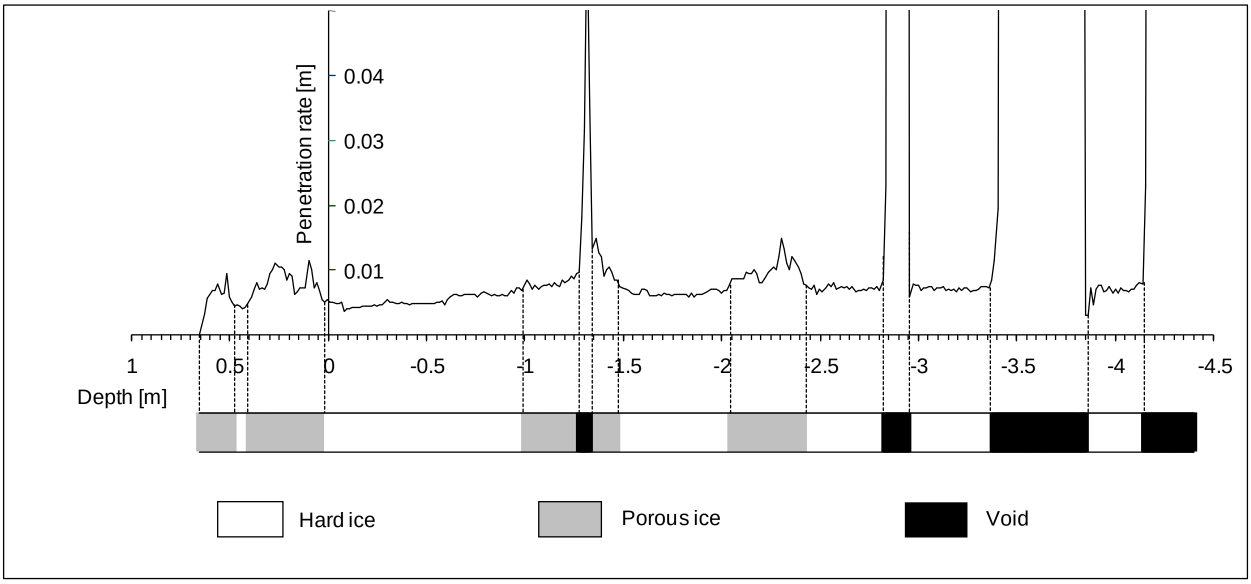

Figure 1. Example of thermal drilling record. A strip is drawn under the diagram schematically showing ice ridge structure at the drilling point. White colour shows areas along the borehole corresponding to hard ice; grey colour, areas corresponding to porous ice or drill transition from ice into void; and black colour, voids. Dotted lines show boundaries of these areas.

The ice ridge geometry and internal structure are identified by means of processing the thermal drilling records. This procedure is established and described in previous papers, for example (Morev and Kharitonov, 2001; Kharitonov, 2005). This technology is protected by patent of Russia No. 2153070 (Morev et al., 2000). The drilling rate depends on the power supply, ice porosity and ice temperature. The location of voids, hard and porous ice along the drilling hole is identified by the thermodrill penetration rate. The obligatory condition for this identification to be valid is drilling at constant thermal capacity or recording the changes of capacity during drilling. Within the segments of porous ice and, especially, the voids filled by snow, shuga or air, the penetration rate of thermodrill sharply increases. In addition, the distance from snow (ice) surface to the sea level is measured. The thermal drilling data processing gives such characteristics as the above-water and under-water parts of the ice cover, the boundaries of the consolidated layer (CL) of the ice ridge, the boundaries of the voids and the boundaries of ice layers of various porosities.

Boreholes were drilled in ice ridge at 0.5 m intervals in the present study.

RESULTS

In May-June 2011, when these studies were started, coordinates of «NP-38» drifting station changed from 80N, 177W to 81N, 171W. After the change of the team on October 1, 2011 the name of the drifting station was changed to «NP-39». In April 2012 coordinates of «NP-39» drifting station were 84N, 116W. First-year ice ridge was formed 22/03/2011 and investigated from 16/05/2011 to 22/06/2011 and from 8/04/2012 to 19/04/2012. All boreholes were drilled in ice ridge along the profile laid across the ridge crest at 0.5-m interval. 74 records of penetration rate at ice ridge were made in 2011 and 43 records - in 2012. In April 2012, exact location of the cutting line could not be found, so the new line was run in about the same place. Main morphometric characteristics of the ridge under consideration are demonstrated in Table 1.

Table 1. Basic characteristics of investigated ice ridge near the drifting station "NP-38"- "NP-39" (by records of electrical thermal drilling in 2011-2012).

	Coincident parts of cross-section	
	May-June 2011	April 2012
Maximum total ice thickness [m]	23.37	17.29
Average total ice thickness [m]	12.78	8.45
Maximum sail height [m]	6.10	3.83
Average sail height [m]	1.05	0.63
Maximum keel depth [m]	17.08	13.94
Average keel depth [m]	10.79	7.47
Estimation of average CL thickness [m]	2.0	2.4
Average level ice thickness nearby ice ridge [m]	1.7	1.7
Maximum snow thickness on the ice ridge [m]	3.06	1.08
Minimum snow thickness on the ice ridge [m]	0.23	0.09
Average snow thickness on the ice ridge [m]	0.98	0.66
Ratio of the maximum keel to maximum sail	2.8	3.6
Sail slope angle [degree]	43	32
Keel slope angle [degree]	47	44
Average sail porosity	0.04	0.01
Average keel porosity (including consolidated layer)	0.04	0.06
Average total porosity	0.04	0.05

According to the energy conservation law, the drill penetration rate V is inversely proportional to the volumetric content of the ice solid phase *VCI* (Kharitonov, 2008). Thus, constructing $1/V$ dependence on depth, we shall obtain the distribution of volume content of solid ice phase *VCI* with depth at each point of drilling. Drilling points were spaced at 0.5 m. Next, a grid based on multiple X and Z values is built, where X is an array of values of distance along the profile (linear coordinates of drilling points); and Z, an array of values of depth readings on records. On this grid, *VCI* surface is built; the colour of the surface nodes is assigned by *VCI* values. Dark colour corresponds to voids; white colour, hard ice. Intermediate grey colours correspond to porous ice. Linear colour interpolation between grid nodes is realised. Fig. 2 presents sections of investigated ice ridge constructed applying this procedure.

One can get acquainted with similar cross-sections of two other ridges in (Kharitonov, 2012).

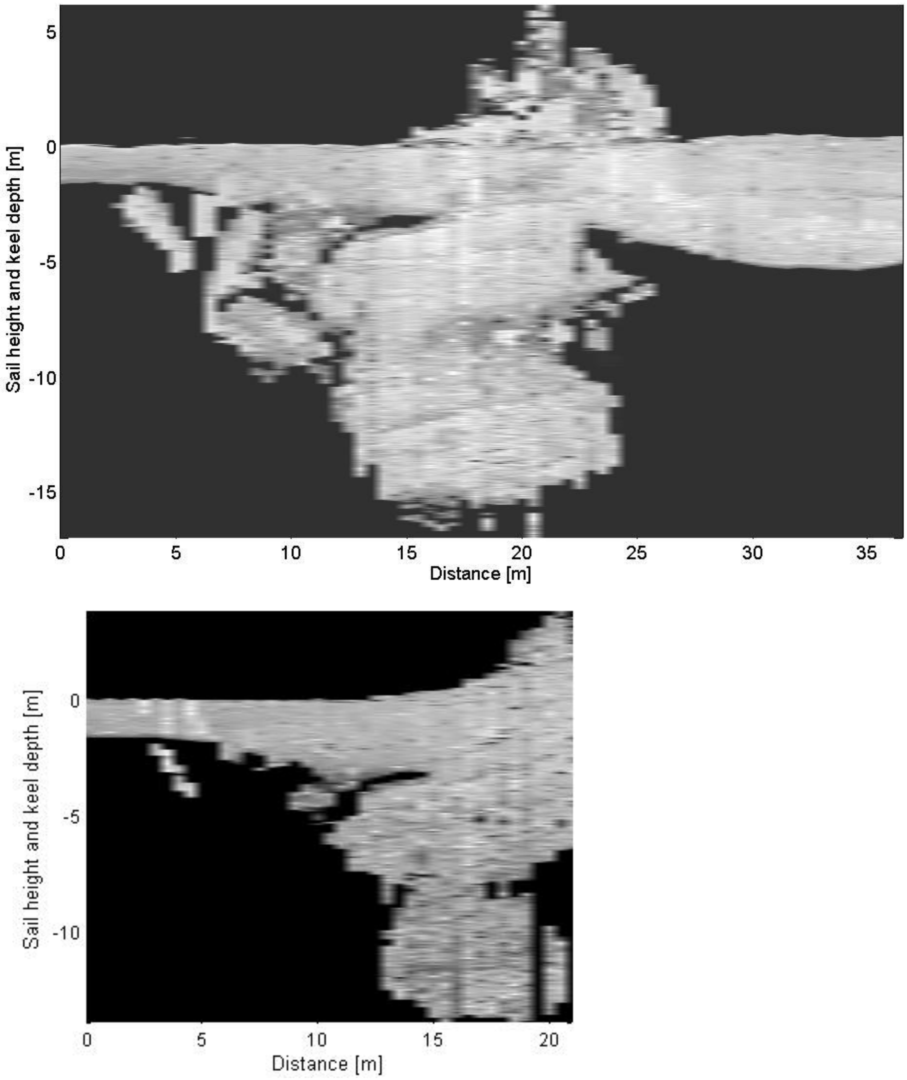

Figure 2. Resulting cross-sectional profiles of ice ridge. Upper plot shows the profile in May-June 2011; lower one is the profile in April 2012. Depth and distance scales are the same. In the right part of the upper plot there is a fragment of a multiyear ice ridge, at the edge of which ice ridge formed. Another two cross-sectional profiles are presented in (Kharitonov, 2012).

ANALYSIS

In July-August 2011, a puddle formed on level ice area left of the ridge sail. As a result of its freezing and under the action of subglacial currents level ice adjoining the left part of the ridge became much more level (distance 0...6 m, see Fig 2, the lower drawing). The upper left part of the ridge keel (distance 5...10 m) consisting of several blocks was also subject to thawing and destruction under the action of subglacial currents. One of the blocks, though it significantly diminished in size, remained in place, since, apparently, it was frozen into level ice with its upper part. The consolidated ridge layer (CL) became more pronounced especially at a distance of 7...14 m. Its thickness, on the average, increased by 0.4 m.

Ridge sail also changed: its thickness reduced by 40%, and porosity decreased from 4% to 1%.

Let us carefully consider the ridge keel area at a depth of 7...9 m and at a distance of 16...22 m. In Fig. 2 (upper drawing), this is a grey area with bright white and dark spots indicating that the area is filled with porous ice with individual blocks of hard ice and voids. Under the action of thawing and subglacial currents this keel area appeared to be «washed out» (see Fig. 2, lower drawing).

Having averaged *VCI* distributions for all the holes, it is possible to obtain the average distribution of the volumetric content of the solid phase versus depth for the ice ridge investigated. The averaging process is shown in detail in (Kharitonov, 2013). Fig. 3 shows two *VCI* distributions with depth for the investigated ice ridge. From the curves one can estimate a change in the internal structure of the ridge after a year.

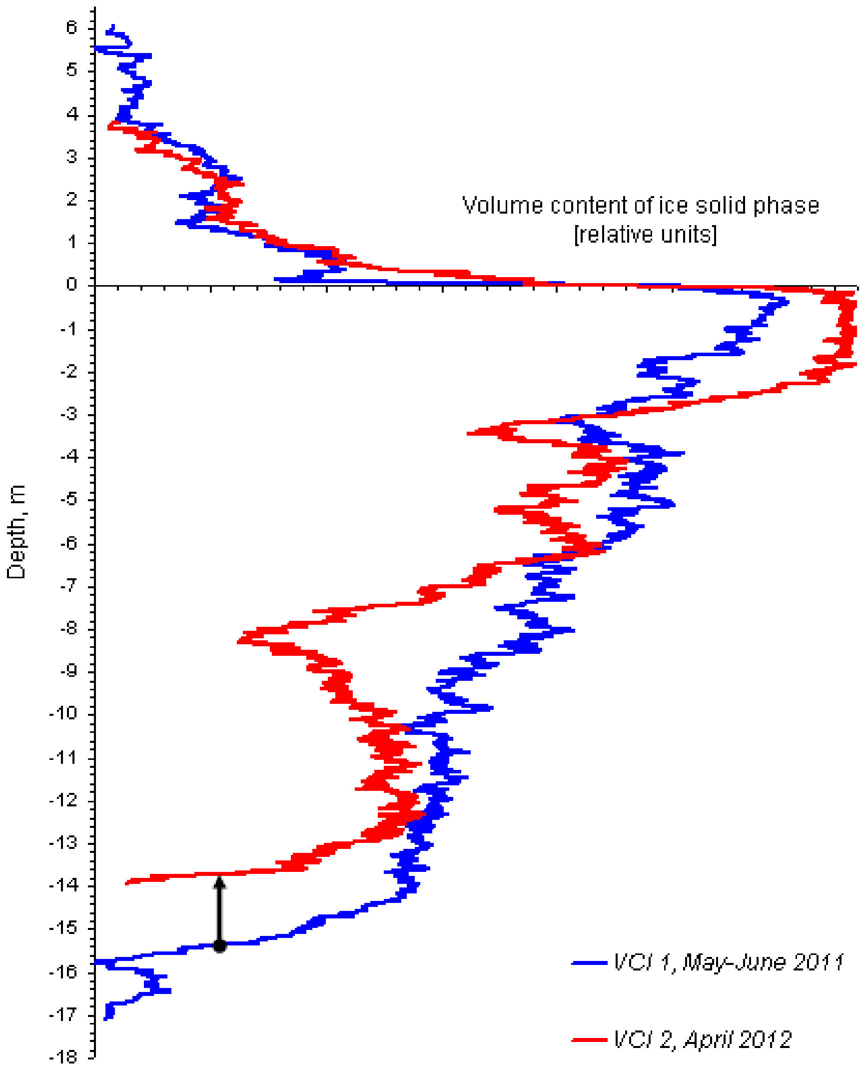

Figure 3. Depth-wise distributions of the volume content of solid phase of ice *VCI* of ice ridge. An arrow shows a change in the depth at which there is a sharp decrease in *VCI* associated with thawing of the lower large ice block in the ridge keel.

Analyzing the curves in Fig. 3 one can note the following changes in the ridge structure. In the sail area, *VCI* 2 curve is smoother unlike *VCI* 1 suggesting that the ridge sail becomes more homogeneous, the number and size of the voids diminish. A plateau on curve *VCI* 1 at the sea level points to a distinct upper boundary of the CL. A similar plateau on the *VCI* 2 curve looks less gentle pointing to a diffuse upper boundary of the CL. Apparently, in this case there is an effect of the sail porosity reduction in the area where it adjoins the CL. Some sail blocks as a result of summer thawing directly adjoin the CL thereby «raising» its upper boundary. The CL proper on the *VCI* 2 curve is distinguished more clearly, *VCI* in the depth range of –0.3…–1.7 m is virtually unchanged. *VCI* in the depth range of –2.3…–3.4 m resembles a straight line indicating that the distribution of the lower CL boundary is close to a uniform one. *VCI* 2 drop in the area of –8 m depths reflects the keel narrowing at this horizon.

The table shows that the maximum depth of the ridge keel decreased over the year by 3.2 m. An arrow in Fig. 3 shows a decrease in depth amounting to about 1.7 m, at which a marked decrease of *VCI* occurs. Hence, it can be concluded that thawing of the lower large keel block occurred by the value of 1.7 m, and the rest of the keel depth reduction 3.2–1.7=1.5 m was due to thawing and removal of small ice blocks. These blocks, which were on the lower edge of the keel, are clearly visible in the upper drawing of Fig. 2 at a depth of 15 m and at a distance of 15...21 m.

DISCUSSION AND CONCLUSIONS

StrubKlein et al. (2009) compared the morphometric characteristics of the first- and second-year ice ridges. According to their analysis, the ratio of the maximum keel to maximum sail calculated for the second-year ridges is two to three times higher than what Timco and Burden (1997) report. The erosion process may be faster in the air than in the water and so the sail height would decrease faster than the keel thickness (StrubKlein et al., 2009). In our case, this ratio also increased one year later. The ridge sail decreased by 37%, and the keel by only 18%.

As was expected, macroporosity of the ridge sail decreased from 4 to 1%. However, keel porosity increased from 4 to 6%. This unexpected result can be accounted for by the fact that small ice blocks on the lateral part of the keel appeared to be «washed-out» by subglacial currents.

The sail of the second-year ridges investigated by StrubKlein et al. (2009) was no more than 0.7 m, so the keels of some ridges were fully consolidated. The CL of our ridge increased during the year, on the average, from 2 to 2.4 m. CL thickness to total ridge thickness ratio increased from 9 to 14%, i.e., ridge consolidation proceeds rather slowly.

Distance-wise distribution of the CL thickness agrees well with the concept proposed by Tyshko K.P. of AARI (personal communication), according to which on edges of ice ridge sail, where the minimal (0.05-0.20 m) excess of ice above water level is observed, temperature gradient is stronger than inside the sail; and, therefore, CL thickness in these areas is greater.

As a result of the performed analysis the following conclusions can be drawn:

- Ridge sail decreased by 40%, its porosity diminished from 4% to 1%.
- Keel reduction by 3.2 m was partly due to thawing and removal of small ice blocks from its lower part (1.5 m) as well as due to thawing of the lower large block of ice keel (by 1.7 m).
- Washing out of small blocks from the lateral part of the ridge keel under the action of subglacial currents can slightly increase the average porosity of the ridge keel.
- Consolidated layer of the investigated ridge increased during the year, on the average, by 0.4 m. Thus, the consolidation rate of this ridge can be estimated at 5% a year.

The results presented in this paper are intended to be used as addition to previous investigation. Those parameters need to be reliable therefore one year is not sufficient. The investigations should go on for some more years. The data collection in the Central part of Arctic basin is getting consequent but more fieldworks have to be performed to confirm the results.

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