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CONTENT

Ice conditions in the Arctic

Shipping and shipbuilding

Biota in the Arctic

5TH ISSUE OF SCIENTIFIC AND INFORMATION ANALYTICAL JOURNAL “RUSSIAN ARCTIC” DEDICATED TO ISSUES OF SHIPBUILDING FOR THE ARCTIC

KIRA ZMIEVA

“RUSSIAN ARCTIC”
CHIEF EDITOR

By decree of the President of Russia V.V. Putin dated May 7, 2018 No. 204 "On National Goals and Strategic Tasks of the Development of the Russian Federation for the Period until 2024" set the task of developing the Northern Sea Route and set indicators for such development - ensuring cargo through it up to 80 million tons per year by 2024 .

The task is complicated by the need to organize year-round navigation in the northern seas, as well as toughening environmental requirements for Arctic vessels.

To achieve the ambitious goals set, it is necessary to develop new approaches to the design and creation of modern large-capacity Arctic transport ice-breaking vessels, as well as the creation of innovative intelligent systems for assessing ice conditions and the probability of emergencies along the Northern Sea Route during year-round operation.

The authors of the current issue of the journal presented both an assessment of the current state of the domestic transport and icebreaking fleet, and ways of further development of the Arctic shipbuilding to realize the mineral and raw materials and logistics potential of the Arctic zone of the Russian Federation.

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THE RESULTS OF COMPUTER SIMULATION OF THE PROBABILITY OF ACCIDENTS DUE TO SHIP NIPS BY DRIFTING ICE ALONG THE NORTHERN SEA THROUGHWAY

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Results of testing of computer simulation model for assessment of probability of accidents with tankers due to pressure by drifting ice are presented. The testing was carried out for the navigation route «Sabetta Port – Kara Gate Strait – Murmansk Port» and for the first ten-days period of May, during the most difficult ice conditions of the navigation. The probabilities of the accidents were calculated. There was analyzed the model response to variations of its parameters values.

Keywords: simulation, accident probability, nips

Introduction

Modern civilization is hydrocarbon-based: energy sector and chemical industry are powered by oil, oil products and natural gas. Exhaustion of old fields forces the exploitation of new oil and gas fields in the Subarctic region and on the shelves of the Arctic seas. This fact requires the development of systems to transport hydrocarbons, in particular, sea transport systems of the Northern Sea Route (NSR) [1, 2, 3].

In accordance with the project Yamal LNG the third LNG (liquefied natural gas) train is already launched in the largest LNG plant located in Sabetta at the Yamal Peninsula. In the near future it is planned to increase its total capacity and come to level of production of 17.4 million tons of liquefied natural gas per annum [4]. Project is based on the resources of the Yuzhno-Tambeyskoye (South-Tambey) gas field which includes reserves of more than 1 trillion cubic meters of natural gas. Liquefied natural gas is exported by six modern carriers by standard navigation routes [5, 6]. Achieving the plant total capacity will increase traffic requirement. Besides, the Northern Sea Route is used for transporting large amount of oil. In the current time hydrocarbons are exported by tankers from the offshore Varandey oil terminal and ice-resistant oil platform Prirazlomnaya located in the Pechora Sea (south-eastern part of the Barents Sea), Kharasavey sea terminal located at the west of the Yamal Peninsula in the Kara Sea, ports of Sabetta and Novy Port at the east of Yamal Peninsula in the Gulf of Ob. Transportation is carried out by modern tankers and LNG carriers. Ice strengthening of vessel class Arc7 allows them to navigate independently stern first in ice up to 2.1 m thick [7, 8].

Operation of any transport system is accompanied by accidents resulting in oil and liquefied gas spills and environmental pollution [9, 10, 11]. During ice navigation an emergency situation may be caused by ship collision, stranding, docking impact by coastal terminal or platform, collision with icebergs and ice formations [12]. All reasons listed above are human errors, since abidance by the safety navigation rules and properly functioning radar facilities can reduce the risk of accidents caused by these reasons to near-zero values. Force majeure reason of accident is ship besetting under ice pressure. All wrecks of ships in the Arctic Ocean were caused by ship besetting, except war losses [13]. Ice cover is the major hazard to navigation along the Northern Sea Route and hindrance to business activities in the Arctic [14]. Computational modeling allows to predict the location, strength and probability of zones of possible ship besetting under ice pressure, but it can't entirely eliminate the possibility of besetting.

The study aims to test the computer model of evaluation of accident probability due to ice pressure on the route "Sabetta–Kara Strait–Murmansk" (Fig.1).

Materials and methods

To evaluate the probability of accident a Monte Carlo-based computer model was created and improved by V.Yu. Tretyakov. This method is used for simulation of random events in case of achieving critical values by some parameters (e.g., vessel under pressure in level ice of specified thickness, etc.)

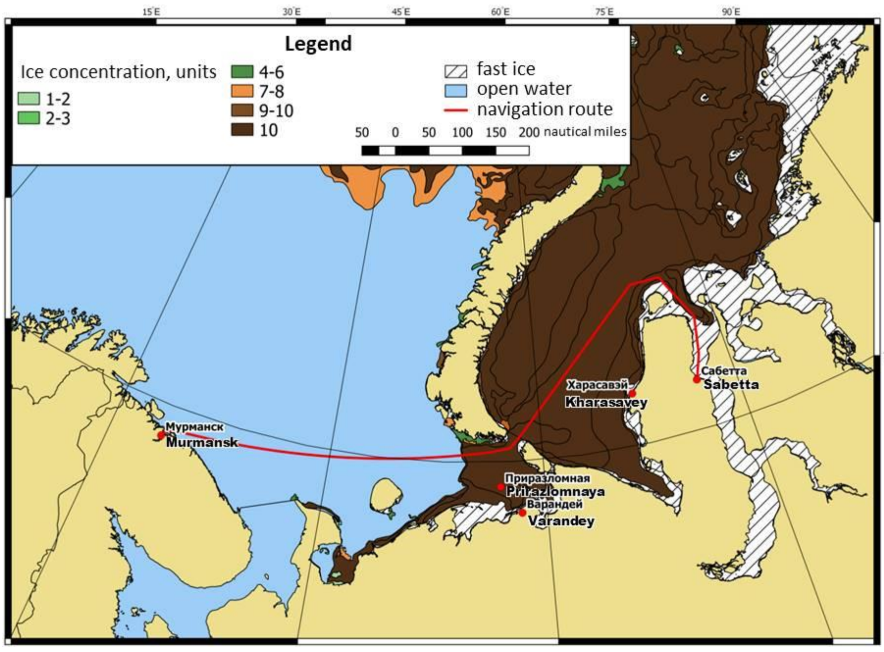

Figure 1. Map of the route. Ice conditions are of the period 10-20 of May, 2018

In the model an accident occurs if vessel is in the zone of ice pressure and ice strength is upper than an amidship. If ridge concentration is more than 2 units than ice strength is taken to be equal to the greater value between level ice strength and strength of consolidated layer of ridges. During the model numerical simulations ice cover characteristics are set as stochastic variables (not deterministic), and their statistical distributions are model parameters. The cumulative distribution functions are following: function of probability for vessel to get into zone under ice pressure;

summarized length of a route in very close floating ice; relative lengths of parts of route in very close floating ice of various age; area of homogenous ice zones; lengths of parts of the route under ice pressure and without ice pressure; thicknesses of ice of various age; ridge concentration; ratio of ridge concentration to total ridge and hummock concentration; lengths of linear ridges; widths of ridges; ratio of ridge width to ridge altitude; thickness of consolidated layer of ridges. In Monte Carlo simulation, a random number generator provides a decimal fraction in the [0,1] interval which is considered as value of cumulative distribution function of the given characteristic of ice cover. Based on this value the quantile is estimated which is a specific value of ice characteristic. In the model we take into account only static interaction between hull and ice. Strength of the hull's elements is estimated according to the requirements of the Russian Registry of Shipping. If randomly generated ice strength and its statistical distribution exceed the strength of a vessel, this cause hull destruction and emergency situation. Statistical distributions of ice characteristics are based on ice maps of the Arctic and Antarctic Research Institute (AARI) archive, data on AARI expeditions and literature sources. Ice compression strength depends on many factors. Study on ice compression strength in ice interactions with different structures are high-demand and carried out by Russian [15-19] and foreign [20-24] specialists.

Ice strength depends on its thickness. During the period from the beginning of sustainable ice formation to the beginning of summer thawing ice thickness is determined by its age. Ridging develop predominantly in young and thin first-year ice (FYI). Newly-formed ridges are made of single ice rubbles that have the same thickness as the parent ice floe. Thus new ridges don't pose a risk of ship besetting under ice pressure. The situation changes when the consolidation of part of single ice rubbles occurs and forms so called consolidated ice layer. It is supposed that navigators are able to avoid ridges if ridge concentration is up to 2 units according to Russian nomenclature (i.e. 2/5). In this case strength of level ice alone is taken into account; notably, both strength of deformation and strength of fracture are examined [25], and the lowest value is taken as the ice strength.

According to studies [26, 27] ridge concentration is 50% of total hummock and ridge concentration. Spatial orientation of ridges is random [27, 28], thus distribution of ridge orientations is set as proportional and mean angle between the direct course of a vessel and the ridge line is 45%.

Pre-processing of statistical distributions of summarized lengths of parts of the route characterized by specific parameters of ice cover is based on vector maps of ice conditions from AARI archive. These maps were made by the Centre of ice meteorological information of AARI on the base of remote sensing data [29].

Processing of vector map is made with use of ArcGIS as follows: polygonal objects of ice maps are crossed by linear object of navigation route. As a result a layer of linear objects is created that have the same sets of attributes as those of the crossed polygons. After that selection of objects according to their attribute values is done and lengths of the objects are calculated. Objects with total ice concentration not less than 9 units (9/10) with presence of ice older than young stage are identified, subsequently the selected objects are added to the new layer of parts of the route. Next step is to sort objects by age and to add them into separate layers. Lengths of individual objects and summarized lengths of objects that meet certain criteria are calculated. These result in ten-days series of lengths of the route segments in close ice, in close ice with presence of young (up to 10 cm thick), grey (10-15 cm thick), grey/white (15-30 cm thick), thin FYI (30-70 cm thick), medium FYI (70-120 cm thick), thick FYI (more than 120 cm thick). Besides, ten-days series of summarized lengths of parts of route in close ice with partial concentration of thick first-year ice of at least 5 tenths and summarized lengths of parts of route in close ice with sum of partial concentrations of thick first-year ice and medium first-year ice of at least 5 tenths are calculated.

The origin set of numeric variables for statistical distribution of parameter values of the model should be homogeneous. Thus the analysis of obtained numerical series for presence of interannual trend is made based on cumulative curves. Method of cumulative sums originally was applied in hydrology to examine the presence or absence of directed trends in the interannual dynamic of annual river discharges [30]. Afterwards it was applied for preliminary interannual variability analysis of any environmental parameters. Summary of this method is the following. A plot is made with years on the x-axis and cumulative sums of parameter values of specific years on the y-axis. In our case these are the values of the same within-year (intra-annual) ten-day interval of different years. Cumulative sum for particular year is the sum of values from the beginning of the time series to this particular year inclusive. For the first year it is the value itself, for the second year it is the sum of the values of both the first and the second year, etc. Data points of cumulative sums on the plot are connected with a line. The line must be close to the straight line in case of the absence of interannual variability. The kinked or broken-line curve show that there is a trend and the data is heterogeneous.

For curves that are close to straight line the original numerical series is divided into halves to examine its homogeneity. For kinked or broken-line curve the original numerical series is divided into parts in the points of inflection. If number of elements is not enough for statistical analysis, than original numerical series is divided into two parts in the point of the most significant inflection. Next step is testing the null hypothesis that two parts belong to one population, that means the absence of significant differences between these two samples. Verification is made in Mathcad with use of Mann-Whitney-Wilcoxon and Siegel-Tukey nonparametric tests.

Statistical distributions of model parameters were made in Mathcad based on methods of Hazen, Kritskiy-Menkel, Tchegodayev and Gringorten. Statistical distributions that were obtained by different methods varied inessentially. Therefore statistical distributions calculated by Gringorten method which combine three other methods were used in the model (Fig.2).

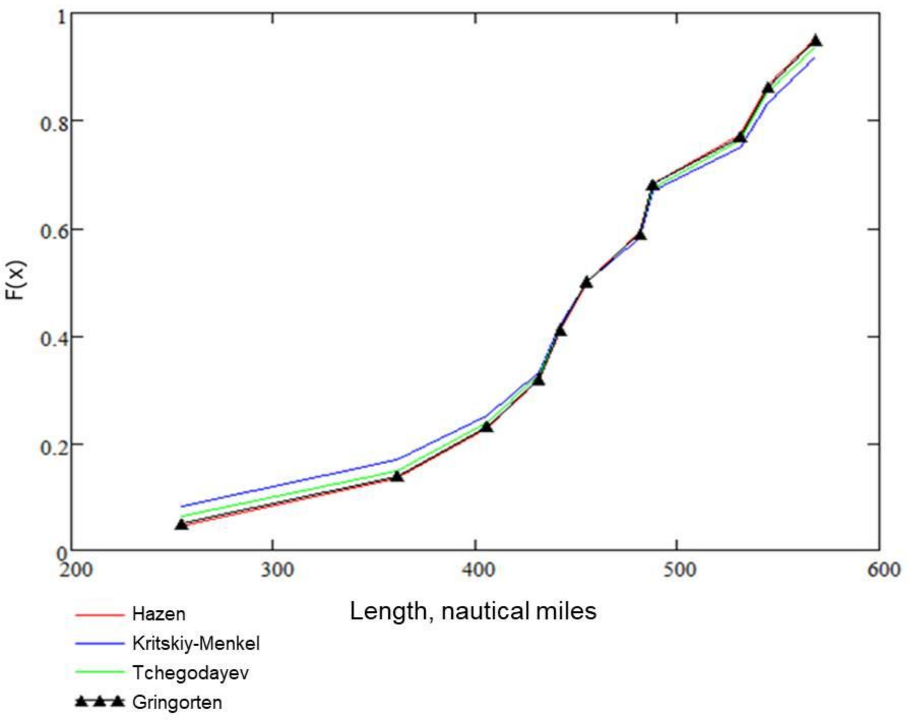

Figure 2. Cumulative distribution function of length of the route in close ice for the first ten-day period of May calculated by different methods.

Statistical distributions of parameters are put in txt-files which are multiply used for calculations during numerical experiments.

Model is built in Delphi algorithmic language. It provides for both automatic and forced end of individual numerical experiment (series of navigations). User sets number of simulations in one computer calculation. Statistical distributions of model parameters remain constant in an individual calculation. Automatic end of numerical experiment (series of navigations) occurs in case of stabilization of the ratio of number of accidents to number of navigations. If A is a ratio of number of accidents to number of navigations to the end of this simulation, B is a ratio of number of accidents to number of navigations in case of previous accident, than numerical experiment ends on condition that | A – B | < (A*0.001). Numerical experiment also ends in case of 10001 accident-free navigations.

However, there is a possibility for maximal number of navigations per ten-days period to be substantially less than number of navigations which provides stabilization of the ratio of number of accidents to number of navigations. In this case in one numerical experiment (series of navigations) maximal number of navigations which is expected for a given ten-days interval throughout the entire period of operation of this sea transport system is set. The numerical experiment is forced to end after accomplishing of this number of iterations without regard for stabilization of accidents to navigations ratio. Both in automatic and forced end of numerical experiments user establishes a number of numerical experiments in one computer calculation. The ratio of number of accidents to number of navigations is regarded as probability of accident. Since one computer calculation consists of a series of numerical experiments, the probability of accident should be regarded as a random variable with mathematical expectation (E) and root-mean-square deviation (RMSD). According to central limit theorem, statistical distribution of a random variable will approximate a normal distribution since it is contributed by variety of factors. As an upper bound of accident probability we suggest to use sum of E and triple RMSD with running series of not less than 30 numerical experiments with forced end. In that case probability of greater accident rate according to three-sigma rule is only 0.15%. Thus this approach should be applied to estimate expected damage.

Results and discussion

The model was tested for the most difficult ice conditions of the first 10-days period of May. The ratio of number of accidents to total number of navigations in case of automatic end of numerical simulations for 70000-toner Arc7 vessel was 0.023. The most important stage of simulation modeling in scientific researches is model sensitivity testing to parameters varying. For this purpose we set a number of simulations with fixed maximum and minimum parameters according to their statistical distributions. For example, to learn model sensitivity to variation of total hummock and ridges concentrations we have compared results of simulations of situation of absence of ridges and situation of maximum ridge concentration of 4.5 units (i.e. up to 90% of ice area is covered by ridges). This procedure is necessary to verify the model: if changing the value of specific parameter is evidently supposed to cause accident but has no effect on simulation results, then there is an appreciable error in model algorithm or program code. Besides, this procedure reveals the most sensitive parameters of the model, which require additional field study and/or specific processing of previous data of expeditions, experiments, satellite data, etc. Results of simulations for determining the most important parameters are represented in Table 1. “Reference” scenario means that all values are based on files of statistical distributions and random numbers generation. Otherwise input values for testing model for sensitivity to a specific parameter are set by user. Processing and averaging of results is made using R.

Table 1 – Model outputs for different parameters.

Model parameters	Parameter minimum and maximum	Probability of accident (average for 30 simulations)
«Reference» scenario	-	0.023
Length of route in close ice	min – 255 nm (nautic miles)	0.016
	max – 567 nm	0.028
Ridge concentration	min – 0 units (0/5)	0

	max – 4.5 units (4.5/5)	0.030
Probability of ship besetting under ice pressure	min – 0	0
	max – 0.02	0.044
Length of parts of route under ice pressure	min – 2.9 m.miles	0.017
	max – 69.7 m.miles	0.027
Length of parts of route without ice pressure	min – 6.2 m.miles	0.441
	max – 1609.7 m.miles	0.009

Thereby, parameters that governed the probability of accident are following: length of the route in close ice, total ridge and hummock concentration, probability of ship besetting under ice pressure and length of parts of route under ice pressure.

The results of 450 numerical simulations with varying vessel ice classes and vessel displacements are presented in Table 2.

Table 2 – Simulation results of navigations of different vessel ice classes and displacements

Vessel ice class	Displacement, Thousand tons	Probability of accident (average for 30 simulations)
Arc5	45	0.025
	70	0.025
	85	0.024
Arc6	45	0.025
	70	0.024
	85	0.025
Arc7	45	0.024
	70	0.024
	85	0.023
Arc8	45	0.022
	70	0.024
	85	0.023
Arc9	45	0.022
	70	0.022
	85	0.020

The results are visualized on Figure 3. The data indicates that stronger ice class reduces probability of accident. Thus, the model simulates correctly the increasing strength of the hull in case of increasing ice class.

Furthermore, about 600 model simulations were made with forced setting a value of number of navigations in one experiment for ice classes Arc5, Arc6, Arc7, Arc8, Arc9 with displacement of 70000 tons. Number of navigations varied, setting equal to 30, 100, 500 and 1000 in one experiment. Simulation results are shown in Table 3.

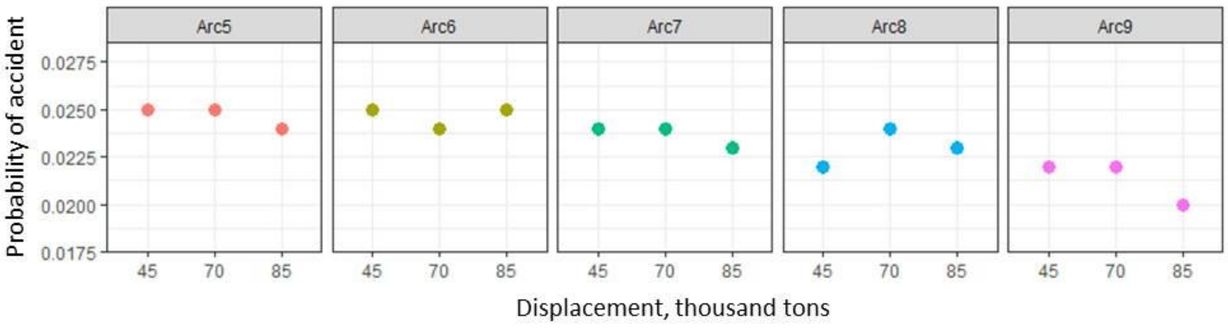

Figure 3. Simulation results for different ice classes of vessels

Table 3 – Simulation results with forced setting of number of navigations

Ice class	Number of navigations in one experiment	Probability of accident (average for 30 simulations)
Arc5	30	0.104
	100	0.040
	500	0.026
	1000	0.023
Arc6	30	0.091
	100	0.046
	500	0.025
	1000	0.024
Arc7	30	0.132
	100	0.051
	500	0.024
	1000	0.023
Arc8	30	0.257
	100	0.043
	500	0.023
	1000	0.023
Arc9	30	0.097
	100	0.039
	500	0.024
	1000	0.022

Conclusions

In this study the computer model of evaluation of accident probability due to ship besetting under ice pressure on the route “Sabetta–Kara Strait–Murmansk” was tested. To conduct numerical experiments the distributions of parameters of the model (i.e. characteristics of ice cover) are prepared, these are: thickness of consolidated layer of ridges, ratio of ridge width to ridge altitude, percentage of ridge concentration, total ridge and hummock concentration, lengths of parts of route without ice pressure, length of navigation route in close ice, relative length of route in close ice with presence of thick FYI, medium FYI, thin FYI and young ice. For data preparation ten-day interval vector maps of ice conditions on the route for the period 1997-2018 from AARI archive were processed. Obtained series of lengths were tested for having a trend based on method of cumulative curves and were tested for homogeneous by use of Mann-Whitney-Wilcoxon and Siegel-Tukey nonparametric tests. Statistical distributions were based on methods of Hazen, Kritskiy-Menkel, Tchegodayev and Gringorten.

The main conclusions from the results of simulations include the following:

1) Parameters that markedly affect the accident probability are length of the route in close ice, total ridge and hummock concentration, probability of ship besetting under ice pressure, lengths of parts of route under ice pressure;
2) Calculations with forced end of numerical experiments with small number of navigations show accident probability several times higher than those with more than 100 navigations or in case of automatic end;
3) Probability of accident due to ice pressure for ice class Arc7 is 0.023 on navigation route “Sabetta–Kara Strait–Murmansk” during first ten-day period of May which is characterized by the most difficult ice conditions on the route.

Risk assessment is crucial for strategic planning of logistic systems for production and transportation of hydrocarbons in the Arctic.

It is necessary to note that research activities in this field are in progress. For instance, lengths of parts of route in various types of ice have already been calculated for another high-demand navigation route “Sabetta-the Bering Strait”.

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DEPENDENCE OF THE MODERN ICEBREAKER FLEET FROM ICE CONDITIONS ON THE RUSSIAN SEAS

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The article considers the current state of the Russian icebreaker fleet. The possibility of using such a parameter as the sum of degree-days of frost to characterize light, medium and heavy ice conditions in the non-Arctic seas is proved. The analysis of restrictions of the regime of ice navigation of vessels of different ice categories in the waters of the non-Arctic seas for light, medium and heavy ice conditions is carried out. A quantitative assessment of the compliance with technical specifications of the icebreaker fleet on the seas with different ice conditions in these seas. It is shown that the power of the modern icebreaker fleet allows navigation on the Russian seas to be equally successful in conditions of mild and moderate, and in conditions of severe and extremely severe winters. At the same time, the increase in the power of the icebreakers under construction and design and the decrease in the thickness of ice due to sustainable warming in all Russian seas increase the guarantees of safety of the navigation of ships and icebreakers in ice and reduce the dependence of ice navigation on the severity of ice conditions. Based on the analysis of the construction and operation of the icebreaker fleet in the XXI century, it is concluded that the real difficulties of winter navigation in the non-Arctic seas are associated primarily with an increase in the number and size of vessels which participate in icebreaking operations.

Keywords: ice conditions, ice cover of the seas, ice thickness, power of the icebreaker, safety of the navigation, sum of the degree-days of frost

Introduction

Planning of maritime operations in the Russian seas during the ice period requires long-term forecasting into the forthcoming ice season. For this task Roshydromet engages Arctic and Antarctic Research Institute (AARI) to make background forecast for the Arctic seas for June-September, and Hydrometeorological Research Centre of Russian Federation (Hydrometcentre of Russia) to make background forecast for the non-Arctic seas for the period from October till June of the forthcoming ice season. The AARI makes forecasts for the Arctic seas in March and June with earliness of 1 to 4 months. The Hydrometcentre makes forecast for the non-Arctic seas at the beginning of October with earliness of 2 to 8 months for different elements of ice regime (dates of beginning of ice formation and clearance of ice; maximum winter ice thickness; ice cover and duration of ice period in harbor areas). Accuracy of long-term forecast of the Hydrometcentre of Russia is 70-75% [2].

Years of discussions regarding usefulness of long-term forecasts, and the lack of their acceptance by our foreign colleagues haven't yet convinced Roshydromet to abandon the practice of making long-term forecasts. Long-term forecasts of AARI and Hydrometcentre of Russia are used in FGI (Federal Government Institution) 'The Administration of the Northern Sea Route' and FSUE (Federal State Unitary Enterprise) 'Rosmorport' for planning of icebreakers operation areas during the summer navigation in the Arctic and winter navigation in non-Arctic seas. The main practical task of long-term ice forecasting is to inform the maritime community about prospective severity of ice conditions in a certain sea. These conditions are supposed to be easy (E), moderate (M) or difficult (D).

The term 'difficult ice conditions' is subjective and implies not only a certain geographic latitude and power of icebreaker fleet, but also the particular climate characteristics in which navigators are accustomed to operate. Shippping companies have changed significantly their definition of 'difficult ice conditions' over the past decade. On several occasions (e.g. in January, 2008 and in March, 2020) the experts of the Ministry of Transport of the Russian Federation (Mintrans of Russia) consulted with Roshydromet on whether the ice conditions in the Sea of Azov were extremely difficult for navigation. In fact, in January, 2008 about 150 vessels awaited for icebreaker assistance near the ice edge, though by winter classification by sum of degree-days of frost (DDF), the winter of 2007/2008 (as well as the winter of 2011/2012) in the Sea of Azov was determined as moderate winter according to climatic stereotype of 20th century, while severe winter in the Sea of Azov is characterized by fast ice thicknesses of 45-60 cm [3].

Similar problems have occurred in the Gulf of Finland where severe winter (according to stereotype of 20th century) hadn't been observed for already 30 years (the last severe winter was in 1986/1987). During the navigation of 2010-2011 ('moderate winter') vessels were assisted by 10 icebreakers, however, due to the difficult ice situation, nuclear icebreaker 'Vaygach' had to be sent to the Gulf of Finland for the first time in the history. Icebreaker support was required to assist oil supertankers from Primorsk. Nuclear icebreakers assistance in the Gulf of Finland took place also in 2012 (nuclear icebreakers 'Rossiya' and '50 Let Pobedy') and in 2013 (nuclear icebreaker 'Rossiya').

This paper aims to determine the relevance of technical characteristics of icebreaker fleet in the different seas of Russia to sea ice conditions not only for the modern period of global warming but also for the most severe winters observed in 20th century.

1. Data on hydrometeorological conditions and icebreaker fleet status

Table 1 contains information about time-series of environmental characteristics used for analysis of easy, moderate and difficult ice conditions in different seas.

Table 1 – Time series of environmental characteristics

Sea	Sea region or observation	Characteristics	Observation period	Observation period, years

	station			
Kara Sea	Dikson Island	DDF	1921-2018	98
		FT	1926-2018	93
White Sea	Arkhangelsk	DDF	1813-2018	206
	Mudyug Island	FT	1914-2018	105
Baltic Sea	St.Petersburg	DDF	1811-2018	208
	Kronstadt	FT	1911-2018	108
	Vyborg	FT	1930-2018	89
Sea of Azov	Rostov-on-Don	DDF	1882-2018	137
	Taganrog	FT	1924-2018	95
Caspian Sea	Astrakhan	DDF	1846-2018	173
	Bol’shoy Peshnoy Island	FT	1930-2018	89
	Iskustvenniy Island - Lagan	FT	1953-2018	66
Bering Sea	Anadyr	DDF	1916-2018	103
		FT	1963-2018	56
Sea of Okhotsk	Magadan	DDF	1933-2018	86
		FT	1933-1994	65
	Poronaysk	DDF	1909-2018	110
	Ayan	FT	1934-2018	85
Sea of Japan	Aleksandrovsk-Sakhalinskiy	DDF	1891-2018	128
		FT	1953-2018	66

Note: DDF – sum of degree-day of frost, FT - fast ice thickness

The paper often refers to a vessel class, therefore Table 2 contains characteristics of ice classes of icebreakers and vessels.

Table 3 contains permissible marine operations and the corresponding ice conditions in the Arctic seas and the severe non-Arctic Bering Sea.

Table 4 contains established restrictions for navigation in non-Arctic harbor areas.

Table 2 – Characteristics of ice classes of icebreakers and vessels

Ice class	Characteristics of icebreaking operations permitted	Total power, kW
Icebreaker, LL1	In the Arctic seas (AS) on coastal routes and shore ice belt routes in high latitude all year round. Capable of forcing the way in compact ice field over 2.0 m thick.	≥47807
Icebreaker, LL2	In the AS during the summer period and for operation on coastal routes during the winter period. Capable of forcing the way in compact ice field less than 2.0 m thick.	22065 - 47807
Icebreaker, LL3	In shallow waters and mouths of rivers flowing into the Arctic seas during the winter period without assistance as well as for operation on coastal routes in the Arctic seas under convoy of icebreakers of higher category. Capable of forcing the way in compact ice field up to 1.5 m thick.	11032-22065
Icebreaker, LL4	In harbor and roadstead water areas without assistance all the year round as well as for operations in the non-Arctic freezing seas (NAS) under convoy of icebreakers of higher category during the winter period. Capable of forcing the way in compact ice field up to 1.0 m thick.	< 11032
Vessel, Arc 9	In AS in close ice up to 3.5 m thick during winter-spring navigation and up to 4.0 m thick during summer-autumn navigation	-
Vessel, Arc 8	In AS in close ice up to 2.1 m thick during winter-spring navigation and up to 3.1 m thick during summer-autumn navigation; in navigable passage astern an icebreaker in ice up to 3.4 m thick during winter-spring and summer-autumn navigation.	-
Vessel, Arc 7	In AS in close ice up to 1.4 m thick during winter-spring navigation and up to 1.7 m thick during summer-autumn navigation; in navigable passage astern an icebreaker in ice up to 2.0 m thick during winter-spring navigation and up to 3.2 m thick during summer-autumn navigation.	-
Vessel, Arc 6	In AS in open ice up to 1.1 m thick during winter-spring navigation and up to 1.3 m thick during summer-autumn navigation; in navigable passage astern an icebreaker in ice up to 1.2 m thick during winter-spring navigation and up to 1.7 m thick during summer-autumn navigation.	-
Vessel, Arc 5	In AS in open ice up to 0.8 m thick during winter-spring navigation and up to 1.0 m thick during summer-autumn navigation; in navigable passage astern an icebreaker in ice up to 0.9 m thick during winter-spring navigation and up to 1.2 m thick during summer-autumn navigation.	-
Vessel, Arc 4	In AS in open ice up to 0.6 m thick during winter-spring navigation and up to 0.8 m thick during summer-autumn navigation; in navigable passage astern an icebreaker in ice up to 0.7 m thick during winter-spring navigation and up to 1.0 m thick during summer-autumn navigation.	-
Vessel, Ice 3	Independent navigation open brush ice in NAS and in compact ice up to 0.7 m thick in navigable passage astern an icebreaker	-
Vessel, Ice 2	Independent navigation in open brush ice in NAS and in compact ice up to 0.55 m thick in navigable passage astern an icebreaker	-
Vessel, Ice 1	Independent occasional navigation in open brush ice in NAS and in compact ice up to 0.4 m thick in navigable passage astern an icebreaker	-

Vessel, UL	Independent navigation in AS during summer and autumn in easy ice conditions; all-year round in NAS	-
Vessel, ULA	Independent navigation everywhere in the World Ocean during summer and autumn	-

Table 3 - Restrictions for different ice classes to navigate in the Arctic seas and in the Bering Sea

Type of ice conditions	Description of ice conditions	Ice class of vessels	
		independent navigation	navigation under icebreaker assistance
Easy	New, young and thin first-year ice (up to 0.7 m thick), appearance and presence of medium first-year ice (less than 1.2 m thick) up to 25%	Arc 4 or higher ice class	Arc 4 or higher ice class
Moderate	Medium first-year ice (up to 1.2 m thick) in amount of 25% and more, which may include thick first-year ice (more than 1.2.m thick) inclusions up to 25%	Arc 7 or higher ice class	Arc 6 or higher ice class
Difficult	Thick first-year ice (more than 1.2 m thick) and multi-year ice (more than 2 m thick) in amount of at least 25%	Arc 8-Arc-9	Arc 7 or higher ice class

Table 4 – Restrictions for different ice classes to navigate in non-Arctic seas

Type of ice conditions		Ice cover thickness	Ice class of vessels		
Northern seas	Southern seas		independent navigation	navigation under icebreaker assistance	not allowed for navigation
Easy	Easy	10-15 cm	Ice 1 or higher ice class	Vessels without ice strengthening	Tugs and tows
Moderate	Moderate	15-30 cm	Ice 2 or higher ice class	Ice 1	Vessels without ice class, tugs and tows
Moderate	Difficult	30-50 cm	Ice 3 or higher ice class	Ice 1 and Ice 2	Vessels without ice class, tugs and tows
Difficult	Extremely difficult	>50 cm	Arc 4 or higher ice class	Ice 2 and Ice 3	Vessels without ice class or Ice 1, tugs and tows

Note: Northern seas here are the White Sea, the Gulf of Finland, seas of Far-East; southern seas here are the Sea of Azov and the Caspian Sea.

Table 4 shows:

- Ice-strengthened vessels Arc 4 and Arc 5 are allowed to navigate independently only in easy type of ice conditions;
- Ice-strengthened vessels Arc 6 are allowed to navigate independently in easy ice conditions and with icebreaker assistance in moderate ice conditions;
- Ice-strengthened vessels Arc 7 are allowed to navigate independently in moderate ice conditions and with icebreaker assistance in difficult ice conditions;
- Ice-strengthened vessels Arc 8 and Arc 9 are allowed to navigate independently in all types of ice conditions.

Comparison of Table 3 and Table 4 shows that similar ice conditions are considered as easy in the Arctic seas and in the Bering Sea, and extremely difficult in the Sea of Azov and the Caspian Sea.

'Easy' and 'difficult' ice conditions vary in the southern and the northern seas. Characteristics of ice-going vessels and the power of icebreaker fleet in different seas vary considerably. Historically association of icebreakers and vessels operating in specific sea is based on the moderate ice conditions in this sea. Table 5 represents real operating areas of icebreakers in the Russian seas approved by the Mintrans for the period of 2017-2018, and calculated average power of icebreakers (shaft power or propeller power for pod driven icebreakers).

Table 5 – Operating areas of icebreakers and icebreaking vessels in 2017-2018, approved by the Mintrans for icebreaker assistance in the freezing ports of Russia.

Sea, region	Operating area	Icebreaker, tugboat	Power, kW
Kara Sea	Kara Sea, Port of Sabetta	NIB '50 Let Pobedy'	49000
	Kara Sea, Port of Sabetta	NIB 'Yamal'	49000
	Gulf of Ob (Ob Bay), Port of Sabetta	NIB 'Vaygach'	32500
	Yenisey Gulf	NIB 'Taymyr'	32500
	Sabetta port area	IB 'Moskva'	16000
White Sea	Sea, route	IB 'Dikson'	7000
	Sea, route	IB 'Admiral Makarov'	26500
	Ports of Arkhangelsk, Severodvinsk, Onega	IB 'Kapitan Evdokimov'	3800
	Ports of Arkhangelsk and Kandalaksha	IB 'Kapitan Kosolapov'	2500
	Ports of Arkhangelsk and Onega	IB 'Kapitan Chadaev'	3300
Gulf of Finland	The gulf, route	IB 'Kapitan Sorokin'	16200
	The gulf, route	IB 'Ermak'	26500
	The gulf, route	IB 'Murmansk'	18000
	The gulf, route	IB 'Kapitan Nikolaev'	16200
	The gulf, route	IB 'Novorossiysk'	18000
	The gulf, route	IB 'Sankt Peterburg'	16000

	Port of St. Petersburg	IB ‘Mudyug’	7000
	Port of St. Petersburg	IB ‘Semen Dezhnev’	3450
	Port of St. Petersburg	IB ‘Ivan Kruzenshtern’	3900
	Ust-Luga Sea Port	IB ‘Karu’	4160
	Ust-Luga Sea Port	IB ‘Kapitan Plakhin’	3300
	Ports of Vyborg and Vysotsk	IB ‘Kapitan M.Izmaylov’	2500
	Ports of Vyborg and Vysotsk	IB ‘Yuriy Lisyanskiy’	3500
Sea of Azov	Sea, route	IB ‘Kapitan Moshkin’	3800
	Sea, route	IB ‘Kapitan Demidov’	3800
	Sea, route	IB ‘Kapitan Chudinov’	3800
	Sea, route	IB ‘Kapitan Zarubin’	3300
	Sea, route	IB ‘Kapitan Krutov’	3300
	Port of Taganrog	T/IB ‘Kama’	1660
	Ports of Azov and Rostov-on-Don	T/IB ‘Kapitan Kharchikov’	1660
	Ports of Azov and Rostov-on-Don	‘Fanagoriya’	544
	Port of Yeysk	‘Tekhflotets’	1180
	Port of Yeysk	‘Kolguyev’	860
Caspian Sea	Sea, Ports of Olya, Astrakhan	IB ‘Kapitan Chechkin’	3300
	Sea, Ports of Olya, Astrakhan	IB ‘Kapitan Bukaev’	3300
	Sea, Ports of Olya, Astrakhan	IB ‘Kapitan Metsayk’	3800
Sea of Okhotsk	Sea, route, Port of Magadan	IB ‘Magadan’	7000
	Sea, route, Prigorodnoye Sea Port	IB ‘Kapitan Khlebnikov’	16200
Strait of Tartary	Strait, route	IB ‘Krasin’	26500
	Strait, route, Port of Vanino	MPSV ‘Spasatel Kavdejkin’	5760
	Port of Vanino	T ‘Khasanets’	884
Peter the Great Gulf	Gulf, Port of Vladivostok	T ‘Viktor Muhortov’	883
	Gulf, Vostochny Port	T ‘Olimp’	1910
	Gulf, Port of Olga	T ‘Barkhat 1’	600
	Gulf, Port of Posyet	T ‘Khasan’	2029
	Gulf, Port of Posyet	T ‘Aleut’	2029

Note: NIB – nuclear-powered icebreaker, IB – icebreaker, T – tugboat, MPSV - multipurpose salvage vessel

2.Principles of classification of ice conditions into easy, moderate and difficult in the Arctic and non-Arctic seas

According to the researches in the non-Arctic seas mild winters correspond to easy ice conditions, moderate winters correspond to moderate ice conditions, severe winters correspond to difficult ice conditions [1]. Classification of winters by sum of degree-days of frost is usual and has proved to be well in characterizing ice conditions in different seas. The eminent expert in ice navigation theory, particularly in icebreaking capability in the Arctic and non-Arctic seas, Gordiyenko P.A. used this approach as basic in his papers [9-11]. For his research on icebreaking capability, Gordiyenko looked at the movement through ice of various thickness of the diesel icebreaker ‘Moskva’ built in 1960 and possessing significant, for that period, propeller power of 16000 kW (with total power 19000 kW). Five new diesel icebreakers coming into commission in 2008-2016 (with the lead icebreaker of the series ‘Moskva’) have total power 21000-27840 kW.

Recently the power of icebreakers has increased; furthermore, global climate is warming. Thus it is important not only to study whether it is enough to use sum of degree-days of frost to characterize different types of ice conditions, but also to determine whether the power of icebreaker fleet of a particular sea corresponds to observed ice conditions, and to understand what does ‘difficult ice conditions’ mean in this particular case.

‘Difficult’ ice conditions in the Gulf of Finland are only a relative term considering the modern state of the icebreaker fleet, for example, of the Northern-West basin Subsidiary of Rosmorport. The main reason of involving nuclear icebreaking fleet to the Gulf of Finland was not the severity of winters but necessity of providing broad waterways for supertankers.

Nevertheless, the probability of actually severe winters like those described in unique observational materials on ice cover of 20th century, still exists. Data on ice conditions during the most severe winters of the entire period of observation, which corresponds to the most difficult ice conditions, is of great practical value. Designers of hydraulic structures and icebreakers base their calculations on extreme winter data. Thus, to estimate possible ice loads on the bridge pillars during the construction of the Kerch Strait Bridge, ice thickness in Taman, which was observed during the most extreme winter on the Sea of Azov in 1954 (64 cm), was used.

Moreover, engineers enhance the power of nuclear icebreakers using information on extreme ice conditions in the Arctic region, which was observed in 1950-1990. Designed icebreaking capability of the most powerful up to date nuclear icebreakers ’50 Let Pobedy’ and ‘Yamal’ is 2.2-2.9 m (real value – 2.25 m). In 2012 AO ‘Baltic Shipyard’ started building a lead ship of the new class of icebreakers – project 22220 (LK-60Ya). The ships of the class have beam of 34 m, which is 4 meters wider than their predecessors, the ‘Arctica’ class icebreakers. It is essential for assisting large cargo ships. Moreover, the icebreaker of new class is able to combine function of deep-draft icebreaker for operating in the Central Arctic, and shallow-draft icebreaker working in the mouths of Siberian Rivers. This dual-draft icebreaker takes aboard 9000 tons of ballast water and changes its draft form 10.5 to 8.5 meters by the discharge of ballast water. The power of this class of ships is up to 60000 kW. The first ship of this class having legendary name ‘Arktika’ is expected to come into service in 2020, the next are expected to come into service nuclear-powered icebreakers ‘Sibir’ (in 2021) and ‘Ural’ (in 2022). At present, the construction of new project of nuclear icebreaker 'Lider' with power of 120000 kW, the beam of 47.7 m and designed icebreaking capability of 4.3 m is under discussion. This is the plan of Russian shipbuilders who enhance the guaranteed reliability of navigation in any ice conditions every decade. However, it would be good to observe balance between a desire to obtain funding for construction new super-icebreakers and real necessity of building such icebreakers.

Long practice of hydrometeorological and ice services of navigation in the non-Arctic seas during the cold periods shows that downward bias of average sum of degree-days of frost of specific ice season may cause problems for ice navigation in any seas.

The basis of dividing ice conditions in the Arctic seas into easy, moderate and difficult has been elaborated in AARI for many years. The expansion of industrialization of the North, longer navigation period, as well as an expected increase of cargo traffic in the Arctic by several times already to the 2024, require to specify types of ice conditions.

The peculiarity of winter ice conditions in the Arctic is the presence of residual ice in the beginning of new ice formation. During the ice seasons of 1960-1980s this factor as well as the cooling level (characterized by sum of degree-days of frost) affected the difficulty of ice conditions of the forthcoming and also the next-year ice seasons. The main underlying principle of the classification is unambiguous identification of ice conditions in the Arctic as easy, moderate or difficult. There is no identification of easy, moderate or difficult ice conditions in the normative documents of Rosmorrechflot (Federal Agency for Sea and Inland Water Transport of the Russian Federation) and Roshydromet. Few documents contain directives on permission for vessels to navigate the Northern Sea Route (NSR) in various ice conditions [8] and averaged information on permissible navigation areas and ice navigation conditions [7]. Valuable data for identification of easy, moderate or difficult ice conditions were accumulated during winter navigation of vessels by 'Norilsk Nickel' in the south-western part of the Kara Sea and in the Yenisei Gulf.

Linear relations between DDF and some ice characteristics are studied to analyze the possibility of using the sum of degree-days of frost (DDF) as a single parameter to identify the type of ice conditions in different seas. Table 6 represents these relations.

Table 6 –Correlation between sum of degree-days of frost (DDF) and ice characteristics in 7 non-Arctic seas

Sea, sea region	Relation between parameters:	Linear function	K
Kara Sea	DDF in Dickson and H_{max} in the area of station Dickson	0.0301*DDF+29.7	0.72
	DDF in Dickson and L_{max} in the Kara Sea	0.0172*DDF-50.4	0.55
White Sea	DDF in Arkhangelsk and H_{max} in the area of station Mudyug	0.0276*DDF+31.1	0.70
	DDF in Arkhangelsk and L_{max} in the Funnel of the White Sea	0.0223*DDF+50.4	0.61
Baltic Sea	DDF in St.Petersburg and H_{max} in the area of station Kronstadt	0.0321*DDF+29.9	0.76
	DDF in St.Petersburg and H_{max} in the area of station Viborg	0.0296*DDF+33.2	0.72
	DDF in St.Petersburg snd L_{max} in the Gulf of Finland	0.0696*DDF+36.2	0.78
	DDF in St.Petersburg snd L_{max} in the Baltic Sea	0.0683*DDF+0.1	0.87
Sea of Azov	DDF in Ristiv-on-Don and H_{max} in the area of station Taganrog	0.0589*DDF+11.7	0.86
	DDF in Ristov-on Don and L_{max} in the Sea of Azov	0.1116*DDF+30.4	0.76
Caspian Sea	DDF in Astrakhan and H_{max} in the area of station Peshnoy	0.0589*DDF+11.7	0.86
	DDF in Astrakhan and H_{max} in the area of station Iskustvenniy Island	0.0449*DDF+7.5	0.84
	DDF in Astrakhan and L_{max} in the North of the Caspian Sea	0.0347*DDF+65.3	0.77
Bering Sea	DDF in Anadyr and H_{max} in the area of station Anadyr	0.0356*DDF+3.2	0.75
	DDF in Anadyr and L_{max} in the Bering Sea	0.0088*DDF+5.5	0.62
Sea of Okhotsk	DDF in Magadan and H_{max} in the area of station Ayan	0.0473*DDF+4.2	0.68
	DDF in Magadan and L_{max} in the Sea of Okhotsk	0.0298*DDF+6.6	0.68
	DDF in Poronaysk and L_{max} in the Sea of Okhotsk	0.0428*DDF+3.5	0.74
	Average DDF in Poronaysk and Magadan and L_{max} in the Sea of Okhotsk	00.0421*DDF-8.5	0.77
Sea of Japan, Strait of Tartary	DDF in Aleksandrovsk-Sakhalinskiy and H_{max} in the area of station Aleksandrovsk-Sakhalinskiy	0.0473*DDF+4.2	0.68
	DDF in Aleksandrovsk-Sakhalinskiy and L_{max} in the Strait of Tartary	0.0298*DDF+6.6	0.68

Note: Hmax – maximum ice thickness for the ice season(cm); Lmax – maximum ice coverage during the ice season (%); K – correlation coefficient between calculated and observed characteristics.

Analysis of Table 6 represents strong correlation of sum of degree-days of frost with characteristics of ice conditions in the non-Arctic seas (for generalized period 1950-2018). Meanwhile, variability of correlation coefficient for different seas and characteristics varies from 0.6 to 0.8. The Kara Sea reveals weak correlation between DDF and average ice covering in September (K=0.55), indicating a necessity for additional parameters to describe the level of difficulty of ice conditions in the Arctic seas. AARI uses data on age characteristics of drift ice or on state of the arctic ice massif [12].

Table 7 provides averaged quantitative information on permissible ice thickness at which vessel is able to navigate astern an icebreaker in open passage with low speed (2-5 knots) without increasing risk of damage due to interaction between ice and the hull. Table 8 provides information on permissible speed of vessel to navigate independently in different ice conditions.

Table 7 – Ice class of vessel and corresponding permissible ice thickness for navigation with icebreaker assistance

Ice class	Ice age, Ice thickness, m	
	Winter-spring navigation	Summer-autumn navigation

Arc 4	Thin first-year ice, up to 0.7 m	Medium first-year ice, up to 0.9 m
Arc 5	Medium first-year ice, up to 0.8 m	Medium first-year ice, up to 1.2 m
Arc 6	Medium first-year ice, up to 1.2 m	Thick first-year ice, up to 1.5 m
Arc 7	Thick first-year ice, up to 1.8 m	Multi-year ice, up to 3.2 m
Arc 8	Multi-year ice, up to 3.2 m	Multi-year ice, up to 3.4 m
Arc 9	Multi-year ice, up to 3.5 m	Multi-year ice, more than 3.5 m

Table 8 – Permissible speed (Vp) for independent navigation of different ice classes in various ice conditions

Ice class	Vp., knots	Ice concentration, tenths	Ice age	Ice thickness, m	
				Winter-spring navigation	Summer-autumn navigation
Arc 4	6-8	1-6/10	First-year ice	0.6	0.8
Arc 5	«	1-6/10	First-year ice	0.8	1.0
Arc 6	«	1-6/10	First-year ice	1.1	1.3
Arc 7	«	7-8/10	First-year ice	1.4	1.7
Arc 8	10	7-8/10	Multi-year ice	2.1	3.0
Arc 9	12	9-10/10	Multi-year ice	3.5	4.0

Data listed above shows that guiding limit of ice thickness for independent navigation of ice-strengthened vessels Arc 4-Arc 6 with permissible speed up to 6-8 knots (easy ice conditions) is 0.6-1.1 m with partial concentration of first-year ice up to 6 tenths. Various speed, ice thickness and partial concentration of ice of different age may give various combinations of speed-thickness-concentration, however, permissible ice thickness is the determining factor for vessels.

Taking into account the principle of strict selection of criteria for classification, easy ice conditions for vessel classes Arc 4-Arc 6 and particularly Arc 7-Arc 9 are those with predominance of new ice, young ice and thin first-year ice (up to 0.7 m).

Using the same approach, the limits of moderate ice conditions, which allow navigation with icebreaker assistance for ice-strengthened vessels Arc 6 and independent navigation for ice-strengthened vessels Arc 7, are ice thicknesses up to 1.2 and up to 1.4 m, respectively.

Taking into account the principle of strict selection of criteria for classification, moderate ice conditions for ice-strengthened vessels Arc 6-Arc 7 and stronger classes (Arc 7-Arc 9) are those with predominance of first-year ice (ice thickness up to 1.2 m).

Difficult ice conditions, which allow navigation without restrictions for vessel classes Arc 8-Arc 9 and with restrictions for vessel class Arc 7, are those with thick first-year ice and old ice (ice thickness more than 1.2 m).

These limits coincide with ice age categories, which are identified on the Arctic sea-ice maps by international and national symbols of nomenclature of sea ice. Thus, determining the ice age is a standard procedure that doesn't make any problem for captains and navigators of icebreakers and ice vessels.

However, it should be considered that transformation of thin first-year ice to medium and subsequently to thick first-year ice can lasts from 10 to 40-50 days. The beginning of a thicker ice type formation doesn't mean univocal change of type of ice conditions as it reduces subsequently the period of navigation. Establishing the fact of older ice age type must be determined reliably by satellite images and shipboard observations. The experience of icebreaker assistance and support of navigation shows that navigation should be continued till there is a possibility to avoid unfavorable ice by maneuvering.

The experience of navigation and statistical calculations demonstrate that a vessel is able to avoid of unfavorable ice with partial concentration of 1-2 tenths by moving and maneuvering. It is substantially more difficult to avoid unfavorable ice with partial concentration more than 2-3 tenths, and it is totally impossible with 4-5 tenths.

All mentioned above allows to extend the limits for chosen criteria of determination of the type of ice conditions. But it should be considered that the accuracy of interpretation of satellite images and determining of ice age and ice cover boundary is about ±1 tenths. Therefore it is suggested to establish 3 tenths (30% from total amount of all ice types) as a limit of permissible presence of unfavorable ice. This approach ensures the presence of unfavorable ice in case of mistake of interpretation (which occurred rarely) not more than 4 tenths (40%) from the total ice concentration, i.e. the level of concentration when it is impossible to avoid unfavorable ice.

In the south-western part of the Kara Sea fast ice forms a narrow belt along the coastline in shallow waters and thus is not significance for navigation. Therefore it is suggested to exclude it from considering ice age categories.

In the north-eastern part of the sea fast ice formation all along the western passages to the Vilkitskiy Strait is possible. Fast ice there is an area of dynamic navigation and thus it is essential to consider its composition.

Considering the above it is suggested to establish the following criteria (i.e. limiting values) to determine type of ice conditions in the Kara Sea for winter season.

Easy ice conditions - new, young and thin first-year ice (up to 0.7 m) is observed, the presence of medium first-year ice up to 30% ($S_{av} < 30\%$) is possible;

Moderate ice conditions – medium first-year ice (up to 1.2 m thick) is observed in amount of 30% and more ($S_m \geq 30\%$), the presence of thick first-year ice up to 30% ($S_{th} < 30\%$) is possible;

Difficult ice conditions – thick first-year ice (more than 1.2 m thick) and old ice are observed in amount not less than 30% ($S_{th} \geq 30\%$).

During the winter-spring seasons first-year ice of autumn formation prevails in the Arctic sea routes in conditions of global warming of the 21th century, thus it is worthwhile to correlate ice types and sum of degree-days of frost the same way it was made above for the non-Arctic seas.

Table 9 shows results calculated by function from Table 6 for ice thickness (H, cm) and sum of degree-days of frost (DDF) in the area of station Dikson (correlation coefficient K=0.72).

Equation of converse relation is:

$$DDF=33.2*H-987$$

Table 9 – Ice class and corresponding permissible ice thickness for winter-spring navigation

Ice class	Ice age, Ice thickness, cm	DDF, ˚C
Arc4	Thin first-year ice, up to 70 cm	<1340
Arc5	Medium first-year ice, up to 80 cm	<1670
Arc6	Medium first-year ice, up to 120 cm	<2300
Arc7	Thick first-year ice, up to 180 cm	<4990
Arc8	Multi-year ice, more than 200 cm	<5650
Arc9	Multi-year ice, more than 200 cm	<5650

Note: maximum observed DDF in the area of the Dickson Island was 5800˚C (in 1968/1969)

The experience of previous research [1] shows that relation between DDF and ice characteristics of non-Arctic seas are the same in the area of 600-700 km from the representative observation station. This statement is true for station Arkhangelsk (White Sea) with meridional extent of about 500 km; for station Rostov-on Don (Sea of Azov) with meridional extent of about 180 km; for station Astrakhan (northern Caspian Sea) with meridional extent of about 270 km; for station Aleksandrovsk-Sakhalinskiy (Strait of Tartary) with meridional extent of about 650 km.

Meridional extent of the Baltic Sea is 1200 km. The correlation coefficient between DDF in Saint-Petersburg and maximum ice cover in the Gulf of Finland is K=0.78. This relation is appropriate for the Gulf of Finland. However, the question is whether it is appropriate for the full area of the Baltic Sea. The area of interest is the northern part of the sea including the Gulf of Bothnia, which northern coastline is 700 km far from Saint-Petersburg.

To verify the relation for the full area of the Baltic Sea, the relation between DDF in Saint-Petersburg and maximum ice cover of the Baltic Sea is calculated using the data of FIMR (Finnish Institute of Marine). The correlation coefficient in this case is even stronger (K=0.87) in comparison with the correlation coefficient for the Gulf of Finland. Evidently it is because in our study we artificially limit the area of ice cover in the Gulf of Finland in the west, which makes the correlation weaker.

Meridional extent of the Bering Sea is about 1500 km, but ice covers usually the northern part of the sea. The longest ice route from Kresta Bay to the edge of ice cover is about 800 km. Sum of degree-days of frost is calculated using data of station Anadyr.

It should be taken into account that warm water masses of the Pacific Ocean affect the location of the edge of ice cover in the far-Eastern seas (thus, affect the ice cover) and thereby reduce the impact of DDF on ice cover. Correlation coefficient between DDF in Anadyr and maximum ice cover in the Bering Sea is K=0.62 and is considered as sufficient. Correlation coefficient between DDF and ice thickness in Anadyr is significant (K=0.76).

The Sea of Okhotsk covers an area of 1 583 000 km^2, with meridional extent of 2200 km. Ice is observed in all regions of the sea. It is the most difficult sea to determine the ice conditions. The large extent of the sea causes the differences in temperature and ice regime in the northern, central and southern parts of the sea. Thus, extremely severe winter in the northern part of the Sea of Okhotsk was observed in 1965-1966, with abnormally low temperatures extended to the south to the latitude of the Shantar Islands; at the same time moderate winter was observed in the southern part of the sea. Typical situation during the severe winters in the central and southern parts of the Sea of Okhotsk is almost total covering by ice. Such situation was observed in 2001, with severe winter in the area from Bolshoy Shantar Island to Yuzhno-Kurilsk and, at the same time, moderate winter in the north of the Sea of Okhotsk (according to the data of Okhotsk and Magadan stations). In this case it is reasonable to divide the sea into two parts: northern part (northward of 54º N), and central-southern part (southward of 54º N). Calculations for the northern part of the Sea of Okhotsk are based on the data of station Magadan, calculations for the central-southern part are based on the data of station Poronaysk.

Table 10 provides information on the criteria of various ice conditions in the non-Arctic seas.

Table 10 – Criteria of different ice conditions in the non-Arctic seas

Sea, sea region	Station	Criteria based on DDF, °C		
		Easy ice conditions (mild winter)	Moderate ice conditions (moderate winter)	Difficult ice conditions (severe winter)
White Sea	Arkhangelsk	<1140	1140-1710	>1710
Baltic Sea, Gulf of Finland	St.Petersburg	<480	480-940	>940
Sea of Azov	Rostov-on-Don	<215	215-585	>585
Caspian Sea	Astrakhan	<265	265-640	>640
Bering Sea, Gulf of Anadyr	Anadyr	<3310	3310-3940	>3940
Sea of Okhotsk, northern part	Magadan	<2150	2150-2575	>2575
Sea of Okhotsk,	Poronaysk	<1530	1530-1960	>1960

mid-southern part				
Sea of Japan, Gulf of Tartary	Aleksandrovsk-Sakhalinskiy	<1635	1635-2015	>2015

3.Relation between sum of degree-days of frost and the power of icebreakers fleet in the Russian seas

It is possible to use the sum of degree-days of frost not only for specification of ice conditions. Linear relationship between DDF and the technical characteristics of icebreaker is useful for planning maritime operations.

Positive practical experience of using icebreakers to support winter navigation in the non-Arctic Russian seas and year-round navigation in the Arctic seas, as well, enables Mintrans of Russia to set the operating areas for icebreakers. The most powerful icebreakers operate in the Arctic, while low-powerful icebreaking vessels operate in non-Arctic southern seas.

Table 11 represents the correspondence of average icebreaker power in a certain sea to average DDF, average thickness of fast ice (H_f) and floating ice (H_{fl}) in the period of maximum ice development.

To evaluate ice conditions correctly it is important to learn the correlation between the thicknesses of fast and float ice. Karelin [4] analyzed data on ice thickness measurements during the drift of icebreaker ‘Lenin’ in 1937-1938 in the Arctic and compared them with fast ice thickness; thus in his research he concluded that ice thickness of smooth floating ice was 5-25% less than thickness of fast ice. Mironov in his researches [5, 6] shows that the difference between floating and fast ice thicknesses was 25-30% according to the observational data in the Laptev Sea in April-May 1988. In Table 11 the thickness of floating ice is calculated as 20% less than the thickness of fast ice.

Data from Table 11 (columns 4 and 6) enables to plot the relation between DDF and floating ice thicknesses in the Russian seas (Figure 1) with strong correlation (K=0.97).

Table 11 – Average power of icebreakers (Sav) and corresponding average ice characteristics

Sea, sea region	Sav, kW	Station (DDF/H_f)	DDF, °C	H_f, cm	H_{fl}, cm
1	2	3	4	5	6
Kara Sea	40750	Dikson/Dikson	4400	158	126
White Sea	16750	Arkhangelsk/Mudyug Isl.	1480	70	56
Baltic Sea, Gulf of Finland	18480	St.Petersburg/Krondstast	770	51	41
Sea of Azov	3600	Rostov-on-Don/Taganrog	400	37	30
Northern Caspian Sea	3470	Astrakhan/Iskustvenniy Isl.	460	28	22
Sea of Okhotsk, northern part	11600	Magadan/Ayan	2300	118	94
Sea of Japan, Gulf of Tartary	1610	Aleksandrovsk-Sakhalinskiy/ Sovetskaya Gavan	1790	100	80
Sea of Japan, Peter the Great Gulf	1490	Vladivostok/Vladivistok	1120	55	50

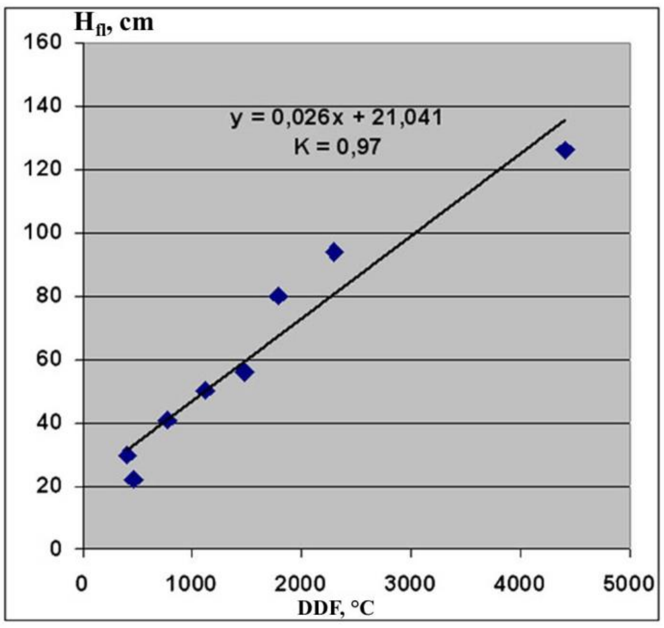


Figure 1 – Relationship between the thickness of floating ice and the sum of degree-days of frost.

Equation of this linear relationship is:

H_{fl}=0.026·DDF +21 (1),

H_{fl} – average thickness of floating ice, cm

DDF – sum of degree-days of frost, °C.

Equation of converse relation:

DDF=36.023· H_{fl}-657 (2)

Data of Table 11 is also used to plot the relationship between average power of icebreakers and:

- thickness of floating ice corresponding with average ice conditions in various seas (Fig. 2a);
- average actual sum of degree-days of frost (Fig. 2b).

Icebreaker power which is required for different ice thicknesses, thus, is calculated using the relation:

S_{av}=254.5· H_{fl}-3655.7 (3),

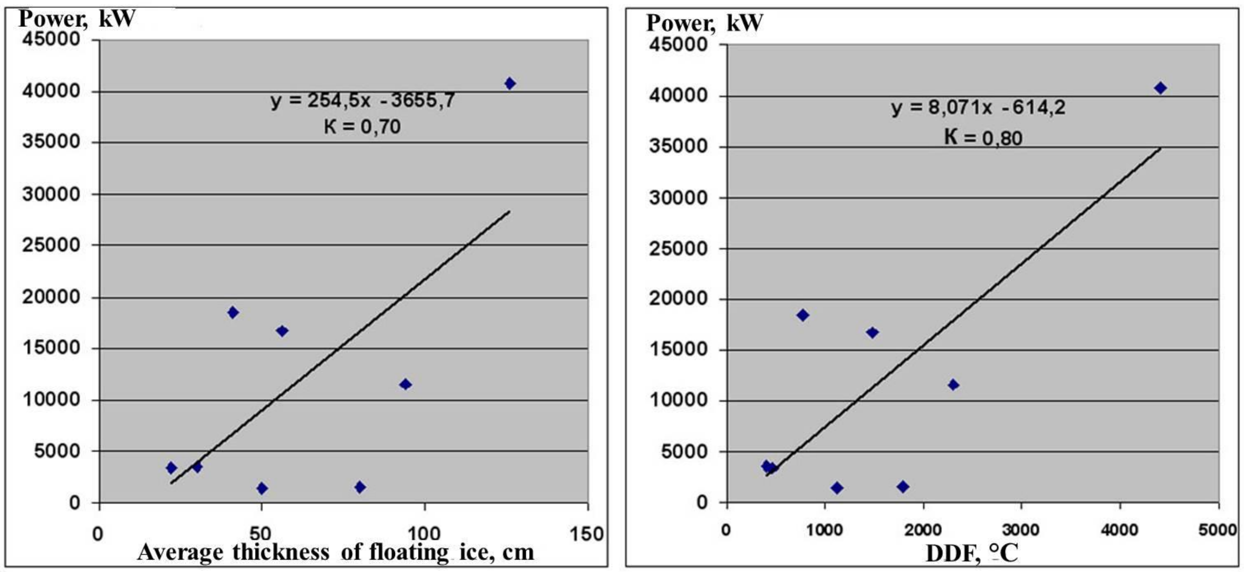
S_{av} – average power of icebreaker, kW,

H_{fl} – average thickness of floating ice, cm.

Icebreaker power (S_{av}) for a particular sum of degree-days of frost is calculated using the relation:

S_{av}=8.071· DDF-614.2 (4).

Figure 2b shows the possibility of using air temperature data for evaluation of the required average power of the icebreaker fleet.



a) b)

Figure 2 – Relationship between average power of icebreaker and (a) floating ice thickness or (b) sum of degree-days of frost.

Table 12 provides data on designed icebreaking capability during the maritime operations in the Russian seas. Sum of degree-days of frost (column 7 of Table 12) corresponding with designed ice thickness is calculated by equation (2).

Table 12 – Designed icebreaking capability and corresponding sum of degree-days of frost

N	Icebreaker	Ice class	Delivered power, kW	Shaft power, kW	V_o, knots	H_{max}, m	DDF, °C
1	2	3	4	5	6	7	8
1.	’50 Let Pobedy’	NIB, LL1	49000	55200	22	2.2-2.9	7268
2.	‘Yamal’	NIB, LL1	49000	55200	22	2.2-2.9	7268
3.	‘Taymyr’	NIB, LL2	32500	36800	18.5	1.7-2.0	5467
4.	‘Vaygach’	NIB, LL2	32500	36800	18.5	1.7-2.0	5467
5.	‘Krasin’	IB, LL2	26500	30420	19.8	1.6-1.7	5107
6.	‘Admiral Makarov’	IB, LL2	26500	30420	19.8	1.6-1.7	5107
7.	‘Ermak’	IB, LL2	26500	30438	19.5	1.6-1.7	5107
8.	‘Murmansk’	IB, LL3	18000*	27840	17	1.0-1.5	2945
9.	‘Vladivostok’	IB, LL3	18000*	27840	17	1.0-1.5	2945
10.	‘Novorossiysk’	IB, LL3	18000*	27840	17	1.0-1.5	2945
11.	‘Kapitan Dranitsyn’	IB, LL3	16200	18240	13	1.0-1.5	2945
12.	‘Kapitan Nikolaev’	IB, LL3	16200	18240	19	1.0-1.5	2945
13.	‘Kapitan Sorokin’	IB, LL3	16200	18270	19	1.0-1.5	2945
14.	‘Kapitan Khlebnikov’	IB, LL3	16200	18264	19	1.0-1.5	2945
15.	‘Sankt Peterburg’	IB, LL3	16000*	21000	17	1.0-1.5	2945
16.	‘Moskva’	IB, LL3	16000*	21000	17	1.0-1.5	2945
17.	‘Tor’	IB, LL4	8200	10172	15	0.8-1.0	2224
18.	‘Dikson’	IB, LL4	7000	9560	16.5	0.8-1.0	2224
19.	‘Mudyug’	IB, LL4	7000	9560	16.5	0.8-1.0	2224
20.	‘Magadan’	IB, LL4	7000	9560	16.5	0.8-1.0	2224
21.	‘Karu’	IB, LL4	4160	5550	13	0.8-1.0	2224
22.	‘Kapitan Evdokimov’	River IB	3800	4815	14	0.7-0.9	1865
23.	‘Kapitan Metsayk’	River IB	3800	4815	14	0.7-0.9	1865
24.	‘Kapitan Moshkin’	River IB	3800	4815	14	0.7-0.9	1865
25.	‘Kapitan Demidov’	River IB	3800	4815	14	0.7-0.9	1865
26.	‘Kapitan Chudinov’	River IB	3800	4815	14	0.7-0.9	1865
27.	‘Kapitan Chadaev’	River IB	3300	4650	14	0.7-0.9	1865
28.	‘Kapitan Chechkin’	River IB	3300	4650	14	0.7-0.9	1865
29.	‘Kapitan Bukaev’	River IB	3300	4650	14	0.7-0.9	1865
30.	‘Kapitan Krutov’	River IB	3300	4638	14	0.7-0.9	1865
31.	‘Kapitan Zarubin’	River IB	3300	4650	14	0.7-0.9	1865
32.	‘Kapitan Plakhin’	River IB	3300	4650	14	0.7-0.9	1865
33.	‘Ivan Kruzenshtern’	IB, LL4	3900	4500	14	0.7-0.9	1865
34.	‘Semen Dezhnev’	IB, LL4	3450	4500	14	0.7-0.9	1865
35.	‘Yuriy	IB, LL4	3500	3975	14	0.7-0.0	1865

	'Lisyanskiy'						
36.	'Kapitan M.Izmaylov'	IB, LL4	2500	3912	13	0.6-0.7	1504
37.	'Kapitan Kosolapov'	IB, LL4	2500	4400	13	0.6-0.7	1504
38.	'Sevmorput'	LASH, UL		29420	20.8	0.8-1.0	2945
39.	'Spasatel Kavdejkin'	MPVS, Arc5		5760	15	0.8-1.0	2224
40.	'Khasan'	T, Arc4		2029	12	0.6-0.7	1504
41.	'Aleut'	T, Arc4		2019	12	0.6-0.7	1504
42.	'Olimp'	T, Ice3		1910	11.5	0.5	1144

*Note: V_o - open water speed, LASH - nuclear-powered icebreaking LASH (lighter aboard ship) carrier, MPSV - multipurpose salvage vessel, T – tugboat. For the icebreakers with pod drives (matched with *) the term 'shaft power' is incorrect, the correct one is 'propeller power'.*

Data provided by the Table 12 are used to plot the relationship between the designed power of icebreakers and:

- ice thickness corresponding with lower limit of designed icebreaking capability (it is evident that upper limit of icebreaking capability is rare achievable);
- sum of degree-days of frost corresponding with lower limit of designed icebreaking capability.

The equations of linear regressions relate the icebreaker power to designed ice thickness and DDF. The designed power of icebreaker is correlated with ice thickness by equation:

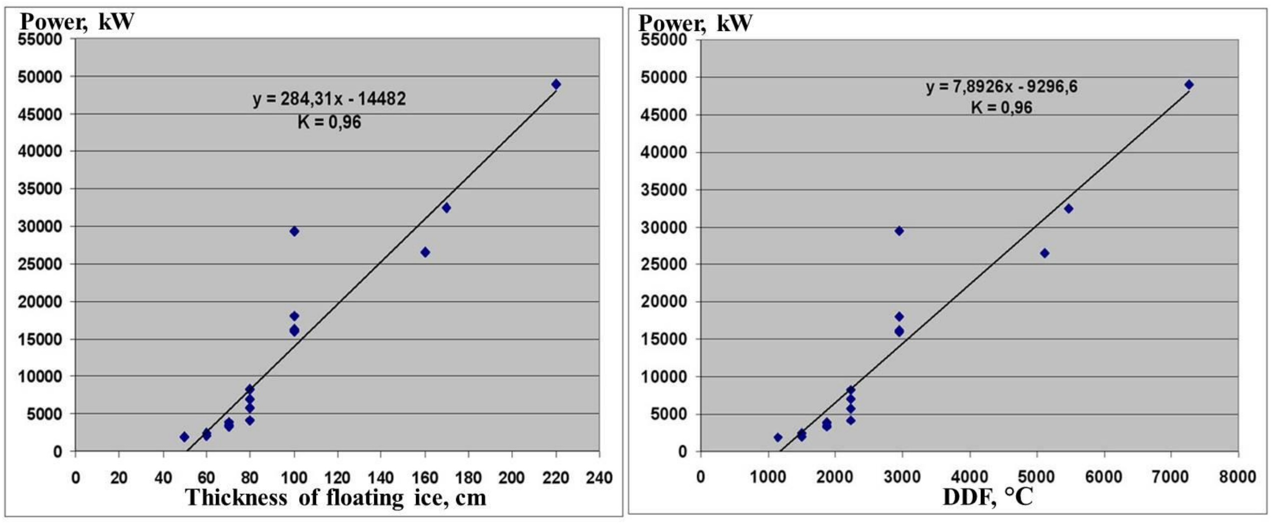
$S_d=284.31\cdot H_d-14482$ (5),

S_d – designed power of icebreaker, kW;

H_d – designed ice thickness, cm.

Designed power of icebreaker is correlated with sum of degree-days of frost by equation:

$S_d=7.8926\cdot DDF-9296$ (6).



a) b)

Figure 3 – Relationship between the designed power of icebreaker and the thickness of floating ice (a) or the sum of degree-days of frost (b) associated with lower limit of designed icebreaking capability.

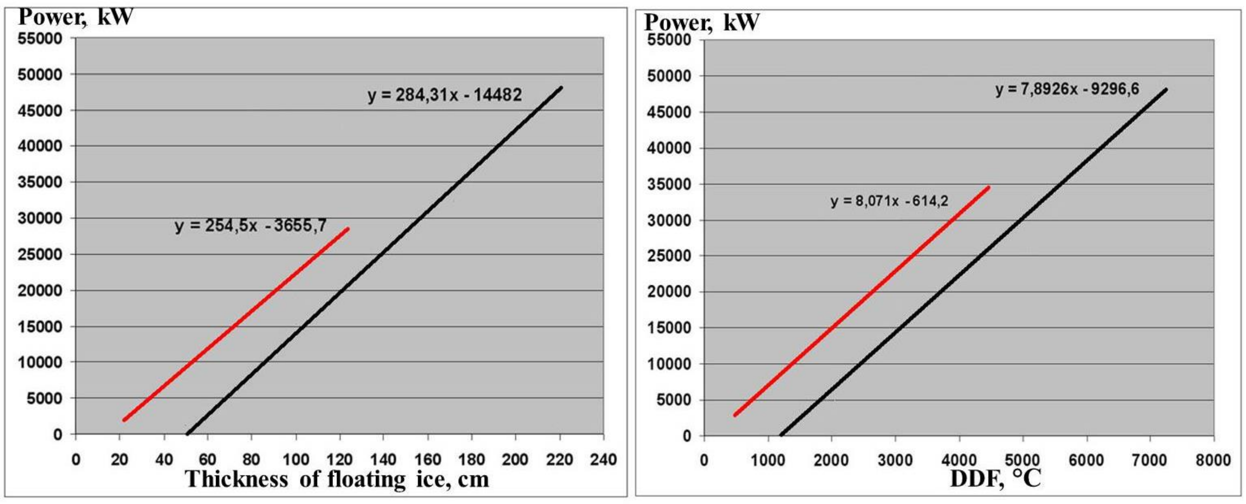
Figure 4a represents the combined plots of correlation between:

a) ice thickness and average power of actual icebreakers operated in different seas;
b) ice thickness corresponding with lower limit of designed icebreaking capability, and designed power of icebreaker.

Figure 4b represents the combined plots of correlation between:

a) sum of degree-days of frost and average power of actual icebreakers operated in different seas;

sum of degree-days of frost, corresponding with lower limit of designed icebreaking capability, and designed power of icebreaker.



a) b)

Figure 4 – Relationships between power of icebreaker and a) designed (black line) and average actual (red line) ice thickness; b) designed (black line) and average actual (red line) sum of degree-days of frost.

Analysis of relationships in the Figure 4a reveals that average power of icebreakers, which provide the satisfying assistance of vessels in the Russian seas, exceed the optimal (designed) power for equal ice thicknesses. This is due to fact that actual icebreakers often operate in areas of hummocked ice, which require more power input to break it. Besides, ice conditions can be more difficult than moderate.

Figure 4b is of special interest. Analysis of relationships reveals that sum of degree-days of frost during winters with moderate ice conditions is significantly less (by about 1000ºC) than sum of degree-days of frost corresponding with power of icebreakers usually operated in the Russian seas. Icebreaker fleet, thus, has considerable power reserve in case of more difficult than moderate ice conditions. To evaluate whether this reserve power is sufficient to operate in conditions of extremely severe winter, the deviations of extreme values of DDF from mean values are calculated (Table 13). According to the data, the reserve is sufficient.

Table 13 – Deviations of extreme values of sum of degree-days of frost (DDF_{max}) from mean values (DDF_{mean})

Sea, sea region	Observation station	DDFmax	DDFmean	Δ DDF
White Sea	Archangelsk	2325	1480	845
Gulf of Finland	St. Petersburg	1800	770	1030
Sea of Azov	Rostov-on-Don	1277	400	877
Northern Caspian Sea	Astrakhan	1240	460	780
Sea of Okhotsk, northern part	Magadan	2955	2300	655
Sea of Okhotsk, Central-southern part	Poronaysk	2276	1720	556
Mean	**790**			

Conclusions

The research has indicated the following:

1. Sum of degree-days of frost is sufficient to characterize ice conditions in the non-Arctic seas and can be used alone to determine the type of ice conditions. To characterize ice conditions in the Arctic seas additional parameters should be used.
2. Sum of degree-days of frost can be also used for calculation of powers of icebreakers in particular ice conditions to set operating areas.
3. The power of the modern icebreaking fleet enables to navigate successfully in the Russian seas equally in conditions of mild and moderate winters, and in conditions of severe and extremely severe winters.
4. Icebreaker fleet has considerable power reserve which is sufficient to cover all possible deviations of temperature regime which can turn moderate ice conditions into difficult.
5. Long-term ice forecasts of the forthcoming ice navigation season predict mild and moderate winters corresponding with easy and moderate ice conditions due to global warming.
6. The power of icebreakers built in 21th century exceeds significantly the power of icebreaker fleet in the latter half of the 20th century. Meanwhile, two opposite processes are observed: increasing power of built and designed icebreakers from the one hand, and decreasing ice thickness in all Russian seas due to sustainable warming from the other. Thus, the approach of classification of ice conditions into easy, moderate and difficult, which is based on temperature variability (DDF), doesn't represent real challenges of ice navigation.
7. Actually challenging conditions for ice navigation are revealed to occur in following situations:
   - Lack of icebreakers for assistance due to increasing ship traffic on the route;
   - The beam of an icebreaker is insufficient to assist super-ships (for ex., super tanker with beam of 50m);
   - The main icebreaker in the region is underpowered for moderate ice conditions in the sea (for ex., IB "Magadan" in the Sea of Okhotsk);
   - Icebreaking capability is decreased due to exhausted lifetime;
   - Convoy of vessels meets with hummocked and ridged ice zone; there is presence of vessels with ice class which is not in compliance with moderate ice conditions in the sea;
   - A technical accident.

   The concept of easy, moderate and difficult ice conditions corresponding with winter severity is still used by navigators in excuse of problems during their winter navigation, though ice conditions are usually not the main challenge. Obviously, during the loss of way in ice as a result of any reason, the presence of ice complicates a situation and turns almost any ice conditions to difficult.

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SPECIFIC FEATURES OF HEAVY-TONNAGE VESSELS-ICEBREAKERS INTERACTION IN ICE CONDITIONS

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This article shows that it necessary nearly constant icebreakers operation in creating of marine transportation systems directed at export of hydrocarbon row materials eastward. The main approaches for heavy-tonnage vessels escorting by icebreakers have been considered. The specific features of these approaches have been described.

Keywords: heavy-tonnage vessel, icebreaker, ice channel, ship escorting in ice, ship speed

Introduction. Economic analysis of the effectiveness of almost any marine transport system intended for transporting cargo in the Arctic regions shows that achieving high performance is possible only when heavy-tonnage ice vessels are used as part of such systems [1,2]. Currently, the most developed marine transport systems in the Arctic are those meant for transportation of liquefied natural gas (LNG) from the areas where it is produced, and, accordingly, these are heavy-tonnage LNG vessels that are now most frequently navigating in the Arctic waters. This is confirmed by the analysis of the structure of the transport fleet in the waters of the Northern Sea Route [3,4].

Theoretically, there are several scenarios for using heavy-tonnage vessels in freezing waters in marine transport systems, including in the Arctic seas. The main difference between these scenarios is the degree of independent navigation of a heavy-tonnage vessel in ice. It is possible to imagine a transport system based on the almost constant independent navigation of a heavy-tonnage vessel in ice conditions. It is also quite likely that the transport system, which is based on the powerful icebreaker fleet, and the movement of a heavy-tonnage vessel in ice conditions is mainly carried out while piloted or escorted by an icebreaker. The choice of a particular transport system largely determines the requirements for design of the heavy-tonnage vessel.

The main directions of LNG export from the Russian Arctic. When choosing a concept and, consequently, approaches for the design of a heavy-tonnage ice vessel, an important role is played by the strategy for the development of the transport system in which it is supposed to be used. Currently, the main shipping terminals for hydrocarbon raw materials are located in the bays of the Kara sea. Possible directions of transportation of the extracted products are shown in Fig. 1.

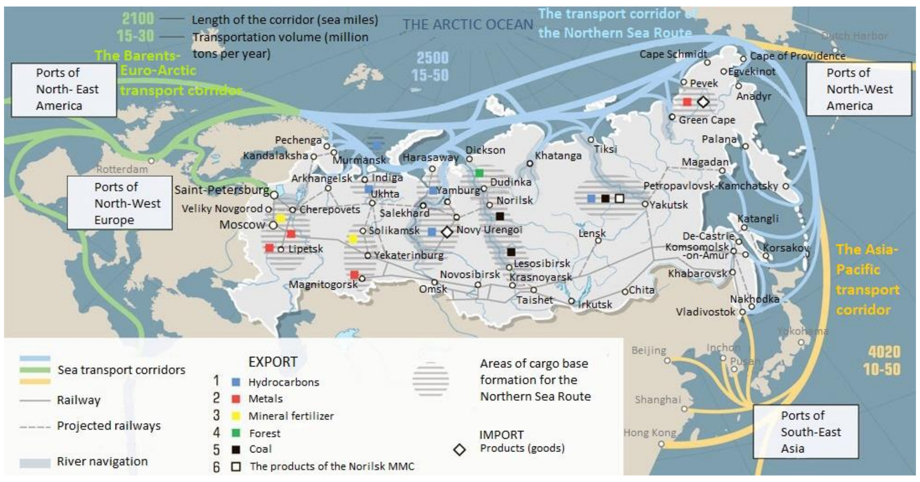

Fig. 1. The marine transport system of Russia

For the LNG transport systems that were considered until recently, the Western direction of transportation was the main one, focused on the European gas terminals. This orientation of transport systems imposed several requirements for the ice worthiness and seaworthiness of heavy-tonnage ships carrying LNG. The main requirements were:

- maximum enhancement of the possibility of independent navigation of heavy-tonnage vessels in ice conditions;
- ensuring high performance on clean water.

These requirements were determined by two major factors. This was a relatively short navigation distance of a heavy-tonnage vessel in ice conditions, and this navigation should not be carried out in the most severe seas of the Western sector of the Russian Arctic. The greatest ice difficulties could occur only when crossing the Kara sea during the high period of ice cover development from March to May. It should be noted that the seas of the Western sector are the most studied in terms of hydrology and ice regime, they have satellite information about the distribution of ice, and reliable forecasting methods have been also developed. The thickness of the thermal ice cover rarely exceeds 1.5 m. All this is superimposed by the general decrease of the Arctic sea ice, which has been observed recently. The analysis of combination of all these factors gave some reason to hope that the regime of independent navigation of heavy-tonnage vessels in the Western sector would be the main one.

The second important factor is the relatively short length of the route from the ice edge to the European ports, such as Rotterdam, for example. This allowed to hope for the economic feasibility of transporting hydrocarbons by one vessel to the port of destination without intermediate transshipment and ensuring the necessary rhythm of deliveries cycle. In case of possible violations of the schedule of movement of heavy-tonnage vessel in ice conditions, it is almost always possible to make up for lost time on clean water, using the available power reserve.

An attempt to meet the above requirements led the Finnish specialists to create the concept of double-acting ships (DAS), which were supposed to show good economic performance when navigating both on clean water and in ice. From the time of proclamation and until present moment, the concept of double-acting ships has undergone quite significant changes and is now practically reduced to providing increased icebreaking capability when astern moving. We are no longer talking about good indicators for clean water [2]. The first heavy-tonnage Arctic vessels created to meet the above requirements have already started operating in the Arctic as part of the Yamal LNG project (Fig.2). In total, 15 gas carriers will be built at the Daewoo Shipbuilding and Marine Engineering shipyard in South Korea to serve the needs of this Yamal LNG project. The vessels have the same deadweight of 85 thousand tons, a length of 295 m and a width of 50 m. The capacity of Yamalmax class gas carriers is 172.6 thousand cubic meters of gas.

Fig. 2. "Vladimir Rusanov", the Yamal Max type heavy-tonnage vessel for LNG transportation (photo by D.V. Labuzov, dmitry-v-ch-l.livejournal.com)

Recently, there has been an active discussion of the possibility of creating the marine transport system focused on the export of hydrocarbon raw materials from production areas in the Eastern direction to the Asia-Pacific region. The functioning conditions of the marine transport system in the Eastern sector of the Arctic are significantly more complex than the ones in the Western sector [5]. This circumstance imposes certain requirements on the composition of such transport system. First of all, it seems that the previously existed requirement for the possibility of active independent navigation of a heavy-tonnage gas carrier during year-round operation should be put off. This follows from the comparison of the length of route sections in ice conditions in the Eastern and Western directions. In addition, in all respects, the ice conditions in the Eastern sector of the Arctic are more severe. When moving eastwards, the probability of a dangerous situation occurring when a heavy-tonnage LNG vessel sails alone increases dramatically even in seasons with a light type of the Arctic navigation. Therefore, despite the high icebreaking capacity of modern gas carriers and successful examples of their independent navigation on the NSR, the involvement of icebreakers for the organization of year-round LNG transportation is one of the main tasks in the development of the marine transport system. In this case, there is an additional requirement for ensuring the average speed of ships during navigation. It must be at least 10 knots to ensure the rhythm of deliveries cycle [6].

Reorienting the export direction of products from West to East imposes certain requirements on the ice quality of icebreakers and heavy-tonnage vessels being the part of the transport system. For icebreakers, this is the ability to move at the specified speeds in ice with a thickness of 1.5 – 2.0 m. A new requirement is also imposed on heavy-tonnage vessels – the ability to move at the specified speeds in the channel behind the icebreaker. At the same time, depending on the ratio of the width of the hull of a heavy-tonnage vessel and an icebreaker, this channel can be "wide" or "narrow". A "wide" channel is formed when the icebreaker is leading, and its width is more than or approximately equal to the width of the vessel being piloted. In this case, the heavy-tonnage vessel practically does not interact with the edges of the channel, and its ice resistance is determined by the interaction with small-sized ice in the channel. A "narrow" channel occurs when the width of an LNG tanker is more than the width of the icebreaker piloting it. In this case, the ship is forced to break the edges of the channel with its hull. It is obvious that during this movement, part of the ship's hull interacts with solid ice, and part with broken ice, which, in the channel, is behind the icebreaker. It can be expected that the hull shape of the heavy-tonnage vessel, which was designed for independent navigation, will not be optimal for operating conditions in "wide" or "narrow" channels.

Interest in the use of heavy-tonnage vessels in the Eastern sector of the Arctic also arises from the problem of organizing a transport corridor linking Europe and Asia. Table 1 shows data from the Federal State Unitary Enterprise “Atomflot” on the distance and time spent on moving cargo from Murmansk to the main ports of the Pacific region, which demonstrate the attractiveness of such transportation. Further, we will discuss in more detail the features of navigation of heavy-tonnage vessels in ice when moving independently and under pilotage of icebreakers.

Table 1 - Distance and time spent on cargo transportation (at an average speed of 14.0 knots)

From Murmansk	Via the Suez Canal miles/days	By the Northern Sea Route, miles/days
Kobe (Japan)	12291/36,6	6010/17,9
Busan (Korea)	12266/36,5	6097/18,1
Ningbo (China)	11848/35,3	6577/19,6

Methods of piloting heavy-tonnage vessels by icebreakers. The influence of the LNG export direction on the composition and operation of the marine transport system was discussed above. The sea transport systems, oriented to export LNG to the West, have been repeatedly analyzed (see, e.g., [2] and the given references), so it appears most relevant to consider in more detail the transport system, oriented to export LNG to the East.

The operation of such transport system, as well as system oriented in the Western direction, implies the possibility of independent navigation of heavy-tonnage vessels in the Eastern sector of the Russian Arctic. The difference is that such navigation is almost impossible during the period of maximum development of the ice cover. In addition, in seasons of hard and extreme type of navigation, independent navigation of heavy-tonnage vessels is likely to be impossible all year round. Thus, when using heavy-tonnage vessels in the Eastern sector of the Arctic, the role of the icebreaker fleet in the functioning of the marine transport system increases significantly.

The interaction of an icebreaker and a heavy-tonnage ice vessel is a new problem for marine ice engineering [7], which has become actively studied only recently. For a long time, the vast majority of experts believed that the main mode of movement of a heavy-tonnage vessel in ice was independent navigation, which was carried out when astern moving (double-action technologies, see, for example, work [8]). Therefore, most research was focused on the study of independent navigation of heavy-tonnage vessels in ice, including the mode of astern movement (see works [9], [10], etc.). A relatively small number of research works is devoted to the interaction of icebreaker with heavy-tonnage vessel.

A channel in the ice for piloting heavy-tonnage vessel can be made by one or two icebreakers. The features of interaction between a heavy-tonnage vessel and one icebreaker are determined by the ratio of the width of the vessel B_S and the width of the channel made by icebreaker $B_C \approx 1.1 \div 1.2 B_1$, where B_1 -is the width of the icebreaker. If $B_S \leq B_C$, then the movement of a heavy-tonnage vessel does not formally differ from the movement of any vessel in the ice channel. Let us call this situation as the movement of the ship in a "wide" ice channel. In case $B_S > B_C$, a heavy-tonnage vessel has to destroy the edges of the channel with its hull during the movement. This movement is called a "narrow" channel movement.

When laying the ice channel with two icebreakers, a sufficiently wide channel can be formed, through which a heavy-tonnage vessel can freely move (Fig. 3). Such a channel can be created if the following condition is met: $1.1(B_{11} + B_{12}) \geq B_S$, i.e. the total width of the channels behind the two icebreakers must exceed the width of the vessel being piloted. Otherwise, the heavy-tonnage vessel will have to further expand the channel with its hull.

Fig. 3 – Simulation of heavy-tonnage tanker pilotage by two icebreakers (bottom right – channel formed by two icebreakers)

Features of movement of heavy-tonnage vessel through the "wide" channel. It should be noted that currently there are no technical means to create the "wide" ice channel for the heavy-tonnage vessels. The third-generation nuclear icebreakers of project 22220, which are now under construction, and the head icebreaker "Arctic", will be able to create ice channels with a width of $B_C \leq 35 \div 36$m, which is clearly not enough for existing vessels of the "Christophe de Margerie" type. Currently, a nuclear-powered icebreaker leader with a capacity of 120 MW is being designed [11] to be capable of laying a channel in the ice with a width of $50 \div 52$ m, enough in width for piloting most heavy-tonnage vessels. Russian experts have been proposed with the concept of creating a multi-hull icebreaker that can create an ice channel with the width of more than 50 m [12]. The preliminary study of this proposal so far confirmed the high ice qualities of the multi-hull icebreaker and showed the principal possibility of its creation.

Currently, research on the movement of heavy-tonnage vessels through "wide" channels is carried out mainly to ensure the design of new technical means for creation of such channels. Nevertheless, the results of the performed works allow us to draw some conclusions about the features of movement of heavy-tonnage vessels through "wide" channels. Despite the external similarity of the processes of movement along the "wide" ice channel of ordinary and heavy-tonnage vessels, there is one extremely important difference between them. This difference lies in the fact that an ordinary ship always has a width less than the width of the channel, and there is enough distance between the edges of the channel and the shipside. The presence of this distance affects the way the ship's hull interacts with the broken ice in the channel. This ice is partially compacted during the movement of an ordinary vessel and moves apart to the edges of the channel. The presence of channel edges has almost no effect on the nature of the interaction of the hull with broken ice. Sinkage of broken ice by the hull is extremely rare in the presence of ice compressions and strong ice movements.

A heavy-tonnage vessel has its hull width that is comparable to the width of the channel $B_S \approx B_C$. At the same time, the edges of the ice channel prevent the processes of ice spreading. Heavy-tonnage vessel compacts and partially pushes the broken ice in the channel in front of it. The only way to remove the broken ice that interferes with its movement is to cover it with the ship's hull and pass it under the hull. This process is quite energy-intensive, which leads to an increase in the ice resistance of a heavy-tonnage vessel when moving along the "wide" channel. The results of model tests performed in the ice basin of the Krylov research center [13] show that interaction with broken ice in the channel is the main obstacle to increasing the speed of a heavy-tonnage vessel in the "wide" channel. Well-powered vessels of the Yamal Max type cannot develop their speed equal to the speed of channel laying. There was no significant gain in trying to apply some optimization of the shape of the hull contours of a heavy-tonnage vessel, aimed primarily at improving the movement performance in the "narrow" channel (see table 2).

Table 2 – Speed of the Arc7 gas tanker with the original and optimized hull shape in the fresh channel, knots

Thickness of flat ice, m	Channel behind leader icebreaker (B=47,5 m), channel width 52 m		Channel behind icebreaker LK-60YA (B=33 м), channel width 35 m		Comparison of the width of the channel	
					Channel behind icebreaker LK-40 (B=28,5 m), channel width 31 m	Channel behind icebreaker “50 years of Victory” (B=28 m), channel width 30-31 m
	original	optimized	original	optimized	original	optimized
1,5	9	9,2	4,8	8,5	4,9	7,5
2,1	7,1	7,5	2,3	6,2	2,4	6,0

Movement of heavy-tonnage vessel through the "narrow" channel. Currently, using one icebreaker to pilot a heavy-tonnage vessel in ice leads to its movement along the "narrow" channel. For a long time, when considering the possibility of such movement, it was assumed that a heavy-tonnage vessel moved symmetrically relative to the axis of the channel [2]. However, in recent experiments with self-powered models in the Krylovsky center ice basin, a previously unknown effect of breaking the symmetry of such movement was found out. The model of the ship was placed spontaneously in the channel so that one of its sides destroyed the edge of the channel to the required width, and the other rubbed against the opposite edge. Later it was found that a similar pattern of movement of heavy-tonnage vessels was observed in full-scale conditions (see, for example, Fig. 4 [14]).

Fig. 4 . “Propontis” tanker piloted by the “Taimyr”-type nuclear icebreaker

The detected effect was studied experimentally in the ice pool and theoretically. Tests in the ice pool showed that the effect was significantly affected by the slope of the ship's side in the area of the parallel middlebody. When the angle of inclination was zero, the effect was rather vivid. When the angle of inclination was 10º, the effect could be realized or not. To find out the nature of the effect, a simple mathematical model of the observed phenomenon was developed, which allowed to calculate the longitudinal and transverse forces acting on the ship's hull when its midship line deviated from the channel axis [15, 16]. The results of the calculations showed the following.

– The ship's position symmetrical to the channel axis is stable. However, this stable position can be easily violated by relatively small external influences, such as local changes in the thickness or strength of the ice.

– After displacing relative to the channel axis by a certain amount, the vessel is constantly affected by an increasing disturbing force, which leads it to the asymmetric position. The appearance of the disturbing force is due to the peculiarity of the shape of the hull of heavy-tonnage vessels in the area of transition of forebody entrance into a parallel middlebody with straight-walled sides.

– The asymmetric position of the vessel is stable, and a significant effort must be made to remove the vessel from this position using the controls.

– A heavy-tonnage vessel that has a 10º side slope in the area of the parallel middlebody, has a more optimal hull shape. Therefore, the symmetrical position of the ship in the channel is not so easily disturbed. This can only happen with very strong random influences. The value of the disturbing force is smaller and the exit from the asymmetric position is easier.

The possibility of an asymmetric location of a heavy-tonnage vessel in the channel must be taken into account when organizing its pilotage, for example, when assigning a safe distance between ships during the piloting.

Table 2 shows the results of model studies of movement of heavy-tonnage vessels along the "narrow" channels laid by various icebreakers. During the research, we studied the interaction with ice channels of two models that were very similar in main dimensions. The main difference between the models was that one of them had a side slope in the area of the parallel middlebody, which was equal to 10º. In table 2, this model was called optimized. The peculiarity of the tests was that the ice channel was laid by the corresponding self-propelled model of the icebreaker, which were performed on the same scale as the models of heavy-tonnage vessels. In Fig.5 one of the episodes in the course of the model experiment is presented.

Fig. 5. Model studies: movement of a heavy-tonnage vessel model along the channel laid by an icebreaker model.

The results presented in table 2 allow us to draw the following conclusions.

– Received data confirm that the speed of a heavy-tonnage vessel in the channel significantly depends on its width, which, in its turn, depends on the width of the leading icebreaker. When a ship moves in a channel with width equal to or slightly greater than its width, the resistance is determined by the interaction of the hull with broken ice and individual interactions with the protrusions of the channel.

– Experimental data of the work convincingly show that it is possible to significantly increase the speed of a heavy-tonnage vessel in the "narrow" channel by purposefully optimizing the shape of its hull. In the experiments carried out, the increase in the speed of the optimized model was 2-2.5 knots.

Piloting by two icebreakers. This method of piloting heavy-tonnage vessels was the first to be used in the freezing seas of the Arctic type (Fig.3). This tactic allows to pilot in ice a vessel of almost any width. The only requirement is that the total width of the icebreakers exceeds the width of the vessel under pilotage.

When laying the wide channel in ice, icebreakers move stepwise, this way they are able to reduce the total energy consumption (Fig.6). When icebreakers move stepwise, the second icebreaker splits and shifts relatively large fragments of ice cover into the channel formed by the first icebreaker. Therefore, heavy-tonnage vessel does not move in small-broken ice, as in a normal channel, but in large-broken ice with characteristic size of 20-100 m. In order to determine the speed of the vessel's movement along the wide channel, it is necessary to have information about its ice resistance in these conditions. The Krylov State Research Centre developed effective methods for experimental and theoretical determination of ice resistance of heavy-tonnage vessel when moving in large-broken ice and in fragments of ice fields [2, 17].

Fig. 6. Piloting heavy-tonnage vessel with two icebreakers

Piloting by two icebreakers is also preferable for overcoming areas of compressed ice. Even with very strong compressions, the probability of vessel jam in ice is small. There may be a situation where a part of the ship's hull can interact with compressed ice (Fig.7), however, in this case the vessel will be able to continue moving [18].

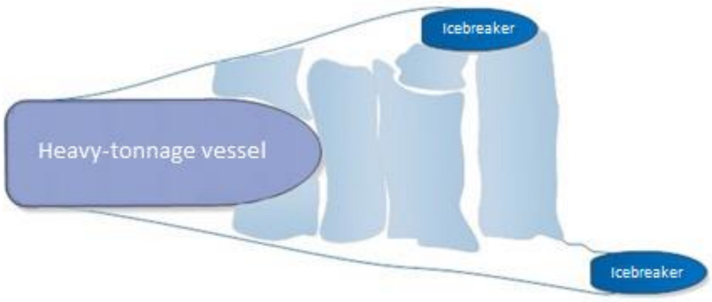

Fig. 7. Partial interaction of the vessel with the channel edges when being piloted by two icebreakers under compression conditions

There is no doubt in the efficiency and safety of piloting heavy-tonnage vessels by two icebreakers. However, due to the increased cost of pilotage and due to the lack of the necessary quantity of icebreakers for mass transport, this piloting tactic cannot be considered as the main one.

Conclusion.

The results presented in this research show that the icebreaking fleet, primarily nuclear-powered, is one of the main components of any marine transport system designed to operate in the Eastern sector of the Arctic. In order to significantly improve the efficiency of such transport system, it is necessary to create new technical means that can lay the "wide" channel in ice for heavy-tonnage vessels.

When designing new heavy-tonnage vessels intended for year-round operation on the entire route of the Northern Sea Route, it is necessary to consider the peculiarities of their interaction with piloting icebreakers. As shown by the results of studies already performed, by optimizing the shape of the hull of a heavy-tonnage vessel while maintaining its cargo capacity and power consumption, it is possible to achieve a significant increase in the speed of movement in the "narrow" channel.

The widespread introduction of new technical tools that create "wide" channels in ice will also require the search for new solutions for the shape of the hull of heavy-tonnage vessels. These solutions will have to minimize losses on overcoming the ice resistance of broken ice in the "wide" channel.

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CURRENT TRENDS AND CHALLENGES FOR THE DESIGNING OF ARCTIC CARGO VESSELS

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The experience of the designing and operation of modern large Arctic icebreaking cargo vessels is analyzed, the main trends of their further development are given. New challenges for designers are associated with a significant increase in cargo transportation volumes and plans for organizing year-round transportation along the entire Northern Sea Route, with stricter environmental requirements for Arctic ships, as well as to some extent with changes in legislation.

Keywords: arctic shipbuilding, icebreaking cargo vessel, Northern Sea Route, ship design, ice class, liquefied natural gas

Modern arctic cargo fleet of Russia

The desire of shipowners to minimize dependence on icebreaker services, as well as the development of new projects for the export of hydrocarbons from the Russian Arctic, have led to the creation of fundamentally new types of icebreaking cargo vessels capable of providing reliable, cost-effective and safe shipping. Such cargo vessels of new generation equipped with electric motor in azimuthing propeller pod units (Azipod of ABB) appeared in the Arctic after Norilsk Nickel mining company, in order to reduce the cost of transportation of production, decided in 2004 to create its own cargo fleet to replace SA-15 ("Norilsk" type) vessels, built in the 1980s. The design of the Arctic container ship with 648 TEU capacity, intended to ensure year-round transportation of Norilsk Nickel cargo on the Arctic line Murmansk-Dudinka, was developed by Kvaerner Masa-Yards research center (currently Aker Arctic Technology) in accordance with the Double Acting Ship (DAS™) concept for the conditions of independent ice navigation in the south-western part of the Kara Sea.

The first prototype diesel-electric arctic container vessel Norilskiy Nickel (see principal parameters in Table 1) was built at the Helsinki shipyard and successfully passed delivery ice trials in the Spring of 2006 [1]. Then another 4 sister ships of this type were built at the Nordic Yards, and by the same shipyard – Arctic product tanker Yenisei, also according to Norilskiy Nickel design concept, with the same dimensions, hull form and propulsion system. Almost at the same time, 3 Arctic shuttle tankers of Vasily Dinkov type were built by Samsung Heavy Industries shipyard for the purpose of exporting crude oil from the Varandey offshore ice-resistant terminal, and for exporting of oil produced by the offshore ice-resistant stationary platform Prirazlomnaya, two shuttle tankers of Mikhail Ulyanov type were delivered from Admiralty Shipyards in St. Petersburg. The main characteristics of both types of tankers, which have some differences due to different design approaches but the same ice class and deadweight, are given in Table 1. Aker Arctic Technology carried out model tests in the own ice tank and designed hull form of these vessels, as well as developed a technical design of Mikhail Ulyanov type tankers [2].

Table 1 - Main characteristics of icebreaking cargo vessels for Russian Arctic, built in the 21st century

Name of the first vessel in series	Norilskiy Nickel (Enisey)	Vasiliy Dinkov	Mikhail Ulyanov	Christophe de Margerie	Shturman Albanov	B.Sokolov (Y.Kuchiev)	Audax
Number of vessels in series	5 + 1	3	2	15	7	1 + 1	2
Years of delivery	2006-09, 2011	2008-09	2010	2016-2019	2016-17, 2019	2018-19	2016
Country of build	Finland, Germany	S.Korea	Russia	S.Korea	S.Korea	China, Finland	China
Ice class	Arc7	Arc6	Arc6	Arc7	Arc7	Arc7	Arc7/PC3
Length overall, m	169	257.3	257.7	299	245	214 (229)	206.3
Breadth, m	23.1	34	34	50	34	34 (32.5)	43
Design draft, m	9.0	14.0	14.0	11.7	9.0	11.7	7.5
Deadweight, ton	14500	70000	70000	80000	38000	43400	24500
Propulsion	1 Azipod	2 Azipod	2 Azipod	3 Azipod	2 Azipod	2 Azipod	2 CPP
Shaft power, MW	13	20	17	45	22	22	24
Icebreaking capability, m (ahead / astern)	1.5 / 1.65	1.7 / 1.7	1.0 / 1.6	1.5 / 2.1	1.4 / 1.7	1.5 / 1.8	1.5

The next big and important step in the development of Arctic cargo vessels was the realization of projects for the export of hydrocarbons from the Gulf of Ob. First of all, this is Yamal LNG project, which envisages the construction of a natural gas liquefaction plant in Sabetta and seaborn transportation of LNG and gas condensate to European and Asian markets. With the most active participation of Aker Arctic, a design concept of the Arc7 ice class LNG carrier with a capacity of about 170 000 m^3 was created. Concept was based on propulsion complex of three Azipod units with a total power of 45 MW, providing independent sailing in ice conditions, both ahead and astern, and moderate icebreaking bow hull lines are also designed for acceptable seaworthiness in open water [3]. The first arctic icebreaking LNG carrier, Christophe de Margerie, successfully passed ice trials and was commissioned in 2016; the Korean DSME shipyard is currently completing the construction of this ship series (known as the Yamalmax type) of 15 LNG carriers.

Specially for the year-round delivery of large size modules for the construction of a gas liquefaction plant in Sabetta, Aker Arctic also designed two unique cargo vessels, built by the GSI shipyard in Guandzhou (China) in the shortest possible time (about 2 years from the date of signing of shipbuilding contract to delivery, including design) – arctic module carriers Audax and Pugnax, having a diesel-electric propulsion with two shaft lines from electric motors to fixed-pitch propellers. In the process of designing these ships, a number of original solutions were applied, including the optimization of very sophisticated ballast system, wide cargo deck with a special heating system, etc. Year-round operation of these vessels in 2016-2018 with the use of escort by nuclear icebreakers in Kara Sea, contributed significantly to the successful completion of the construction and early commissioning of all trains of Yamal LNG plant.

For the export of gas condensate from Sabetta, the Greek shipowner Dynacom under the charter agreement with Yamal LNG ordered two specialized tankers of the Arc7 class. One of them is the Boris Sokolov tanker, built according to the original Aker ARC212 design by Guangzhou shipyard, commissioned in December 2018 and is already successfully exporting gas condensate to Europe. The second vessel, which has a slightly shorter beam (based on the limitations of the construction drydock) and an increased length to ensure the same cargo capacity, was designed and built by Arctech shipyard in Helsinki and commissioned in August 2019. At the beginning of May 2019, Aker Arctic specialists conducted field ice trials of tanker Boris Sokolov, which confirmed the high ice performance of the vessel and the possibility of independent year-round navigation in the ice conditions of the south-western part of the Kara Sea.

Since May 2016, the new Arctic Gates single point terminal, installed by Gazpromneft company in the Gulf of Ob for the transshipment of oil from the Novoportovskoye field, has also been successfully operating. Specially for the export of oil from this terminal, a series of Arc7 ice class shuttle tankers of Shturman Albanov type was created with a maximum deadweight of about 40,000 tons based on a draft limitation at cape Kamenny of about 9 m. Due to an increase in export volumes in addition to six tankers successfully operating on the transportation of crude oil to the transshipment terminal in Murmansk in independent navigation mode, and in the fast ice of the Gulf of Ob – in the channel pre-laid by shallow-draft icebreakers, were ordered with the bottom of this type, which should be delivered in autumn 2019. Model testing and development of hull form of these vessels, to ensure their effective operation in extreme shallow water at maximum ice thickness in the Gulf of Ob, was also carried out in the Aker Arctic ice tank. The main characteristics of modern cargo vessels for the Russian Arctic, created in the 21st century, are given in Table 1.

An analysis of the experience of creating a modern Arctic cargo fleet shows that at the moment there are no technical obstacles for the design of cargo vessels of various types (dry cargo vessels, tankers, bulk carriers, LNG carriers, etc.) of high ice classes (up to Arc7) of practically any size necessary a specific logistic scheme capable for year-round transportation from the Ob-Yenisey area to the west. It should also be noted that this year the construction will be completed of current series of Arctic cargo vessels, which were developed and designed several years ago. It is already obvious that in 2020-21 no any new Arctic cargo vessel will be built. Nevertheless, the Government of the Russian Federation declares a further increase of transportation volumes along the Northern Sea Route (NSR) to 80 million tons (mainly related to new hydrocarbon export projects), which will require a corresponding increase in the cargo fleet. The most important trends for the further improvement of the Arctic cargo fleet on the basis of the current level of development of marine equipment and the main challenges for designers, which must be taken into account in order to make the new vessels as efficient and optimal as possible to ensure the planned volumes of cargo transportation by the NSR and at the same time to met the most recent national and international safety and environmental requirements when operating in the Arctic region, are given below.

Main trends of arctic shipping development

On the base of the experience gained when developing modern Arctic cargo vessels and the trends observed during the process of their design, the following main trends can be noted that affect the further development of the Arctic cargo fleet:

1) Use of Arctic cargo vessels with large capacity.

2) Development of year-round transportation along the whole NSR water area.

3) Use of transportation schemes with transshipment of cargo from Arctic shuttle vessels to vessels without ice class

4) Use of LNG as fuel on new cargo vessels (in addition to LNG carriers) and icebreakers.

For example, the cargo capacity of Christophe de Margerie type LNG carriers of 172,000 m^3 corresponds to the most common capacity of new conventional (open water) LNG carriers, which is a significant economic advantage, despite the need for large amount of dredging in the Gulf of Ob and associated operational difficulties, and also allowed organizing an efficient ship-to-ship transshipment of LNG near Norwegian Honningsvåg.

For new projects for the export of coal and oil from Arctic, bulk carriers and tankers of about 100-115 thousand tons of deadweight are currently being considered. The main restrictions are associated with the presence of minimal water depths along the existing recommended routes, and the situation is complicated by insufficient hydrographic survey of the Northern Sea Route water area. The results of calculating the transit depths on the recommended high-latitude NSR route north of the Novosibirsk Islands are given in [4]. Based on them, it can be concluded that the minimum transit depth on this route is 17 m, which accordingly limits the draft of vessels to a maximum of 16 m. According to the Administration of the Northern Sea Route, the maximum draft with which vessels ever transited along the NSR was 15.4 m (tanker “Propontis”, transit voyage in navigational season of 2013).

Difficult ice conditions force vessels to deviate from the recommended routes both when sailing independently and under icebreaker escort, while a significant difference from the recommended routes in shallow waters increases the risk of accidents associated with touching the ground. A typical description of such a situation is given in the AARI publication [5] on the results of voyages of Yamalmax LNG carriers from Sabetta along the eastern part of the Northern Sea Route in June-July 2018. Accordingly, in the case of organizing year-round navigation along the NSR, when such deviations can to be regular, in the current situation with the exploration of the NSR water area, there is a need for an additional risk assessment and a reasonable choice of the design draft of future vessels.

In addition, in case there is a sufficient traffic in the winter period along the Northern Sea Route, it becomes possible to use a permanent channel through an extensive zone of fast ice, covering the archipelago of the Novosibirsk Islands and the adjacent shallow water areas of the Laptev Sea and the East Siberian Sea, with a view to more stable passage of this area with fairly high speeds. In this case, vessels can use the route through the Sannikov Strait, which imposes a draft limit of 12 m [6].

A great influence on the substantiation of the main characteristics of Arctic cargo vessels, including their cargo capacity, hull form, power and type of propulsion system, has the choice of the optimal transportation scheme. For example, for projects for the export of crude oil from the shallow water areas of the Pechora Sea and the Gulf of Ob, according to the results of a comprehensive feasibility studies, the scheme using shuttle tankers for active ice navigation and the organization of oil transshipment in the Murmansk region was evidently more profitable [7]. However, similar studies of the most efficient logistic scheme for LNG export from the Gulf of Ob westbound showed the economic advantage of direct transportation by large LNG carriers to the ports of Western Europe [3]. The ship-to-ship transshipment of LNG organized at the end of 2018 from in the Honningsvåg area was associated with faster than planned commissioning of the LNG plant and exceeding the planned export volumes. However, in relation to the planned year-round LNG export from the Gulf of Ob eastbound to the countries of Southeast Asia, taking into account significantly different ice conditions and the ratio of the duration of navigation in ice and in open water, the option of organizing LNG transshipment in the Kamchatka region gets certain advantages.

Designing of the fleet for year-round navigation along the entire NSR water area

Thus, at present, new plans for extending the period for eastbound navigation along the NSR are becoming a priority challenge for designers. Now year-round navigation in the NSR is carried out only in the south-western part of the Kara Sea. Throughout the whole NSR water area, vessels navigate mainly from July to November. In recent years, the ice conditions in these months has been favorable enough for the organization of transit voyages and operations for the delivery of supply cargo. It should also be noted that the logistics scheme of the Yamal LNG project, currently used, involves the export by specially constructed icebreaking LNG carriers of Yamalmax type eastbound for the period no more than 6 months (from July to December). More difficult conditions of year-round navigation along the entire NSR area dictate the following main challenges in the design of new vessels:

- Increased requirements for ice class and performance in ice.
- Increased need for icebreaker support.
- Optimization of joint operation of icebreakers and cargo fleet.

The positive factors at present include the fact that in the coming few years three universal nuclear-powered icebreakers of Arktika type with 60 MW power should enter the operation, also the design of nuclear icebreaker-leader with 120 MW power is underway. It is also planned to build four linear icebreakers with a capacity of 40-45 MW, which will operate on LNG fuel. The design concept of such icebreaker (Aker ARC123) was developed by Aker Arctic by order of FSUE Rosatomflot. According to the idea of Atomflot, these icebreakers with a draft of 9 m, and autonomy of operating on LNG of 30 days, will operate mainly in the water area of the Kara Sea, the Gulf of Ob and the Yenisey Gulf, carrying out bunkering by LNG at the terminal in Sabetta, which will allow more active use of nuclear icebreakers in the eastern part of NSR. At the same time, it is known that the operation of vessels with icebreaking assistance in more severe ice conditions compared to those in which it can be operated independently can lead to higher risks of damage to the hull. Also, there is a need to search for optimal methods of escorting and organization of convoys, which must be taken into account in the process of the designing of cargo vessels [8].

An example of the lack of sufficient experience of year-round navigation in the eastern region of the Russian Arctic is the voyage of tanker Boris Sokolov and LNG carrier Boris Davydov from Asia via the Northern Sea Route to Sabetta at the end of December 2018 - January 2019. Initially, it was planned to independently transit of tanker Boris Sokolov on the general background of rather favorable ice conditions, which corresponded well to the level of ice performance of the tanker. However, at the very beginning of ice route in the Bering and Chukchi Seas, operators encountered a number of adverse ice phenomena that were not usual for traditional areas of the western part of the NSR, which significantly slowed down the progress of the vessel. Given the limited supply of the bunker on the tanker, it was decided to wait for the approach of LNG carrier Boris Davydov, whose power plant uses LNG transported in cargo tanks, and which has significantly greater ice performance in astern mode, and after further successful NSR transit of both ships in convoy Boris Sokolov arrived to Sabetta on 20.01.2019.

The planned for the near future organization of LNG export from the Gulf of Ob to the east in year-round mode requires special studies, creation of new generation of icebreaking shuttle LNG carriers, and powerful linear icebreakers. In particular, this means that, for example, new arctic LNG carriers to be build for the Arctic LNG 2 project should differ in design concept from Christophe de Margerie type LNG carriers. Aker Arctic is already carrying out appropriate design studies in this direction, developing optimized solutions for the main dimensions, the shape of bow and the propulsion system.

According to the results of previous studies, the cost of transportation of hydrocarbons from developing projects in Russian Arctic to Asia is significantly higher than to Europe. As shown by technical and economic calculations, the average annual cost of LNG delivery from Yamal to the Asian market in the case of organizing such year-round transportation will be 3-4 times higher compared to year-round transportation to Europe [9]. Estimates of the feasibility of exporting crude oil from the Khatanga region by Aframax class tankers have shown that even for such location of the export terminal, the cost of delivering oil to consumers in Southeast Asia will be 1.5 times higher compared to shipping to ports in Western Europe [10].

The main obstacle to the development of transit transportation of containerized cargo along the Northern Sea Route is the need to ensure a constant schedule of cargo delivery all-year-round. Earlier, Aker Arctic completed a design study of an Arctic container ship with a capacity of 5000 TEU. The creation of a specialized Arctic container ship with increased container capacity will maximize the potential of a future container line using shuttle transit transport of containers along the Northern Sea Route between hub ports.

Using LNG as a fuel on arctic cargo vessels

One of the most effective methods of reducing emissions into the atmosphere is the use of gas fuel on ships, which completely eliminates the emission of sulfur oxides and solid particles, reduces nitrogen oxide emissions by 90% and 30%, and reduces CO2 emissions. This is evidenced by the rapid increase in the number of ships of the worldwide fleet using LNG as fuel. The possibility of a total ban on the use of heavy fuel in the Arctic is also under discussion.

Aker Arctic, having advanced experience in the design of LNG-fuelled icebreakers, has also carried out a number of studies using LNG on cargo vessels that have shown that there are no technical obstacles to this opportunity. The use of diesel electric power plants, which is a standard solution, with dual-fuel medium-speed diesel engines on ships of high ice classes allows avoiding sharp fluctuations of engine load. On tankers and bulk carriers, LNG fuel tanks can be installed on an open deck, which does not entail the use of additional space; on container ships, LNG tanks can be placed only in the ship's hull, due to which their container capacity is slightly reduced.

The possibility of using LNG as fuel on Arctic vessels is limited by the lack of a bunkering system in the Arctic region. One of the possible design and logistics solutions may be the creation and placement along the Northern Sea Route of several floating LNG storages, which can be used both for supplying gas to Arctic settlements and for bunkering cargo vessels following the NSR routes [11]. As a first step, one can consider the intention of Novatek to create a transshipment point with a capacity of 20 million tons on Kamchatka Peninsula by 2023, and investigate the possibility of LNG bunkering of future shuttle container ships at this terminal.

Changes in ice classification of Russian Maritime Register of Shipping ang in the Rules for navigation on NSR

As new challenges for designers the recently introduced changes to the Rules for the classification and construction of ships of the Russian Maritime Register of Shipping (RS) should be mentioned. Following the basic ideology and approaches of the international Polar Code, the Register removed from the "Classification" section tables that contained information on permissible operating areas and ice navigation conditions, characteristics of ice conditions and corresponding operating modes for ships depending on thier ice classes. The new version of the Rules, available on the RS website [12], now contains only one table containing indicative descriptions of ice classes of the Register. According to the Register, the determination of the permissible ice class based on the specific ice conditions in the area of operation is the prerogative of the Harbour Master, the Administration of the Northern Sea Route or the ship operator, and the choice of the ice class of the designed ship should also be justified by its owner or designer.

It should be noted that in general these changes are aimed at providing more opportunities for designers and operators to make an informed choice of the most suitable level of both ice hull reinforcements, parameters of propulsion system and other characteristics of the vessel, based on an adequate assessment of all risks, as applied to the estimated areas of ship operation. At the same time, it is important to maintain a correct understanding of how designed ships will meet operating conditions. It should be noted that, at a glance at the new table, it seems that the Register has tightened requirements for its own Arctic ice classes (for example, the description of the Arc7 ice class indicates navigation during winter-spring navigation in level first-year ice up to 1.4 m thick, but the icebreaking capability of modern vessels of this class is much higher and reaches 2.1 m - see table 1). In addition, the regime of icebreaking assistance has now generally been moved beyond the classification and is entirely at the discretion of the shipowner and designer. In this case, it is necessary that the Polar Ship Certificate issued by Classification Society in accordance with the requirements of the Polar Code should clearly indicate the actual operational limitations when operating in ice for a specific ship design.

This means that the ship designers will need to study the navigation rules even more carefully in those areas for which the polar class vessel is designed, that is, in our case, the "Rules for navigation in the water area of the Northern Sea Route", which are also being prepared for changes. The draft of these changes has been submitted for discussion by all interested parties [13] and is currently being approved by the Russian Government. From the published materials it follows that it is supposed, in particular, to easy the requirements for the admission of vessels with ice classes Arc4 and Arc5 when operating under icebreaking assistance. These proposals are based on the experience gained from the operation of powerful nuclear icebreakers assisting relatively small vessels, in particular using close towing to the most severe ice conditions, which is unacceptable for large cargo vessels requiring special methods for escorting them by icebreakers.

Conclusion

The development of oil&gas projects in the Russian Arctic basin has led to the creation of principally new types of large Arctic cargo vessels for ice navigation, significantly surpassing traditional icebreaking transport vessels in their operational capabilities. Further increase in export volumes, new plans for organizing year-round eastward navigation along the Northern Sea Route, as well as new environmental requirements, pose designers new tasks and challenges in creating cargo vessels capable of providing reliable, cost-effective and safe shipping in the Arctic.

As the main conclusion, it can be noted that the selection of optimal parameters and the further design of future Arctic cargo vessels should be based on the results of a comprehensive feasibility study tailored for each specific shipping project, which shall cover the detailed assessment of ice and navigation conditions in the areas of operation, the estimated traffic volumes and the use of different possible transportation schemes, the availability and capabilities of icebreakers, and all the issues related to the features of operation of the designing vessel in ice.

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О РАСПРЕДЕЛЕНИИ И ИЕРАРХИИ БИОТЫ НА СЕВЕРЕ ТЮМЕНСКОЙ ОБЛАСТИ

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Исследуются количественные закономерности распределения и иерархии биотических показателей севера Тюменской области. Показана их связь с климатическими параметрами: средними температурами воздуха за самый теплый месяц, индексами тепла, сухости, средней годовой температурой, годовой суммой осадков и др. Установлен характер и построены схематические карты их зонального распределения. Определены формулы зависимости основных показателей биоты: численности таксонов растений и животных разного иерархического уровня, продуктивности и фитомассы от индексов тепла, сухости, и др. климатических характеристик. Показано подобие пространственного и временного распределения климатических параметров, а также богатства и разнообразия биоты. Для удобства анализа и оценки распределения биоты разного генезиса введено понятие групповых (долевых) тепловых индексов, относящихся к разным температурным интервалам: 0-5, 5-10, 10-15, 15-t_m, ^oC.

Ключевые слова: Север, биота, климат, индексы тепла и сухости, таксоны, взаимосвязи

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ABOUT DISTRIBUTION AND HIERARCHY BIOTA IN THE NORTH OF TYUMEN REGION

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The article explores quantitative regularities of distribution and the hierarchy of biotic indicators North, Tyumen region. Their connection with climatic parameters is shown: average air temperatures for the warmest month, indices of heat, dryness, average annual temperature, annual amount of precipitation, etc. The nature and schematic maps of their zonal distribution are constructed. The formulas for the dependence of the main biota indicators are determined: the number of taxa of plants and animals of different hierarchical levels, productivity and phytomass from indices of heat, dryness, and other climatic characteristics. The similarity of the spatial and temporal distribution of climatic parameters, as well as the richness and diversity of biota, is shown. For the convenience of analysis and assessment of the distribution of biota of different genesis, the concept of group (fractional) thermal indices, belonging to different temperature ranges, is introduced: *0-5, 5-10, 10-15, 15-t_m, ^oC*

Keywords: the North, biota, climate, indices of heat and dryness, taxa, interactions

Введение

К северу Тюменской области относится территория Ямало-Ненецкого (ЯНАО) и Ханты-Мансийского (ХМАО) автономных округов общей площадью 1304 км^2 (это значительно больше Германии, Франции и Испании вместе взятых) и протяженностью в меридиональном направлении более 1500 км. Это главная кладовая углеводородного сырья России, в ее недрах содержится 91% разведанных запасов газа и 46% нефти.

Общим для региона являются суровые природные условия, определяющие здесь, особенно в его арктической части, скудость биологических ресурсов и трудности хозяйственного освоения. Он включает в себя восемь биоклиматических комплексов (БК). Их наименования и нумерация (I, II, …VIII) приведены на рис.1. Биотическому богатству и разнообразию региона, их зависимости от климата посвящена обширная литература [5, 12, 14], и др. В то же время недостаточно отражены данные о связи климата с различными показателями биоты (всевозможными формами влияния организмов друг на друга и на среду), особенности их распределения в пространстве и времени и связи с определенными температурными интервалами. Целью данной статьи является устранение этих недостатков. Материал распределен по блокам: климатическому и биотическому. В первом анализируются взаимосвязи основных элементов климата (ЭК), во втором – закономерности зависимости биоты, ее флористической и фаунистической составляющей, от ключевых климатических характеристик. Климатические показатели взяты по данным метеостанций. Аппроксимации искомых зависимостей и их достоверность (коэффициент детерминации R^2) определялись по программе Excel.

Основные климатические показатели и их взаимосвязи

Важнейшими комплексными показателями климата являются: индекс сухости $J = B/Ur_г$ (B – годовой радиационный баланс, ккал/см^2; U =0,6 ккал/см^3 – теплота испарения, rг – годовая сумма осадков, см), характеризующий соотношение поступления в почву тепла и влаги, и суммы положительных $\Sigma>0$ и отрицательных $\Sigma<0$ температур воздуха, градусосутки (гс) – индексы тепла и холода, ответственные за теплообмен у поверхности Земли [2]. Входящее в J отношение $B/U= r_m$ – это метрический эквивалент радиационного баланса, характеризующий максимально возможное испарение – испаряемость, а индекс сухости $J = B/Ur_г = r_m/ r_г$ есть количественный критерий, указывающий на избыток (или недостаток) тепла или влаги. Если $J<1$, то в избытке влага, если $J>1$, – тепло. Соответственно, в первом случае жизнь биоты и ее эволюция зависят, в первую очередь, от поступления тепла, во втором – влаги. Таким образом, изолиния $J \approx 1$ делит биосферу на северную (холодную, влажную) и южную (теплую, сухую). Автономные округа находятся в северной фитосфере, характеризующейся возрастанием обилия и разнообразия биоты с севера на юг (в южной фитосфере – наоборот [2]). В агрономии соотношение между теплом и влагой определяется гидротермическим коэффициентом Селянинова $К.о = r_г / \sum>0$, где rг - сумма осадков (см) за теплое время года [15].

На рис.1 – 2 приведены схематические карты [8] биоклиматического районирования севера Тюменской области и распределения определяющих ЭК.

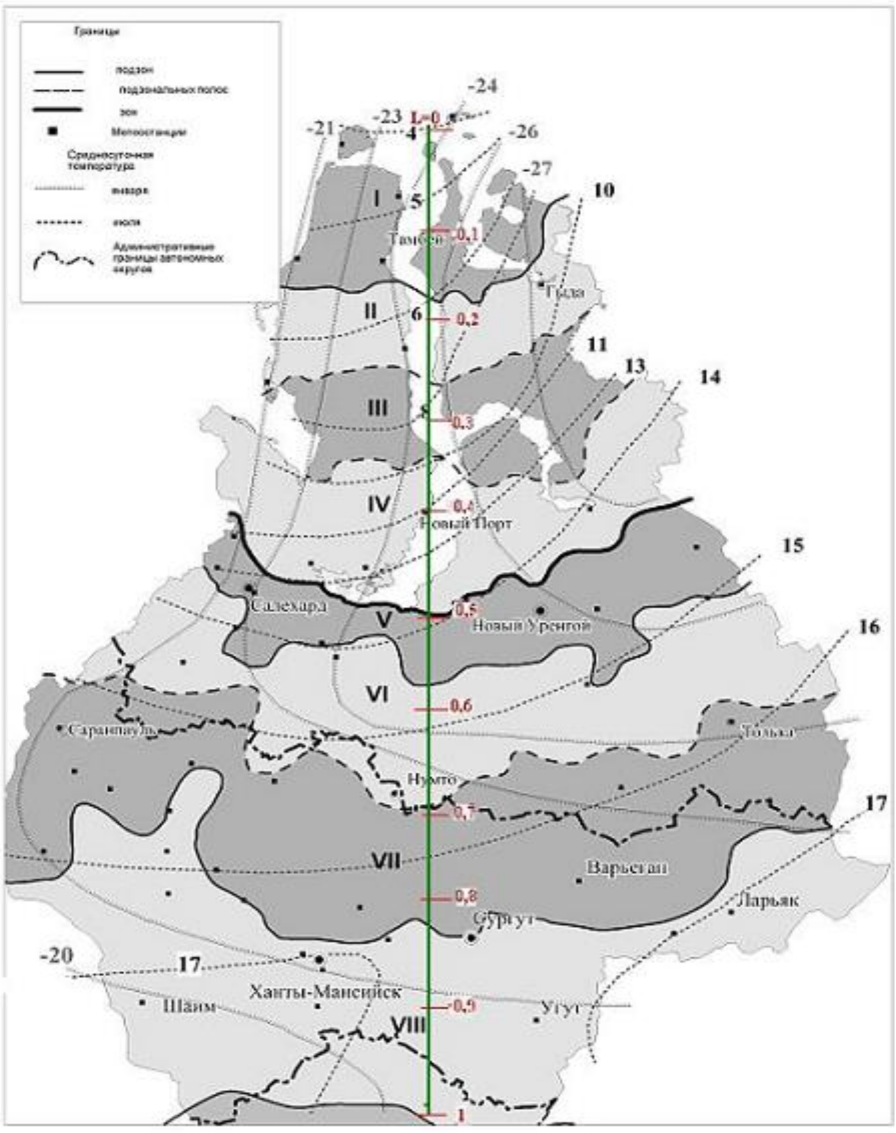

Рис. 1. Биоклиматические комплексы – БК [11]
(I – арктическая тундра, II и III – северная и южная полоса субарктических типичных тундр, IV – субарктические кустарниковые тундры, V - лесотундра, VI и VII - северная и южная полоса северной тайги, VIII – средняя тайга; среднемесячные температуры воздуха января и июля на севере Тюменской обл. Вертикаль L=1 – условный меридиан, может служить масштабной шкалой с ценой деления ~150 км при определении расстояний между изолиниями ЭК.)

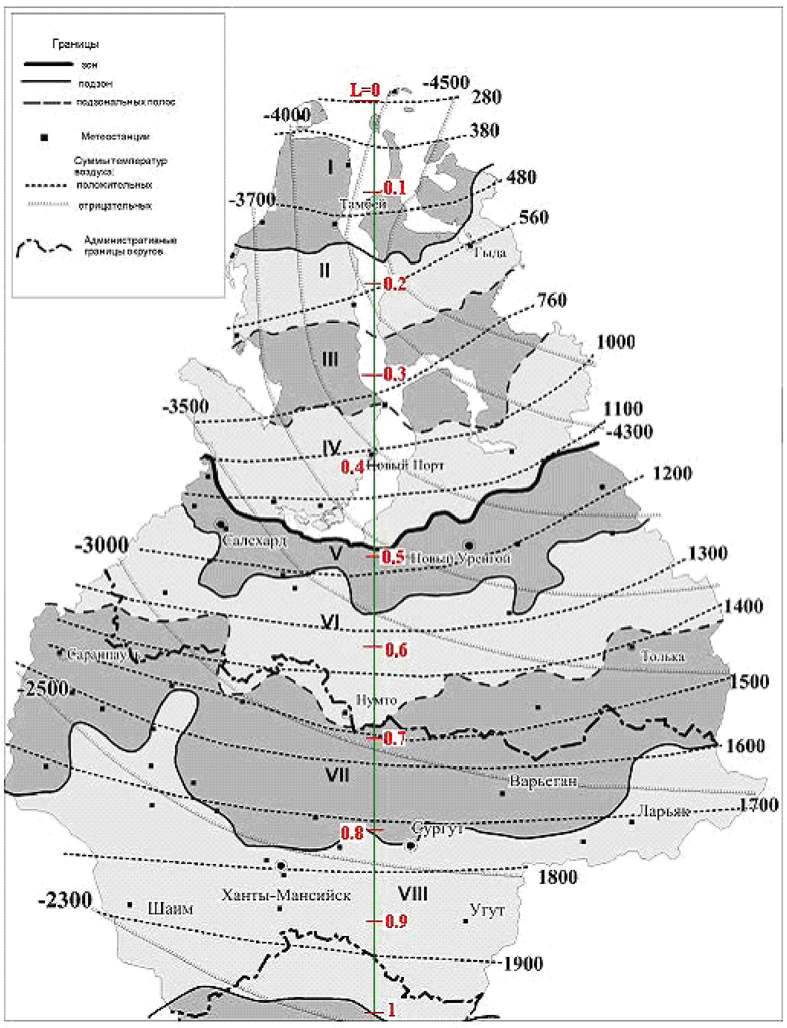

Рис. 2. Суммы положительных и отрицательных температур (градусосутки, гс) на севере Тюменской области [11]
(I – арктическая тундра, II и III – северная и южная полоса субарктических типичных тундр, IV – субарктические кустарниковые тундры, V - лесотундра, VI и VII - северная и южная полоса северной тайги, VIII – средняя тайга; среднемесячные температуры воздуха января и июля на севере Тюменской обл. Вертикаль L=1 – условный меридиан, может служить масштабной шкалой с ценой деления ~150 км при определении расстояний между изолиниями ЭК.)

Все элементы климата (ЭК), как единой системы, взаимосвязаны. На рис.3 приведены графики, связывающие наиболее значимые для биоты ЭК на севере Тюменской области и их аппроксимации; кроме уже известных по тексту обозначений, здесь: $\Sigma>5$ и $\Sigma>10$ – суммы температур выше 5 и 10° С; jrт = rт/ rг – относительная величина суммы осадков за теплый период; Am= tm +(-t1) – амплитуда колебаний температуры воздуха, tm и t1 – среднемесячные максимальная (на побережье и островах – август tm= t8, южнее – июль tm= t7,) и минимальные температуры воздуха.

Территория округов – область многолетнего (ЯНАО) и сезонного (ХМАО) промерзания грунтов

В тундре и лесотундре многолетнемерзлые породы имеют сплошное распространение, их мощность увеличивается от 250-300 м на широте Полярного круга до 500-550 м на 70° с.ш. Южная граница сплошной многолетней мерзлоты примерно совпадает с изолинией Σ> 0 = 1200 гс. Глубина сезонного оттаивания увеличивается с севера на юг, от 1.3 до 2.7 м у песчаных грунтов, и от 0.2 до 0.5 м у торфяных. На рис. 4 показано распределение максимальной глубины сезонного оттаивания hт песчаных грунтов, рассчитанной по известной формуле Стефана [6], отображающей квадратичную зависимость глубины оттаивания от времени или индекса тепла: hт ~ τ 0.5 ~ (Σ>0)0.5 .

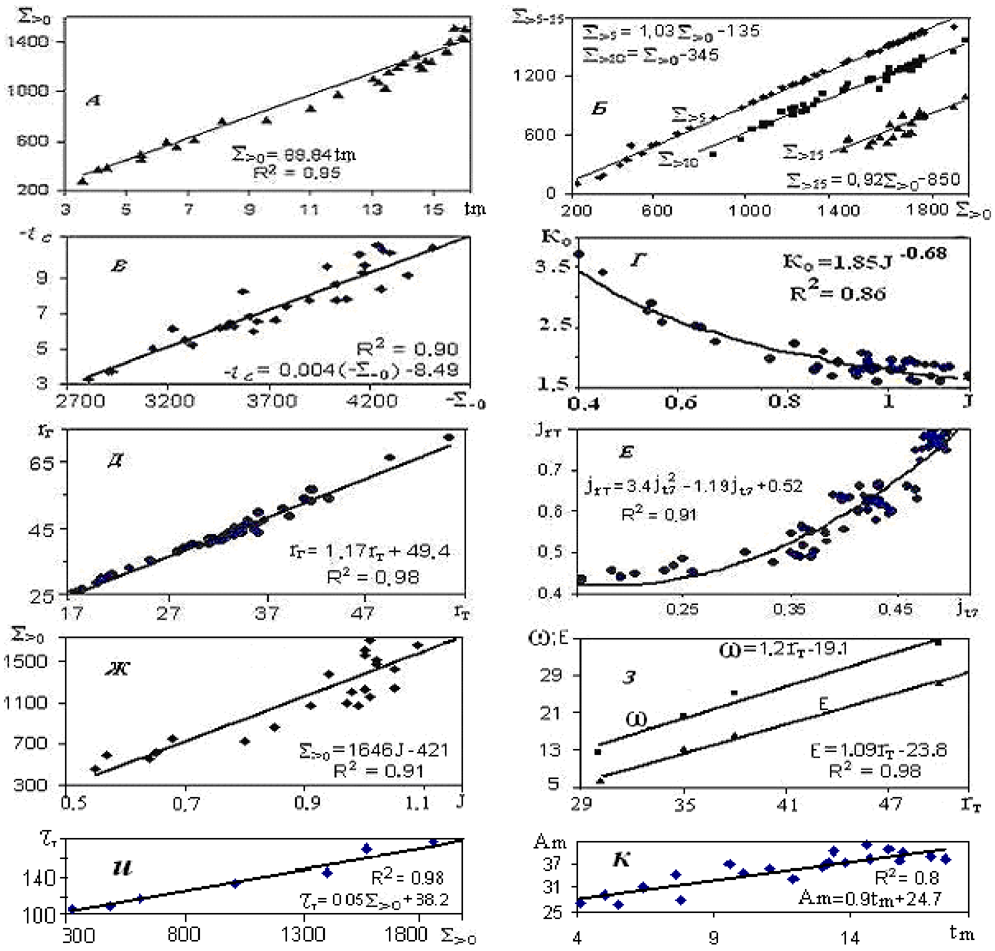

Рис. 3. Графики зависимостей: $\Sigma_{>0}$ *от* t_7 *–* ***А****;* $\Sigma_{>(5\text{-}15)}$ *от* $\Sigma_{>0}$ *–* ***Б****;* t_c *от* Σ_{-0} *–* ***В****;* K_o *от* J *–* ***Г****;* $r_г$ *от* r_m *–* ***Д****;* j_{rm} *от* j_{t7} *–* ***Е****;* $\Sigma_{>0}$ *от* J *–* ***Ж****; ω и E от* r_T *–* ***З****;* τ_m *от* $\Sigma_{>0}$ *–* ***и****; Am от* t_m *–* ***К*** *(обозначения в тексте).*

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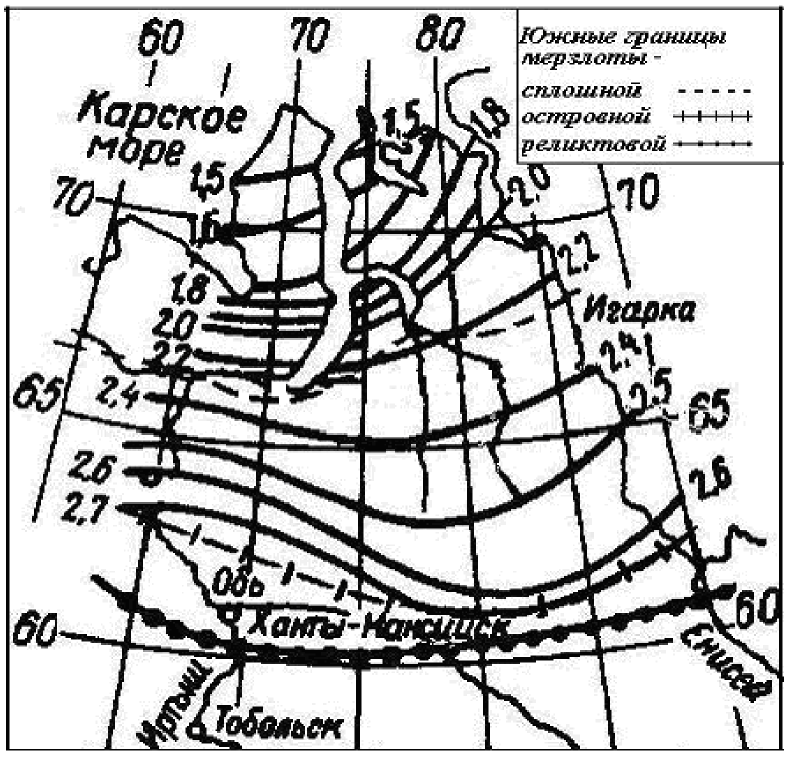

Рис.4. Распределение глубины сезонного оттаивания hт песчаных грунтов [11]

Ход глубины сезонного оттаивания hτ в теплый период года τт в конкретном месте зависит от текущих значений времени τ или индекса тепла (Σ>0)τ .

hτ = hт · (τ / τт)0.5 = hт · [(Σ>0)τ /Σ>0] 0.5 , (1)

Для перехода к другим грунтам значение hт, найденное по рис.4, умножается на понижающий коэффициент, примерно равный: 0.8 для глинистых грунтов, 0.65 для суглинистых и 0.4 для торфяных.

В теплое время года подошва оттаивающего слоя служит водоупором, вызывающим его переувлажнение. Таяние мерзлоты и недостаточное испарение способствуют заболачиванию территории и развитию здесь специфического озерно-болотного ландшафта с преобладанием травянистой растительности. В период таяния мерзлого слоя из него идет интенсивное выделение защемленных газов, преимущественно метана и диоксида углерода – главных виновников парникового эффекта и повышенной пожарной опасности.

О подобии климатических и пространственно-временных показателей

В пределах холодной фитосферы изменение климатических показателей в течение теплого периода года, в частности среднемесячных температур и их сумм, подобно их пространственному изменению в направлении с севера на юг. Влажность почвы здесь избыточна, поэтому биота зависит, в основном, от атмосферного тепла, опосредованного величиной Σ>0. Чем выше Σ>0 (и tм), тем через большее количество природных зон, находящихся севернее арктической пустыни, где Σ>0 близка к 0, дважды (туда к середине лета и обратно к началу зимы) «пробегает» данное географическое место в течение теплого периода года, и тем обильнее и разнообразней его биота. Изменение индекса тепла в теплое время года на равнинной местности подобно изменению этого параметра в меридиональном направлении (с севера на юг). В горах аналогичным пространственным фактором является высотная поясность, когда индекс тепла убывает с повышением высоты. Индекс тепла как время или пройденный путь – кумулятивные величины, изменяющиеся только в сторону увеличения.

На рис. 5 показан многолетний ход годового индекса тепла в Сургуте (а), Салехарде (б) и Березове (в), а на рис. 5 г – ход его суммарного роста в тех же пунктах, но в относительных (нормализованных) величинах j. Все три кривые на рис. 5 г практически сливаются. Графики на рис. 5 д отражают зависимость годового индекса тепла в размерной и безразмерной форме от jL= ΔL/L – относительного расстояния по линии L на рис.1. Из сравнения графиков на рис. 5 г и д следует примерная идентичность (эквивалентность, взаимозаменяемость) всех трех нормализованных величин – индекса тепла, времени и пространства. Т.е. в первом приближении, для всего региона справедливо равенство jΣ>0 = jτ = jL.

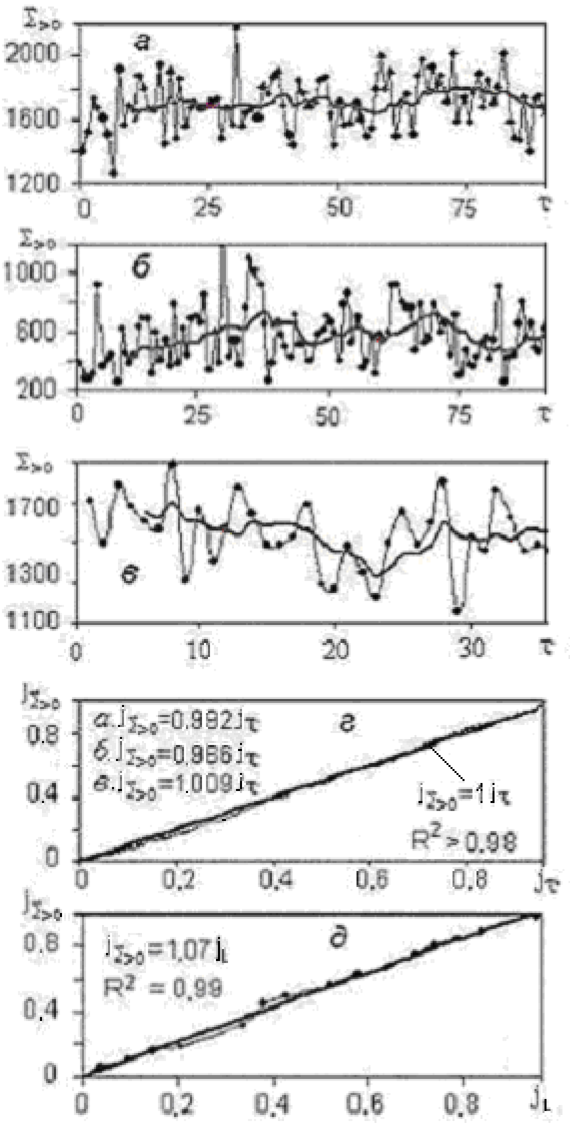

Рис. 5. Ход Σ>0 (гс) во времени τ (годы):
а – Сургут, б – Салехард, в -Березово;
зависимость jΣ>0 от jτ – г и от jL – д

Климатическая зависимость биотического богатства и разнообразия

На графиках рис. 6 показана зависимость количества таксонов разного уровня: видов (В), родов (Р), семейств (С), порядков (П) или отрядов (О), классов (К) и отделов (Од) сосудистых растений ($N_р$) [8] и животных ($N_ж$) [7], а также продуктивности (годичной первичной продукции) Pr, т/(га · год) и фитомассы Vm, т/га [1]. от климатических показателей: $\Sigma_{>0,}$ t_7 и J.

Анализ таблиц и графиков зависимости биотических показателей от индекса тепла показал, что:

а) начиная с уровня классов количество таксонов перестает зависеть от климата, становится примерно постоянным, одинаковым для всех БК;

б) общая формула зависимости параметров биоты от $\Sigma_{>0}$ практически линейна:

$$У=А\Sigma_{>0}+В \quad (2)$$

где У – общее обозначение биотических показателей, А и В – численные коэффициенты, определяемые по табл. 1.

Формула (2) в купе с табл. 1 позволяют определить количество биотических таксонов непосредственно по климатическим показателям – $\Sigma_{>0,}$ t_7 или J.

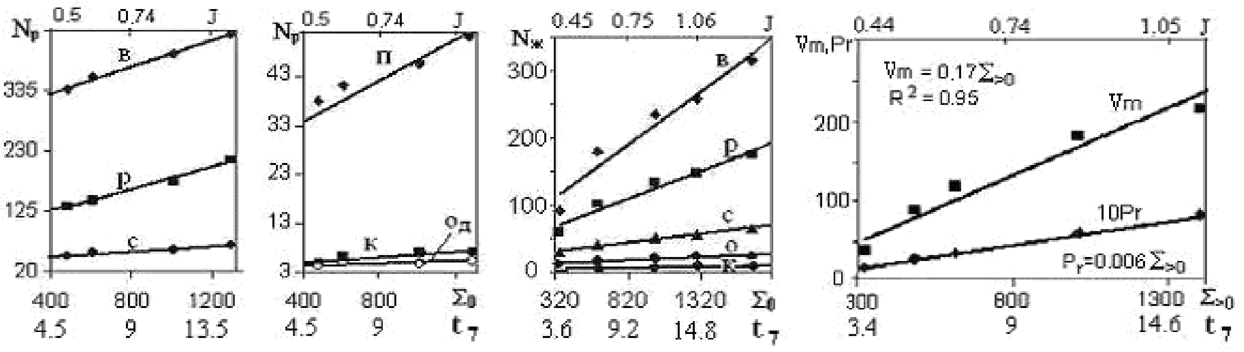

Рис. 6. Графики зависимости $N_ж$, $N_р$, Vm и Pr от $\Sigma_{>0}$, а также от t_7 (вторая нижняя горизонтальные ось) и J (верхняя горизонтальная ось) на севере Тюменской области

Таким образом, количество таксонов любого уровня, примерно до класса, зависит от климата, увеличиваясь с севера на юг. В то же время, как следует из рис.7 (а и б), отношение количества таксонов любого уровня к количеству видов – постоянная величина, не зависящая от климата (т.е. во всех природных комплексах Nр2/ Nр1=0,44; Nж2/ Nж1=0,58 и т.п.). Поэтому, зная количество видов, по формулам на рис. 7 можно рассчитать и количество таксонов более высокого ранга (родов, семейств). Рис.7в отражает устойчивую линейную связь таксонов флоры и фауны, также инвариантную климату.

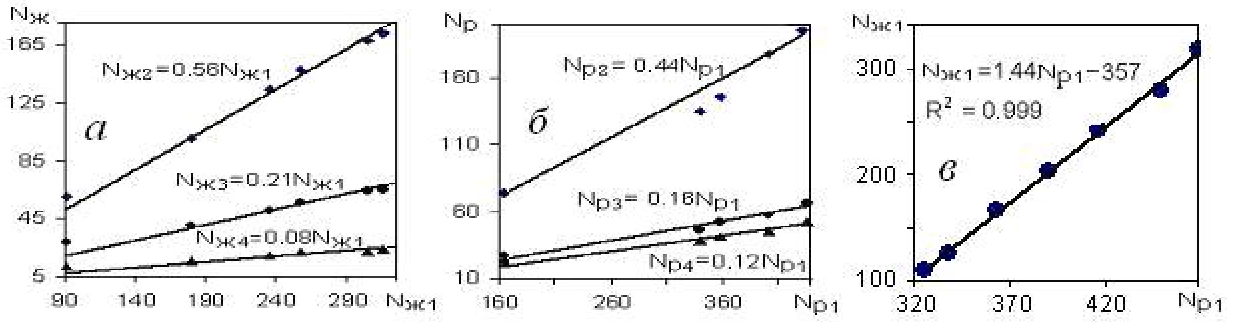

Рис. 7. Зависимость численности таксонов животных $N_{ж2}$ - $N_{ж4}$ от $N_{ж1}$ и $N_{р2}$ - $N_{р4}$ от $N_{р1}$ (а, б), а также $N_{ж1}$ от $N_{р1}$(в); (1 – вид, 2 – род, 3 – семейство, 4 – отряд)

Таблица 1- Постоянные в формуле (1) для основных параметров групп биоты (ГБ): количества таксонов птиц (Пт), млекопитающих (М), всех животных $N_ж$=М + Пт, древесных (Д) и травянистых (Тр) растений, всей растительности ($N_р$), продуктивности Pr и биомассы Bm растений, а также значения R^2

ГБ	Таксоны	A	B	R^2	ГБ	Таксоны	A	B	R^2
Пт	Виды	0.125	53.1	0.92	Д	виды	0.0024	55	0.88
	Роды	0.063	34.9	0.93		роды	0.001	26	0.87
	сем-ства	0.02	16.1	0.94		сем-ства	0.0003	14.3	0.73
	отряды	0.008	5.8	0.9	Тр	виды	0.09	255	0.99
М	Виды	0.031	10.3	0.98		роды	0.09	60	0.97
	Роды	0.017	10.1	0.95		сем-ства	0.02	25	0.94
	сем-ства	0.006	6.8	0.96	$N_р$	виды	0.115	285	0.98
	отряды	0.001	4.5	0.80		роды	0.096	86.3	0.94
$N_ж$	Виды	0.176	49.8	0.98		сем-ства	0.022	36.4	0.91
	Роды	0.091	37.2	0.98		порядки	0.021	25.4	0.9
	сем-ства	0.029	21	0.98		классы	0.003	3.6	0.86
	Отряды	0.01	9.2	0.99		отделы	0.0026	2.7	0.84
Pr	–	0.006	0	0.98	Vm	–	0.17	0	0.96

Температурные интервалы и аффилированные с ними биотические группы

Биотическое разнообразие выражают через различные соотношения между массой или численностью разных групп биоты (совокупность популяций, населяющих определенную территорию, которая функционирует как единое целое благодаря взаимосвязанным метаболическим превращениям) – индексы Шеннона (мера энтропии), Симпсона (мера дисперсии) и др. [4]. Чем больше индекс Шеннона, тем разнообразней биота. Увеличение индекса Симпсона соответствует росту доминирования. Следует отметить, что состав биоты, количество ее систематических групп (таксонов) и соотношения между ними реально определяются только непосредственным подсчетом (переписью) в полевых условиях, т.е. все известные индексы разнообразия биоты рассчитываются по уже установленным ее показателям. Причем ни один из известных индексов не отражает влияние климатических факторов. Между тем именно климат, определяющий тепло- и влагообеспеченность, является главным (первичным) фактором членения биоты, ее многообразия. Он позволяет оценивать, хотя бы приближенно, структуру биоты только по климатическим данным, в частности, по индексам тепла

$\Sigma>0$ и сухости или по максимальным среднемесячным температурам tм.

В климатических справочниках, помимо $\sum>0$, даются суммы температур выше 5, 10 и 15ºС, которые хорошо коррелируют с $\sum>0$ – рис.3. Выделим четыре температурных интервала с разными тепловыми условиями вегетации и соответственно структурой растительности: 1) $\Delta t = 0\text{-}5$; 2) $\Delta t = 5\text{-}10$; 3) $\Delta t = 10\text{-}15$ и 4) $\Delta t = 15\text{-}tm^oC$ и распределим между ними сумму положительных температур $\sum>0$ – условный показатель тепла. Каждому интервалу, а фактически определенному климатическому поясу – 1) арктическому, 2) субарктическому, 3) умеренному и 4) засушливому отвечает определенная группа биоты, существующая при этих температурах: 1)арктическая (Ар), 2)субарктическая или морозостойкая (Мс), 3) теплолюбивая (Тл), 4) сухоустойчивая (Су). В средней тайге и южнее, где

t7 > 15ºС, распределенное условное тепло вычисляется по формулам:

1) $\sum1 = \sum>0 - \sum>5$;

2) $\sum2 = \sum>5 - \sum>10$;

3) $\sum3 = \sum>10 - \sum>15$.

Последний (в данном случае четвертый) интервал определяется по остаточному принципу:

4) $\sum4 = \sum>0 - (\sum1 + \sum2 + \sum3) = \sum>15$.

Такое групповое структурирование условного тепла и обусловленных им биотических показателей объясняет (наряду с историей климата) часто наблюдаемое распространение определенных видов биоты далеко за пределами своего ареала, наличие категории редких видов и ряд других особенностей распределения биоты.

Выделение тепловых интервалов продемонстрируем на примере Сургута, где $\sum>0 = 1734$, $\sum>5 = 1644$, $\sum>10 = 1361$, $\sum>15 = 791$, t7= 16.9ºС, τт = 180 сут, hт = 2.7м. Тогда: $\sum1 = 90$ гс; $\sum 2 = 283$ гс; $\sum 3 = 570$ гс; $\sum4 = 1734 - (90 + 283 + 570) = \sum>15 = 791$ гс.

Доли ($\eta1\text{-}4 = \sum1\text{-}4 / \sum>0$) от всей суммы положительных температур в каждом интервале равны: η1=90/1734=0,05; η2=283/1734=0,16; η3=570/1734=0,33 и η4=791/1734=0,46.

При анализе нужно различать полную (максимальную) сумму положительных температур $\sum>0$ и изменяющуюся (растущую) в течение теплого периода $(\sum>0)\tau$ от 0 до $\sum>0$ (в Сургуте от 0 до 1734 гс). Ход (τ, час) температур воздуха t (ºС) и их сумм $(\sum>0)\ \tau$ в теплое время года в Сургуте показаны на рис. 8. Оба графика с высокой достоверностью (R2 ≈ 0,99) описываются полиномом:

$$(\sum_{>0})_\tau\ ;\ t = a\ \tau^2 + b\ \tau \qquad (3)$$

При расчете $(\sum_{>0})_\tau$ $a = 0.\ 01$, $b = 9$; при расчете t $b = -0.002$, $b = 0.37$

Ход температур воздуха t в теплое время хорошо описывается также синусоидой, а их сумм $(\sum_{>0})_\tau$ – линейной функцией:

$$t \approx t_0 + t_m \sin(\pi\ \tau/\tau_т),\ (\sum_{>0})_\tau \approx \sum_{>0} \cdot \tau/\tau_т \qquad (4)$$

где t_0 – температура начала (и конца) теплого времени года, в умеренных и северных широтах $t_0 \approx 0$ ºС; τ – текущее время теплого периода; $\tau_т$ – длительность теплого периода.

Величину $(\sum_{>0})_\tau$ можно определить и как интеграл синусоиды (5):

$$(\sum_{>0})_\tau = t_m\ \tau_т / 3.14\ [1 - \cos(3.14\ \tau/\tau_т)] \qquad (5)$$

На рис. 8 выделены все четыре интервала температур, соответствующие им индексы тепла и группы биоты снизу вверх: арктическая (Ар), морозоустойчивая (Му), теплолюбивая (Тл), сухоустойчивая (Су).

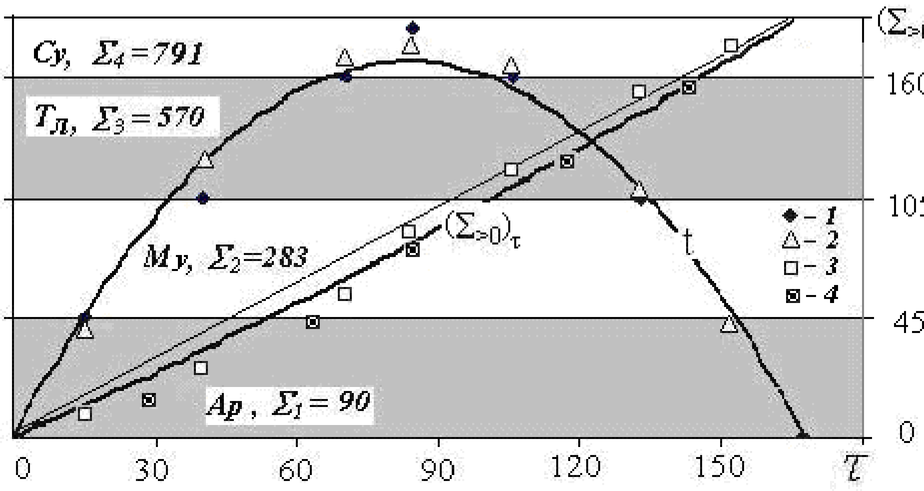

Рис. 8. Ход температур воздуха t (ºС), их сумм $(\sum_{>0})_\tau$ (гс) в теплое время года (τ, сут), в Сургуте и их аппроксимации : 1- синусоидальняя, 2- полиномиальная, 3 – линейная, 4 - косинусоидальняя.

Севернее, где среднемесячные температуры воздуха ниже 15ºС, 4-й участок отсутствует; величины распределенного тепла на остальных участках определяются аналогично, в том числе на 3-м (последнем): $\sum_3 = \sum_{10\text{-}\,t7} = \sum_{>0} - (\sum_{0\text{-}5} + \sum_{5\text{-}10}) = \sum_{>10}$. По такой же схеме составляются формулы для расчета распределенного тепла на Крайнем Севере, где отсутствует третий, а при $t_m \le 5$ºС и второй интервалы. Например, в Тамбее, где $\sum_{>0} = 493$, $\sum_{>5} = 344$ гс, а самая высокая среднемесячная температура летом $t_м = t_8 = 6.4 > 5$ ºС, третий и четвертый участки отсутствуют. Отнимая $\sum_{>5} = 344$ от $\sum_{>0} = 493$, получаем количество условного тепла на первом температурном участке $\sum_1 = \sum_{0\text{-}5} = 149$ гс; остальное относится ко второму участку $\sum_2 = \sum_{>5} = 344$ гс. Групповые $\sum_{1\text{-}n}$ тепловые индексы – константы для каждого географического места (n – число интервалов: от 1 в арктической пустыне до 4 в тайге) можно использовать для оценки богатства и разнообразия биоты.

На уровне групповых индексов тепла также наблюдается подобие (эквивалентность) временных и пространственных (в данном случае вертикальных) страт. Под последними понимаются значения h_τ, фиксирующие нижние границы отдельных слоев сезонного оттаивания, отвечающих за вегетацию выделенных выше 4-х групп биоты. Они рассчитываются по формуле (1), при этом входящие в неё $(\sum_{>0})_\tau$ или τ определяются с помощью формул (3) – (5) либо снимаются непосредственно с графиков, типа показанного на рис. 8. Для примера в табл. 2 приведены выделенные группы биоты Ар, Му, Тл и Су и определяющих их значения τ, $(\sum_{>0})_\tau$ и h_τ для Сургута согласно рис. 8. Во втором столбце таблицы также показаны их величины (нули), отвечающие состоянию дневной поверхности на начало весны.

Таблица 2 - Выделенные группы биоты (ГБ) и определяющие их параметры: τ, сутки; $(\sum_{>0})_\tau$, гс; h_τ, м.

ГБ	-	Ар	Му	Тл	Су
τ	0	55	95	150	180
$(\sum_{>0})_\tau$	0	450	1050	1600	1734
h_τ	0	1.4	2.1	2.6	2.7

Анализ показал, что зависимость биотических таксонов от индекса тепла с несколько большей, но также допустимой погрешностью (0.8-0.9) можно аппроксимировать *упрощенной* формулой (2), при B=0, когда все параметры биоты (не только Pr и Vm, как в табл.1) и суммы температур прямо пропорциональны.

При этом коэффициент пропорциональности равен η_{1-n}, а величина A определяется по табл. 3. Это позволяет вычислять все биотические показатели, в том числе и распределенные по температурным интервалам ($У_{1-n}$) по общей формуле:

$$У_{1-n} = У \cdot \eta_{1-n} \qquad (6)$$

Таблица 3 - Коэффициенты А *в упрощенной формуле (1) для основных параметров групп биоты (ГБ): количества таксонов птиц (Пт), млекопитающих (М), всех животных $N_ж$=М + Пт, древесных (Д) и травянистых (Тр) растений, всех сосудистых растений ($N_р$ = Д+Тр).*

ГБ	Пт	М	$N_ж$	Д	Тр	$N_р$
А	0.56	0.04	0.21	0.19	1.3	0.2

Итоговым результатом работы является табл. 4, в которую сведены основные ЭК, осредненные по выделенным биоклиматическим комплексам (БК) и зависящее от них видовое богатство и разнообразие биоты, общее и распределенное по температурным интервалам.

Из табл. 4 следует, что арктическая биота ($N_{р1}$,. $N_{ж1}$) встречается по всему региону, убывая с севера на юг. Это соответствует фактическим данным. Например, пыльца карликовой березки – эндемика тундры – повсеместно присутствует и в таежных поверхностных палиноспектрах [9]. Сухоустойчивая биота ($N_{р4}$,. $N_{ж4}$) встречается только в таежной зоне и южнее. Распределение численности субарктических (N_2) и теплолюбивых (N_3) видов имеет более сложный волнообразную форму. Причем максимальные значения долевых тепловых индексов и соответствующие им численности видов биоты (и растений и животных) приурочены к биокомплексам III (юг типичной тундры) и VI (север северной тайги).

В табл. 4 приведены только количества видов распределенных по температурам растений и животных. При необходимости по формулам на рис.6 нетрудно определить эти показатели и для последующих иерархических уровней (родов, семейств и т.д.).

Потепление климата и его влияние на биоту

В последние 40-50 лет отмечается повсеместное потепление климата, основным признаком которого является повышение температуры воздуха, как в теплое время года, так и в среднегодовом выражении. Потепление вызывает много негативных последствий, часто катастрофического характера – пожары, наводнения, просадки вечномерзлых грунтов, разрушительные деформации инженерных сооружений и т.п. Особенно оно опасно для Севера, где грозит оттаиванием приполярных и подземных льдов и высвобождением огромных масс воды и защемленных в толще мерзлоты газов. В то же время, очевидно, что повышение температур воздуха играет и положительную роль, увеличивая длительность вегетационного периода и продуктивность биоты. Оценим эту роль для севера Тюменской области, используя климатические справочники 1965 и 2011 годов.

В табл. 5 приведены среднемноголетние значения среднегодовых (t_c) и максимальных среднемесячных (t_m) температур воздуха в ряде пунктов на севере Тюменской обл. за периоды до 2011 и до 1965 гг.

Таблица 4 - Максимальные среднемесячные температуры (tm,ºC); индексы сухости (J) и тепла ($\sum_{>0}$), гс; число видов растений ($N_р$) и животных ($N_ж$) в разных БК (по рис.1). А также долевые тепловые индексы η_{1-4} и распределенные по четырем температурным интервалам числа видов растений (Nр1-4) и животных (Nж.1-4), синим выделены их максимумы

БК	I	II	III	IV	V	VI	VII	VIII
t_m	5,3	6	9	12,5	14	15	16	18
J	0,45	0,5	0,6	0,7	0,75	0,81	0,88	0,96
$\sum_{>0}$	460	610	760	1050	1230	1320	1600	1850
η_1	0,27	0,19	0,15	0,1	0,08	0,07	0,05	0,04
η_2	0,72	0,81	0,85	0,23	0,21	0,19	0,16	0,14
η_3	–	–	–	0,67	0,72	0,73	0,31	0,27
η_4	–	–	–	–	–	–	0,47	0,55
$N_р$	326	338	364	390	410	457	470	480
$N_{р1}$	90	64	55	39	36	31	24	19
$N_{р2}$	236	274	309	90	95	98	84	67
$N_{р3}$	–	–	–	261	280	328	145	130
$N_{р4}$	–	–	–	–	–	–	220	264
$N_ж$	115	127	166	204	233	280	316	323
$N_{ж1}$	31	24	25	20	20	20	16	13
$N_{ж2}$	84	103	141	47	51	53	51	45
$N_{ж3}$	–	–	–	137	161	207	98	87
$N_{ж4}$	–	–	–	–	–	–	151	178

Таблица 5 - Средние значения t_c и t_m за периоды времени до 2011 (a) и 1965г.(b) и их изменения за 50 лет на севере Тюменской области.

№	Пункт	$t_{c..a}$, 2011	$t_{c.b}$, 1965	$t_{m.a}$, 2011	$t_{m.b}$, 1965	$t_{m.a}/t_{m.b}$/
1.	о. Белый	-11.7	-10.4	4.9	4.1	1.19
2.	Харасавэй	-10.5	-9.8	6.6	5.5	1.2
3.	Тазовский	-8.6	-9.3	14.5	13.4	1.08
4.	Сидоровск	-8	-8.5	15.6	14.6	1.07
5.	Н.Порт	-7.8	-9.4	12.2	11	1.11
6.	Ямбург	-6.3	-6.9	14.3	13	1.1
7.	Салехард	-6.3	-6.4	14.7	13.8	1.06
8.	Халесавэй	-5.3	-5.8	17.2	15.9	1.08
9.	Тарко-Сале	-6	-6.7	16.4	15.4	1.06
10.	Яр-Сале	-7.3	-7.5	14.4	13.2	1.09
11.	Надым	-5.9	-6.6	15.9	14.7	1.08
12.	Березово	-3.1	-3.8	16.4	15.8	1.04
13.	Сургут	-2.9	-3.1	17.5	16.9	1.04
14.	Няксимволь	-2.2	-1.2	17.3	15.8	1.09
15.	Х.-Мансийск	-0.8	-1.4	18.3	17.5	1.05

Табл. 5 отражает общую тенденцию к повышению максимальных среднемесячных температур воздуха в последние примерно 50 лет: на 0,6 – 1,5ºС (в среднем примерно на 1 ºС) или на 5-19% со средней скоростью: $v_{tm} \approx 1/50 \approx 0{,}02$ град/год. Причем наибольшее повышение в процентном отношении наблюдается на севере региона,

к югу оно убывает. Что касается среднегодовых температур, то на большей части территории они также повышаются, за исключением островов и побережья Карского моря (о. Белый и м. Харасавэй), где наблюдается некоторое их понижение. Это говорит о том, что потепление происходит, в основном за счет повышения летних температур.

Увеличение индекса тепла вызывает перемещение биоклиматических комплексов (БК) с юга на север и увеличение (в целом) видового богатства биоты. В то же время увеличение максимальной среднемесячной температуры воздуха на один градус на побережье вызовет потерю части ареала арктической наземной биоты, соответственно ее уменьшение и переход в категорию редких видов - объектов Красной книги.

В табл. 6 приведены значения индекса тепла за периоды наблюдений до 1965 г. (числители) и до 2011 г. (знаменатели), взятые из справочников и соответствующие им величины видового богатства и продуктивности, рассчитанные по формуле (2). Аналогично можно оценить влияние потепления на групповые индексы тепла, биомассу и биотические таксоны высших рангов.

Таблица 6 - Индексы тепла ($\sum_{>0}$), гс; продукция (Pr, т/га·год); число видов растений ($N_р$) и животных ($N_ж$) в разных БК (по рис.1), соответствующие климатическим показателям наблюдаемым до 1965 г (числитель) и до 2011 г. (знаменатель).

БК	I	II	III	IV	V	VI	VII	VIII
$\sum_{>0}$	340/432	439/531	658/750	877/969	1097/1189	1316/1408	1536/1628	1700/1819
Pr	2/2,2	2,6/2,8	3,9/4,2	5,3/5,6	6,6/7	7,9/8,4	9,2/9,9	10,2/10,9
$N_р$	327/335	338/346	364/371	390/396	417/421	449/457	469/472	480/491
$N_ж$	110/125	127/143	166/181	204/220	243/259	281/298	316/336	324/365

Повышение максимальных среднемесячных температур воздуха за последние примерно 50 лет на 1°C, согласно табл. 6, должно вызвать увеличение видов: сосудистых растений от 8 арктической тундре до 11 в средней тайге; животных от 15 в арктической тундре до 41 в средней тайге.

Заключение

1. Основными климатическими показателями, определяющими богатство и разнообразие биоты, являются индексы сухости и тепла. Количество биотических таксонов в пределах севера Тюменской области увеличивается с севера на юг вслед за увеличением этих показателей. В то же время, отношение количества родов, видов, семейств, отрядов (порядков), к количеству видов остается постоянным. Количество видов флоры и фауны устойчиво увязано друг с другом, а их отношение также инвариантно климату.

2. За последние 50 лет июльские температуры воздуха на севере Тюменской области повысились примерно на 1°C, а суммы положительных температур – на 93 гс. Такое потепление соответствует увеличению количества видов: растений на 1-3%, животных в – среднем на 8-9%. Т.е., позитивное влияние потепления климата на биоту севера имеет место, но в общем, оно невелико и вряд ли компенсирует связанные с потеплением негативные факторы – эмиссию газов из оттаивающих льдов, пожары, наводнения и т.п.

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