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Morphometry and Internal Structure of Stamukhas in the Ice-covered Seas of Russia

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Abstract—A method for studying stamukhas using the modern field equipment is considered. The peculiarities of morphometric characteristics and parameters of the internal structure of stamukhas are analyzed. The interrelation between the consolidated layer thickness and the accumulated freezing degree days is derived for different seas. The comparative analysis of morphometric characteristics and the consolidated layer in the ice-covered seas of Russia is carried out. It is shown that the formation of stamukhas in different regions has specific features depending on the depth, bottom topography, drift characteristics, ice thickness, and dates of fast ice formation. The maximum thickness of the consolidated layer is registered in the Kara and Laptev seas.

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INTRODUCTION

Stamukhas are hummocked grounded ice accumulations [34]. These are the typical forms of immobile ice on the shallow shelf of ice-covered seas. Usually, stamukhas are situated in the coastal areas at the depth to 20–25 m. There are both individual stamukhas and the chains and systems of stamukhas consisting of several objects. Stamukhas affect the stability of fast ice (being natural anchors) and the ice drift field structure, because ice fields change their drift directions after the collision with stamukhas.

During the winter-spring period, stamukhas located on the shipping routes are high-risk objects for ships and ice breakers, especially under conditions of poor visibility. The cases of emersion of stamukhas and their drift are possible under the significant surge and tidal sea-level fluctuations during the spring-summer period. Due to their great weight, stamukhas can affect hydraulic structures, which dictates a need in their consideration for ice load calculation [1, 18]. Besides, stamukhas can move for insignificant distances and can plough the bottom in winter under the influence of tidal currents. These negative phenomena should be taken into account when designing and laying pipelines along the bottom of shallow sea areas.

The first generalization of the studies of hummocks and stamukhas was made by N.N. Zubov [5], who divided the ice hummocking into three types depending on the origin: thermal, tidal, and wind-induced. The strongest hummocking is the wind-induced one, which reaches the maximum strength in case of winds blowing towards the shore or fast ice. Besides, N.N. Zubov distinguished three forms of hummocking: breaking hummocks, disintegration hummocks, and packed hummocks. The hummock ridge size depends on the relative velocity of ice field drift and on the mass of colliding ice floes. The monograph [5] shows that the prevalent boundary of stamukhas in the Arctic seas is the 20-m isobath. It is noted that stamukhas are stable bodies, and multiyear stamukhas are often registered; the maximum size of the stamukha sail is presented, which reaches 15–20 m in the eastern Arctic seas. It is shown that the ratio of the keel depth to the sail height is equal to 4 for hummocks and 2 (sometimes 1) for stamukhas.

Along with the field studies of hummocks and stamukhas, the mathematical modeling of ice ridge formation mechanisms was developed. For this purpose, the revealed regularities of the structure of the typical forms of hummocks, their spatial distribution, and data on the ratio of the keel depth to the sail height and on the ice ridge width were used. The authors of [26] proposed to divide the process of hummock formation as a result of compression into two stages. At the first stage, the hummock grows both in horizontal and vertical directions; at the second stage, when the critical values were reached, the hummock grows in horizontal direction only. The critical value depends on the thickness of ice blocks the ice ridge is composed of. The numerical calculations performed in [20] confirmed this hypothesis.

One of the approaches to the mathematical modeling of ice hummock formation was the discrete element method which allows presenting the drifting ice cover in the form of the set of the great number of ice floes with specified properties. The numerical solutions to the two-dimensional problems allowed obtaining the realistic forms of ice ridges and the distribution of ice blocks [20, 21].

The studies by A.V. Marchenko [8, 9] presented the description of the dynamic model of hummocking with the averaging scale of about 50–100 m, that is, typical of the width of ice ridges. The mesoscale models of hummocking are based on the mass, momentum, and energy conservation laws. These models simulate the movement of ice fields, the geometric parameters of ice ridges, and the stresses arising along the hummocking line. An important advancement of mesoscale models is their implementation in the large-scale ice cover models in order to take into account the hummocky ice bodies which occupy a significant part of the sea ice surface.

In the 20th century, the observations of stamukhas were mainly carried out during the aerial ice reconnaissance, when their number and coordinates were registered; the stamukha keel depth was indirectly determined from navigation charts. The summarization of aerial observations was performed in [4] for the Russian Arctic seas and in [3] for the northern Caspian Sea. The special field works on studying hummock and stamukha ridges and the instrumental measurements started only in the 1980s–2000s, when the investigation of the ice regime in local areas began for the purpose of development of hydrocarbon fields on the shelf of the ice-covered Russian seas. Originally, the complex studies of ice ridges were made on the shelf of Sakhalin [2, 32], later in the Pechora [7] and Caspian [11] seas, as well as on the shelf of the Kara and Laptev seas [6, 12, 16].

The objective of the present paper is the generalization of data on the morphometry and internal structure of stamukhas based on the thermal drilling and other modern methods, as well as their comparative analysis for different regions of the continental shelf of Russia. As the great volume of field data was generalized and analyzed, we might expect the revelation of new regularities and the extension of modern scientific concepts of the role of physical processes which determine the formation of stamukhas and their peculiarities.

DATA AND METHODS

The complex study of an ice body implies the use of several methods, which complement each other and allow obtaining the most objective pattern. The main methods for the determination of morphometric characteristics are the water thermal drilling with the record of drilling velocity to the computer or logger [13, 17], the tacheometric survey of the upper surface of an ice body, the sonar survey of the lower surface of an ice body, the video recording of the stamukha keel using the remotely operated underwater vehicle.

The tacheometric survey was carried out using the M3 DR Trimble Access electronic tacheometer at the drilling profile points, as well as in all the most significant fragments of the relief of the ice body upper surface.

The sonar survey of the lower surface of the ice body was performed using the Imagenex 881A all-round sonar equipped with the Azimuth Drive rotary drive and orientation module. The results of the sonar survey allow obtaining a three-dimensional image of the surfaces with the accuracy to several centimeters.

The video recording of the stamukha keel as well as the exploration of the bottom for exaration was performed using the Gnom remotely operated underwater vehicle. Usually the submersion of the underwater vehicle by turns with the sodar was carried out to the same mines. The data in Table 1 characterize the volume of stamukha studies performed by the Arctic and Antarctic Research Institute (AARI) using the modern measuring instruments in the recent 20 years in different areas of the ice-covered seas of Russia.

Table 1. The exploration of stamukhas by different methods in the Arctic and ice-covered seas

Sea	Area	Years	N	Thermal drilling	Tacheometry	All-round sonar	ROV
Caspian	Northern part	2001–2004, 2006, 2008	19	+			
Okhotsk	Sakhalin shelf	1998, 2006	3	+			
Kara	Baydarata Bay	2007, 2010	7	+			+
Laptev	Khatanga Bay	2017	16	+	+	+	+

Note: N is the number of investigated stamukhas; ROV is the remotely operated underwater vehicle.

Table 2. The morphometric parameters of stamukhas in the Caspian, Kara, and Laptev seas derived from the AARI winter expeditions and in the Barents and Okhotsk seas derived from literature sources

Parameter	Northern Caspian Sea	Baydarata Bay (Kara Sea)	Khatanga Bay (Laptev Sea)	Southeastern Barents Sea [14]	Northeastern shelf of Sakhalin [2]
n	996	279	517	–	–
Mean stamukha length, m	155	110	117	89	67
Mean sail width, m	47	33	35	32	36
Mean keel width, m					
near the surface	70	65	66	45	39
near the bottom	48	36	24	–	–
Sail height, m					
average maximum	5.2	4.6	6.1	8.1	6.4
maximum	10.0	6.5	14.5	16.0	10.6
Keel depth, m					
average maximum	4.0	6.9	8.2	10.5	10.8
maximum	6.6	8.7	10.3	16.3	15.9
Stamukha thickness, m					
average maximum	8.4	11.3	13.5	16.1	–
maximum	14.2	14.2	24.4	22.1	–
Keel-to-sail ratio	0.9	1.6	1.7	1.3	1.6

Note: n is the number of points of thermal drilling of stamukhas.

The ice studies in the Khatanga Bay of the Laptev Sea utilized almost all methods of studying stamukhas and hummocks [6].

MORPHOMETRIC PARAMETERS OF STAMUKHAS

The maximum and average maximum height of the stamukha sail calculated for each analyzed region was used in the present paper to characterize the stamukha sail. Similarly, the stamukha keel was characterized by the maximum and average maximum values of the stamukha keel depth. The keel-to-sail ratio was calculated using the maximum values of the keel and sail size for each stamukha, the mean value of this parameter for each area was obtained. The same characteristics were calculated for the thickness, length, and width of stamukhas. The length and width of the stamukha sail were obtained by direct measurements. The width of the sail for each stamukha, as well as the keel width near the water surface and the bottom, was specified during cameral data processing.

The parameters of stamukhas calculated from AARI field data and taken from the literature sources are presented in Table 2. In the northern Caspian Sea, the study area embraced almost the whole sea area covered with ice under light and medium ice conditions, which were registered during the seasons of field works. The local areas presented in the table were investigated in the other seas. There is a dash in some

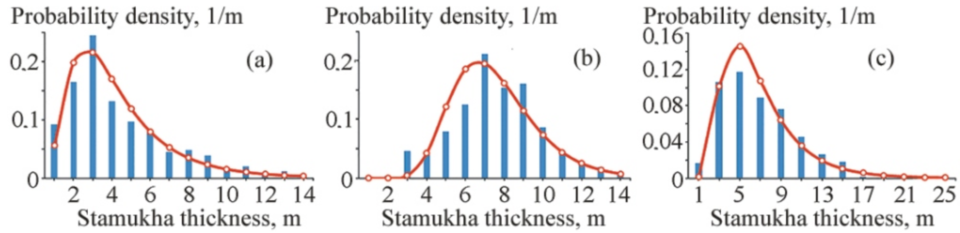

Fig. 1. The probability density distribution for the stamukha thickness in (a) the northern Caspian Sea, (b) Baydarata Bay (the Kara Sea), and (c) Khatanga Bay (the Laptev Sea). The histograms show empirical distributions, and the curves demonstrate the approximation by the lognormal distribution.

cells of the table, as data for the calculation of characteristics for this area are insufficient or absent in literature sources.

The analysis of the table data shows that the characteristics of stamukhas in the seas have essential differences. The length of stamukhas in the northern Caspian Sea exceeds that on the northeastern shelf of Sakhalin by more than twice.

The small horizontal size of stamukhas on the Sakhalin shelf and in the southeastern Barents Sea is largely determined by the features of bottom topography, which is characterized by a rather large depth (8–15 m) and rather short "banks." Usually, drifting hummocky ice is observed in these regions; the hummock keels touch the bottom at small depths, and ice fragments pile on the stationary ice body. However, in the case of high velocities of ice drift, the ice flow quickly goes around a stamukha formed, and fast ice is formed around it; therefore, the horizontal size of the stamukha does not subsequently increase.

The sail height, the keel depth, their ratio, and the thickness of stamukhas also have essential differences. The formation of stamukhas in different areas has specific features depending on a depth and bottom topography, drift characteristics and ice thickness, time of fast ice formation, and some other factors; these features cause differences in stamukha parameters. Such differences indicated a need in detailing data on the peculiarities of ice body parameters in the local areas when designing the engineering facilities.

In terms of the impact on the engineering facilities, important parameters are the keel depth and thickness of stamukhas. The thickness of stamukhas is, to some extent, an integral parameter, which largely determines the mass of stamukhas. The thicker a stamukha is, the great effect on the engineering structures it has under the same depth. According to instrumental data (Table 2), the maximum measured stamukha keel depth was equal to 16.3 m [14]. The authors of [2] note that the aerial observations on the Sakhalin shelf detected the stamukha at the depth of 20–25 m. Although aerial observations are not accurate enough, they demonstrate that stamukhas can be formed at the depth of >20 m.

There is a certain dependence of the sail height on the keel depth for stamukhas. At rather large depths (the Barents Sea, Sakhalin shelf), the values of the mean keel depth in the range of 10.5–10.8 m correspond to the mean values of the sail height within 6.4–8.1 m. At comparatively small depths (the Caspian Sea, the Baydarata Bay (the Kara Sea), and the Khatanga Bay (the Laptev Sea)), the mean keel depth in the range of 4.0–8.2 m correspond to the mean values of the sail height within 4.6–6.1 m.

The ratio of the maximum keel depth to the sail height is used to describe stamukhas. The data in Table 2 show that this ratio is equal to 0.9 for the Caspian Sea and is within 1.3–1.7 (the mean is 1.5) for the other regions. The small values of the keel-to-sail ratio are typical of stamukhas, the respective values for the hummock ridges are within 3.0–6.0.

The cameral processing revealed which drilling points characterize a stamukha, because some points could be drilled in level ice near its foot. The number of thermal drilling points related to a stamukha is given in Table 2. The great volume of data allowed calculating the empirical probability density of the stamukha thickness, which was approximated by the lognormal distribution (Fig. 1). The use of the theoretical distribution function allows computing rare stamukha thickness.

The highest frequency in the distribution of stamukha thickness in the Caspian Sea is observed for the range of 2.5–3.5 m, although the maximum value reaches 14 m. The highest frequency of stamukha thickness in the Baydarata Bay is registered for the range of 6.5–7.5 m (the maximum is 14 m). The

Table 3. The consolidated layer of stamukhas in the Caspian, Kara, Laptev, and Okhotsk seas derived from the AARI winter expeditions

Sea	Area	*N*	*n*	n_{CL}	H_{CL}, m
Caspian	Northern part	19	1066	368 (35)	0.40
Okhotsk	Sakhalin shelf	3	40	30 (75)	1.54
Kara	Baydarata Bay	7	398	398 (100)	2.07
Laptev	Khatanga Bay	16	515	515 (100)	2.49

Note: *N* is the number of explored stamukhas; *n* is the number of thermal drilling points with velocity records; n_{CL} is the number of points in the consolidated layer (the percentage of the total number of thermal drilling points is given in brackets); H_{CL} is the mean thickness of the consolidated layer.

stamukhas in the Khatanga Bay (the Laptev Sea) are characterized by the highest frequency of thickness in the range of 4.5–5.5 m and by the maximum (among the three analyzed regions) values of thickness equal to 25 m.

INTERNAL STRUCTURE OF STAMUKHAS

The consolidated layer is a key parameter of the internal structure and a major morphometric characteristic of large ice bodies. The basic load of large ice bodies on ships and offshore infrastructure facilities is associated with the consolidated layer [19].

The estimates of the distribution of the consolidated layer thickness (CLT) for stamukhas in different regions are based on the data obtained by the thermal drilling with the recording of drilling velocity to the electronic carrier. As a result of the analysis of drilling velocity, the internal structure of ice in each well with an accuracy of 1 cm is divided into three types of layers: solid ice, loose ice, and hollows. Then, the consolidated layer is identified using the drilling profile. This process occurs consecutively and includes two stages: using the formal algorithm and using the expert's correction [25].

Table 3 presents data on the consolidated layer of stamukhas in different regions and the mean values of its thickness. The table shows that the greatest number of wells was drilled in stamukhas in the northern Caspian Sea, where the studies were performed during six years. The consolidated layer in stamukhas in this region was not solid but had a form of separate lenses, and the points with a consolidated layer made up a bit more than a third of all wells drilled. The smallest number of wells with the recording of drilling velocity (40) was made in stamukhas on the Sakhalin shelf, and the consolidated layer was identified in 75% of them. The solid consolidated layer (in 100% of wells) was registered in stamukhas of the Arctic regions (the Baydarata Bay, the Kara Sea, and the Khatanga Bay (the Laptev Sea)). The minimum average CLT (0.4 m) was found in stamukhas in the Caspian Sea, and the maximum mean one (2.5 m) was registered in the Khatanga Bay.

Figure 2 presents the histograms of the CLT distribution for stamukhas in different seas, as well as the approximation of observational data by theoretical functions. The CLT histograms for stamukhas in the northern Caspian Sea and Baydarata Bay are better described by the lognormal distribution and those for stamukhas on the Sakhalin shelf and in the Khatanga Bay are better described with the Weibull distribution.

The CLT distribution for stamukhas in the Caspian Sea shows that the highest frequency (45%) is observed for the range of 0.2–0.4 m, although the maximum value reaches 2.8 m. Stamukhas in the Okhotsk and Kara seas have the highest frequency of CLT in the range of 1.5–2 m; however, the mean and maximum CLT is greater in the Kara Sea stamukhas. The highest values of CLT (the mean and maximum) among all analyzed regions were obtained for stamukhas in the Khatanga Bay, their maximum frequency (31%) corresponds to the CLT range of 2.5–3 m.

The evolution of the consolidated layer in an ice body is caused by various physical processes. The authors of [10] distinguished three main processes: the atmospheric cooling, the penetration of fresher water inside the keel, and the cooling due to the initial cold storage in the inundated ice blocks. The most significant of them are the first two processes. The authors of [10] propose a one-dimensional model of consolidation of hummocky ice bodies under the influence of atmospheric cooling at the top and the heat flux from the ocean to the hummock base. It is noted that the consolidation of hummock keels is accompanied by their melting from below and is explained by the inflow and subsequent freezing of

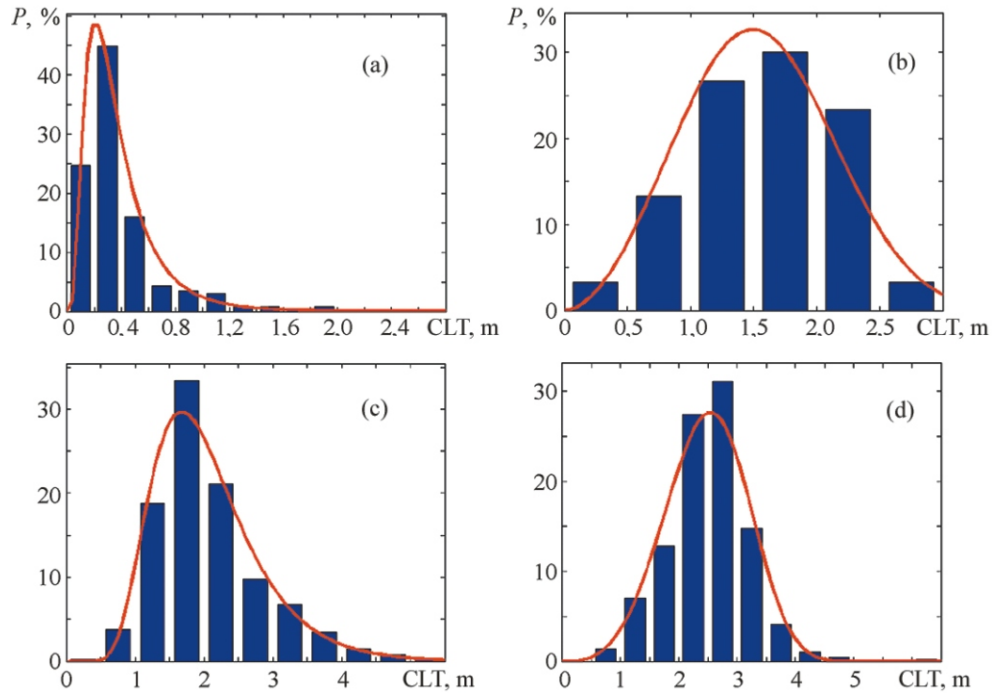

Fig. 2. The distribution of the thickness of the consolidated layer of stamukhas in (a) the Caspian, (b) Okhotsk, (c) Kara, and (d) Laptev seas. The red lines are the approximations by theoretical distributions: (a, c) lognormal and (b, d) Weibull distributions.

meltwater inside the unconsolidated parts of keels. The authors of [28, 29] described the results of model simulations and laboratory experiments on the revelation of relationships between the physical parameters of ice and sea water and the consolidation process. The paper [27] deals with the estimation of the effect of ocean heat fluxes on the hummock keel melting and consolidated layer evolution.

The process of consolidation of stamukhas during the melting was first described in [5] as follows: "Meltwater flowing down and freezing when touching internal cold parts of stamukhas makes them one. The water masses thrown on stamukhas by waves play the same role. The sun and water destruct stamukhas but this is mainly about their shape. Their internal structure strengthens." Later different authors [22, 23] noted an essential contribution of melting to the consolidation of ice bodies; however, these phenomena were especially related to summer processes in old hummocks. The authors of [22] described a model of the hummock consolidation, which is based on the Stefan law and represents a simple analytic dependence connecting CLT with the thickness of surrounding level ice with account of ice body porosity:

$$H^2_{\mathrm{CL}}(t) \quad H^2_{\mathrm{CL},0} \quad \frac{H^2_{\mathrm{i}}(t) \quad H^2_{\mathrm{i},0}}{}. \tag{1}$$

In (1), $H_{\mathrm{CL}}(t)$ and $H_{\mathrm{i}}(t)$ are the thickness of the consolidated layer and level ice at the end of the calculation period; $H_{\mathrm{CL},0}$ and $H_{\mathrm{i},0}$ are the thickness of the consolidated layer and level ice at the initial moment (at the previous calculation step); is the porosity of the unconsolidated part of the hummock.

In general, the CLT growth intensity depends on the regional features of hydrometeorological characteristics, among which air temperature causing a degree of atmospheric cooling and water salinity determining the freezing point may be distinguished. In the present paper, basic attention is given to the relationship between CLT and the temperature regime of the study areas.

G.A. Surkov [31] presented a brief review of the dependences between the accumulated freezing degree days (degree hours) and the thickness of level ice and the consolidated layer for hummocks, which were empirically derived by different authors, and proposed a probabilistic model of changes in the thickness of the consolidated layer and surrounding level ice. The form of the most expressions presented proceeds from the Stefan theoretical formula, which shows that ice thickness is proportional to the squared root of the accumulated freezing degree days. The empirical equation proposed by G.W. Timco and L.E. Goodrich [33] connects CLT (H_{CL}) with the accumulated frost degree-hours $T_{-,\mathrm{h}}$ (C) in the following way:

$$H_{\mathrm{CL}} \quad 0.6\sqrt{\; T_{\;,\mathrm{h}}}\,.$$

D. Blanchet [18] derived the following dependence of CLT on the accumulated freezing degree days (T):

$$H_{\mathrm{CL}} \quad 5.24 \quad 10^{\;8} \quad (\; T\;)^2 \quad 0.001 \quad T \quad 0.68.$$

The authors of [24] associated the CLT variations with the accumulated freezing degree days through the semiempirical coefficient which depends on the thermal conductivity, density, and specific heat of ice formation, with account of the hummock porosity (n_k):

$$H_{\mathrm{CL}} \quad \sqrt{\; T \;/\, n_k}\,.$$

The authors of [30] proposed to determine CLT using the Stefan law for the calculation of the growth of level ice depending on the accumulated freezing degree days, with account of porosity of the unconsolidated part of the hummock.

The authors of [15] derived an empirical interrelation between the mean CLT (cm) for the first-year ice ridges investigated in different areas of the Kara and Laptev seas, and the accumulated freezing degree days (C) calculated using data from the polar stations located in these areas:

$$H_{\mathrm{CL}} \quad 6.64 \quad \sqrt{\; T} \quad 23.1.$$

The present paper attempts to obtain such dependence on the regional temperature conditions for the consolidated layer of stamukhas. Obviously, the temperature conditions vary not only from area to area but also from year to year. Based on the data of the nearest hydrometeorological stations to the study areas, the following accumulated freezing degree days were computed:

—for six winter seasons (2000/2001–2003/2004, 2005/2006 and 2007/2008) for the northern Caspian Sea based on Astrakhan station data;

—for the Sakhalin shelf based Noglinki station data for the season of 1997/1998 and based on Okha station data for the season of 2005/2006;

—for the Baydarata Bay for two seasons (2006/2007 and 2009/2010) based on Marre-Sale station data;

—for the Khatanga Bay for the season of 2016/2017 based on Khastyr station data.

As the exact time of formation of the consolidated layer in stamukhas (as well as the exact time of stamukha formation) is unknown, the accumulated freezing degree days are calculated from the date of the stable 0°C air temperature crossing, and the end of the calculation period corresponded to the middle of the period of studying stamukhas in a specific region. Thus, 11 pairs of values of the mean CLT for stamukhas and the accumulated freezing degree days took part in the analysis over all study areas for 1998–2017. The dependence of CLT (m) on the accumulated freezing degree days (C) obtained from the authors' data with the coefficient of determination $R^2 = 0.89$ is represented by the equation

$$H_{\mathrm{CL}} \quad 0.046 \quad \sqrt{\; T} \quad 0.469. \tag{2}$$

The graph of the linear relationship between the mean CLT and the squared root of the accumulated freezing degree days is presented in Fig. 3.

As a result of increasing the length of observation series and specifying the empirical coefficients, such expression can be used for the estimation of the area-averaged CLT of stamukhas proceeding from the accumulated freezing degree days obtained for this area.

Data on CLT for stamukhas used in the calculations were mainly obtained during the period of maximum development of the ice cover, and the estimation of evolution of the consolidated layer during the melting may be a future research subject.

CONCLUSIONS

Based on the generalization of results of instrumental observations of stamukha parameters and their comparative analysis in different areas of ice-covered seas, the following conclusions were made.

The main reason for differences in the morphometry of stamukhas is the regional features: sea depth, bottom topography, ice drift, ice thickness, and the formation conditions of ice bodies, i.e., the fast ice

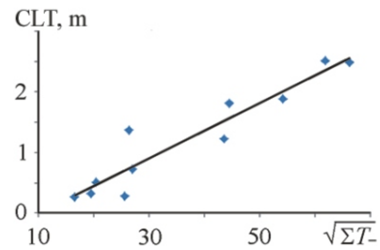

Fig. 3. The interrelation between the thickness of the consolidated layer of stamukhas and the accumulated freezing degree days (C) in different areas of ice-covered seas of Russia.

formation or drifting ice. Such differences indicate a need in detailing data on the features of spatial variability of various parameters of ice bodies in local areas when designing engineering facilities.

The significant relationship was derived between the mean thickness of the consolidated layer of stamukhas and the accumulated freezing degree days, which is caused by the temperature regime of the local sea area. The maximum thickness of the consolidated layer is registered in the Kara and Laptev seas due to severe Arctic climate conditions.

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