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Prediction of ship performance in level ice considering seasonal and regional variability of its physical properties

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ABSTRACT

The ongoing development of Arctic navigation poses the problem of ship ice performance prediction during year-round operation. This task is complicated by a significant variability of physical properties of sea ice that fairly influence ice resistance and basically depend on the geographic region, season, and corresponding climate features. In this study we assumed that ice properties are mainly determined by two parameters, they are air temperature and seawater salinity. It allowed us to propose a method to estimate ship speed in level ice considering the values of these two parameters in a particular region of ship operation. The method is based mainly on the existing formulas to estimate flexural strength, elasticity modulus, Poisson's ratio, and density of sea ice. We joined these formulas into a single calculation algorithm. As an example of its practical application, we carried out calculations of h-v curves for Arktika-type icebreaker (built in 1972) and found their well correlation with the full-scale data for the cases of summer and winter navigation. The paper also contains the results of sensitivity tests of the proposed model that reveal the influence of various factors on ship icebreaking capability. The obtained results could be applied to predict ship ice performance considering seasonal and regional variability of physical properties of ice.

KEY WORDS: Ship ice performance; Ice properties; Seasonal variability; Icebreaking capability; Ice performance curve.

INTRODUCTION

The ongoing digitalization of Arctic shipping requires the development of methods to predict parameters of vessel movement considering actual ice parameters at each point of the route. Such methods could be applied to estimate the expected time of arrival of ships, as well as to develop optimal ice routing algorithms. All ice parameters can be broadly divided into two groups: (1) geometrical and (2) physical and mechanical. The first group includes the parameters that describe ice distribution in some water area and the geometry of ice formations. Total ice concentration, age composition, degree of ridging and melting, snow cover thickness, the geometry of breaks and polynyas, and other local ice features are the examples of the first group of parameters. The second group includes the physical and mechanical characteristics of ice, which in natural conditions can vary in a wide range of values. The key parameters of this group are the flexural strength of the ice, its density, elasticity modulus, and Poisson's ratio.

The degree of influence of geometrical parameters on ship ice performance is significantly higher than the influence of physical and mechanical properties. Indeed, a change in ice thickness by 30% will much strongly affect ship speed than, for example, a change in ice flexural strength by the same 30%. The latter is confirmed by both calculations and full-scale observations. Therefore, almost all existing models of ship performance in ice either do not consider the physical and mechanical properties of ice or consider them as average values, regardless of the specific region of vessel operation. E.g., the flexural strength of ice is usually assumed to be 500 kPa. Such an approach is typical both for studies where semi-empirical formulas are applied to estimate the parameters of ship operation in ice (see, e.g., (Valkonen & Riska, 2014)) and for more complicated numerical models (Su et al., 2010).

Even though the physical and mechanical ice parameters influence ship performance not so much, they affect it systematically. For example, it is known that the strength of ice cover in the Arctic in winter is on average higher than in summer due to the difference in average air temperatures. Accordingly, ship performance in winter and in summer in the ice of the same geometrical parameters will vary, and these differences will be systematic. Another example relates to the effect of salinity. Desalinated ice, which is typical, e.g., for the Azov and Caspian Seas or the Gulf of Ob', is on average more tough than salted ice of the middle part of Arctic Seas. It also causes systematic differences between the parameters of vessel movement in ice of the same geometrical characteristics. Thus, to adequately predict ship performance in ice at different geographic regions and in different seasons, we suggest accounting for the physical and mechanical properties of ice along with its geometrical parameters. This issue was almost not studied in detail before, and this paper attempts to fill this research gap.

1. ALGORITHM TO ESTIMATE THE PHYSICAL AND MECHANICAL PROPERTIES OF ICE

The algorithm to estimate ice parameters is based on well-known and previously published formulas. The main contribution of this study is that we combined them into a single consistent computational algorithm. This algorithm is designed in such a way as to exclude iterative procedures that make calculations faster. Fig. 1 shows an enlarged computational scheme of the algorithm. All symbols in Fig. 1 are deciphered later in this section.

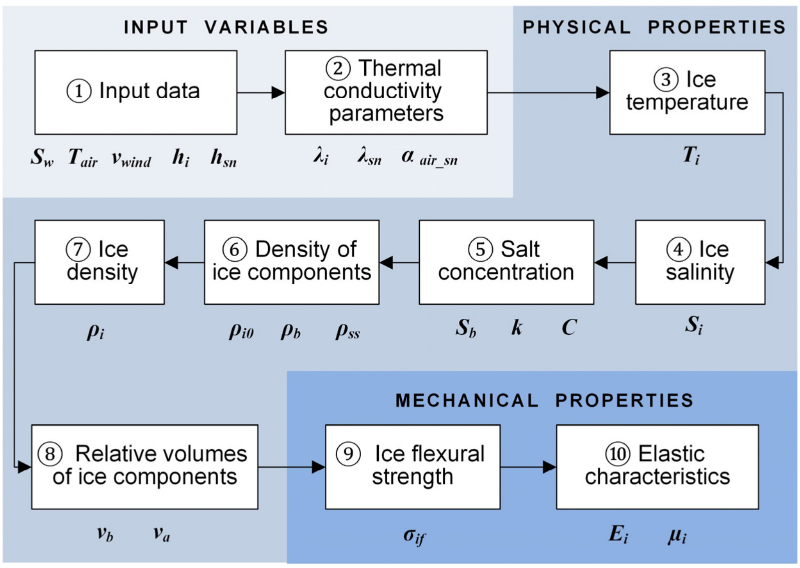

Figure 1. Block diagram of the algorithm to estimate physical and mechanical parameters of ice

The block ① sets the values of the input natural parameters, they are: salinity of seawater surface S_w, ‰ (ppt); surface air temperature T_{air}, °C; surface wind speed v_{wind}, m/s; ice thickness h_i, m; thickness of snow cover h_{sn}, m.

If snow cover thickness h_{sn} is unknown, it can be estimated as a function of ice thickness h_i (m) based on the empirical formula proposed by Shalina & Sandven (2018) as a result of the analysis of representative data on Arctic Seas:

$$h_{sn} = 0.069 \cdot h_i + 0.02 \ \text{[m]} \quad (1)$$

At the second ② step, the parameters of thermal conductivity of snow cover and ice are estimated. Here we assess the thermal conductivity (W/(m·°C)) of sea ice λ_i and snow cover λ_{sn}, as well as the coefficient of heat exchange between atmospheric air and snow α_{air_sn}, W/(m^2·°C). These values are necessary to further calculate ice temperature T_i.

We used a simplified approach to estimate the parameters of thermal conductivity, since we found that their influence on the relative volume of the porous phase in sea ice (and, therefore, on its mechanical properties) is insignificant. The ratio between the coefficients of thermal conductivity of sea ice and snow λ_i/λ_{sn} is quite consistent and varies in a range from 5.5 to 8.5. We took λ_i/λ_{sn} = 7.5 as a basic value. The coefficient of thermal conductivity of snow λ_{sn} can be estimated depending on its density ρ_{sn} according to the empirical formula of Abels-Kondratyeva from (Kozlov, 2004):

$$\lambda_{sn} = a_{sn} \cdot \rho_{sn}{}^2 \ \text{[W/(m·°C)]} \quad (2)$$

where a_{sn} is an empirical coefficient equal to 2.85, when $\rho_{sn} \leq 0.350$ t/m^3, and
3.56, when $\rho_{sn} > 0.350$ t/m^3.

Snow density is not uniform over the thickness of snow cover and depends on its depth and duration of snow accumulation. Nevertheless, based on the experimental data of Warren et al. (1999), it is possible to estimate the value of snow density averaged over snow thickness and season as ρ_{sn} = 0.3 t/m^3. Thus, the values of thermal conductivity coefficients could be estimated as λ_{sn} = 0.26 [W/(m·°C)] and λ_i = 1.95 [W/(m·°C)]. It also corresponds well to the data from (Pringle et al., 2007). Heat exchange coefficient α_{air_sn} can be estimated based on the empirical expression given in (Kozlov, 2004) considering the presence of snow and wind:

$$\alpha_{air\_sn} = k_{sn} \cdot \sqrt{v_{wind} + 0.3} \ \text{[W/(m}^2\text{·°C)]} \quad (3)$$

where k_{sn} is an empirical coefficient defined as follows:

$$k_{sn} = \begin{cases} 5.80, \text{when } h_{sn} = 0 \\ 20.3, \text{when } h_{sn} > 0 \end{cases}.$$

For snow-covered ice and an average wind speed of about 6 m/s that is typical for the sea, the calculated value of the heat exchange coefficient is 51.0 W/(m^2·°C).

At the third ③ step of the algorithm, we calculate sea ice temperature T_i. It is known that in natural conditions the temperature of sea ice varies significantly along its thickness. The vertical temperature profile is traditionally considered to be linear that corresponds to the case when there are no rapid fluctuations of air temperature. Under this assumption, the expression to estimate sea ice temperature T_i could be written as follows:

$$T_i(z) = T_{i\_up} + (T_{i\_lo} - T_{i\_up}) \cdot z/h_i \ \text{[°C]} \quad (4)$$

where z is a position of a design section along the thickness of ice cover h_i, measured from its upper surface, m; T_{i_up} and T_{i_lo} are temperatures of the upper and lower edges of ice cover, respectively, ºC.

When solving ice strength tasks related to calculation and standardization of ice loads, the temperature of ice could be taken at the upper boundary of ice surface z = 0 (Yakimov & Tryaskin, 2013), or in a section spaced by 10% of the thickness z = 0.10·h_i (RS, 2017). Such an approach provides a certain error in a safe direction, since it leads to the underestimation of calculated ice temperature that increases ice strength and, accordingly, ice loads. However, when considering the issues of ship movement in ice, the temperature in the middle of ice cover z = 0.50·h_i is usually adopted (Ryvlin & Kheysin, 1980). The latter was taken as a basic assumption in this study.

The temperature of the lower surface of ice cover can be considered equal to the freezing point of seawater (–1.5 °C ... –1.8 °C) that can be calculated depending on the seawater salinity S_w (‰) based on the data from (Ono, 1967):

$$T_{i\_lo} = -0.05411 \cdot S_w \ [°C] \quad (5)$$

The temperature of the upper ice surface is close to the outside air temperature and deviates from it due to the presence of snow cover and wind. The influence of the latter one is generally small, while a snow cover significantly affects the heat balance due to its relatively low thermal conductivity and high albedo. Description of the influence of snow on ice temperature can be done based on the Newton-Richmann law (6) for convective heat transfer between atmospheric air and snow cover (Petrich & Eicken, 2009), along with condition (7) that describes the equality of average heat fluxes passing through snow and ice cover during a long period of time:

$$F_c = -\alpha_{air\_sn} \cdot (T_{air} - T_{sn}) \ [\mathrm{W/m^2}] \quad (6)$$

$$(T_{i\_up} - T_{sn}) \cdot \lambda_{sn}/h_{sn} = (T_{i\_lo} - T_{i\_up}) \cdot \lambda_i/h_i \quad (7)$$

where F_c is a density of convective heat flux between air and snow, W/m^2; T_{air} is an air temperature, °C; T_{sn} is a temperature of the upper surface of snow cover, °C.

Joint consideration of these expressions allows us to obtain a dependence to estimate a temperature at the upper edge of ice cover:

$$T_{i\_up} = \left(T_{air} \cdot (1 - K_{h\lambda\_1}) + T_{i\_lo} \cdot (K_{h\lambda\_2} - K_{h\lambda\_1})\right) / (1 + K_{h\lambda\_2}) \ [°C] \quad (8)$$

where $K_{h\lambda\_1}$ and $K_{h\lambda\_2}$ are auxiliary dimensionless coefficients introduced here for the compactness of formula (8) and defined as follows:

$$K_{h\lambda\_1} = \left(1 + \alpha_{air\_sn} \cdot (h_i/\lambda_i + h_{sn}/\lambda_{sn})\right)^{-1}; \quad K_{h\lambda\_2} = (\lambda_i/h_i) \cdot (h_{sn}/\lambda_{sn}).$$

At the fourth ④ step, the algorithm estimates the sea ice salinity S_i. It is known that the distribution of salinity over the height of ice cover is uneven; however, a certain averaged value can be used for approximate estimates. For this, we used an empirical formula of Ryvlin (1974):

$$S_i = S_w \cdot \left((1 - b)/\exp(a \cdot \sqrt{h_i}) + b\right) \le S_{max} \ [‰] \quad (9)$$

where S_{max} is the maximum salinity of sea ice, at which it still has mechanical flexural strength, we assume S_{max} = 15‰; $b = 0.13$ is a constant empirical coefficient equal to the ratio of sea ice salinity at the end of the winter growth cycle to the salinity of seawater; a is an empirical coefficient that considers the effect of the rate of ice growth on its salinity.

Coefficient a varies in a relatively narrow range of values from 0.35 at a high ice growth rate (approx. 40 mm/day) to 0.60 at a low rate (approx. 5 mm/day). A rigorous approach to determine the value a is based on the actual rate of ice growth, which can be obtained by solving the heat balance equation on a lower surface of ice cover. To solve such an equation, the basic physical characteristics of sea ice should be known, while they, in turn, depend on the value of coefficient a. To exclude an iterative process in this case, we took an average value of coefficient a as the basic one: a = 0.50. During numerical experiments with a model, we found out that this assumption does not lead to a significant decrease in the accuracy of results (see also Section 2).

At the seventh ⑦ step, the algorithm estimates the sea ice density ρ_i, while the intermediate values are calculated at steps ⑤ and ⑥. The logic of ice density calculation also excludes iterative procedures. This calculation is based on the methodology from (Cox & Weeks, 1983), where the expression to calculate sea ice density ρ_i is written as follows:

$$\rho_i = (1 - \nu_a) \cdot \rho_{i0} \ [\text{t/m}^3] \tag{10}$$

where ν_a is a relative volume of air in sea ice; ρ_{i0} is a density of air-free sea ice that depends on the relative volume of salts, t/m^3.

Cox & Weeks (1983) characterize the content of salts in sea ice by the following parameters that depend on ice temperature T_i: the brine salinity itself S_b; the ratio between the mass of solid salts and the mass of dissolved salts in a brine k; the ratio between the mass of solid salts and the mass of brine C. To perform practical calculations, we used the polynomial approximations of functions $S_b(T_i)$, $k(T_i)$ and $C(T_i)$ from (Petrich & Eicken, 2009). The density of air-free sea ice can be assessed by the equation from (Cox & Weeks, 1983):

$$\rho_{i0} = \frac{\rho_{ifw} \cdot F_1}{F_1 - F_2 \cdot \rho_{ifw} \cdot S_i} \ [\text{t/m}^3] \tag{11}$$

where $\rho_{ifw} = 0.917 - 1.403 \cdot 10^{-4} \cdot T_i$ is a density of freshwater (i.e. pure) ice, t/m^3; $F_1 = F_1(T_i)$ and $F_2 = F_2(T_i)$ are special functions that characterize the salinity of sea ice and depend on its temperature T_i. These functions are defined as follows:

$$F_1 = (1 + k) \cdot S_b \cdot \rho_b \,; \qquad F_2 = (1 + C) \cdot \frac{\rho_b}{\rho_{ifw}} - C \cdot \frac{\rho_b}{\rho_{ss}} - 1$$

where $\rho_{ss} = 1.5$ t/m^3 is a density of solid salts; $\rho_b = 1.0 + 8.0 \cdot 10^{-4} \cdot S_b$ is a density of brine, t/m^3.

The relative volumes of air ν_a and brine ν_b in sea ice can be calculated as follows:

$$\nu_a = 1 - \rho_i \cdot \left(\frac{1}{\rho_{ifw}} - \frac{F_2}{F_1} \cdot S_i \right); \qquad \nu_b = \rho_i \cdot \frac{S_i}{F_1}. \tag{12}$$

According to this approach, the desired value ρ_i can be obtained by substituting expressions (11) and (12) into formula (10) and conducting iterative procedures, since the dependence to determine the parameter ν_a contains the value of ρ_i. To exclude iterations in this case, there should be some additional equation. For this purpose, we suggest using a ratio between ν_a and ν_b that was obtained based on systematization and analysis of a few experimental data given in (Kovacs, 1996) and (Cox & Weeks, 1986):

$$\nu_a / \nu_b = \exp(86.842 \cdot {\rho_{i0}}^2 - 321.048 \cdot \rho_{i0} + 221.744). \tag{13}$$

Equation (13) is valid for the density of air-free sea ice ρ_{i0} determined by the formula (11) in accordance with the approach of Cox & Weeks (1983). The values of ρ_{i0} vary in a range from 0.92 to 0.96 t/m^3 for the temperature and salinity of sea ice observed in real conditions.

The density of sea ice ρ_i can be determined by means of dividing the value $\nu_a = 1 - \rho_i/\rho_{i0}$ from formula (10) by the value ν_b from formula (12) and performing several transformations:

$$\rho_i = \frac{\rho_{i0} \cdot F_1}{F_1 + (\nu_a/\nu_b) \cdot \rho_{i0} \cdot S_i} \le \rho_{i0} \ \text{[t/m}^3\text{]} \tag{14}$$

Equation (14) considers that the density of sea ice cannot exceed the density of air-free sea ice. Fig. 1 shows the sequence of calculations to obtain the value ρ_i according to the presented scheme.

At the eighth ⑧ step, the algorithm estimates the relative volumes of air ν_a and brine ν_b in sea ice using equation (12) and known values of ice temperature, salinity, and density.

At the ninth ⑨ step, the algorithm calculates the flexural strength of sea ice σ_f. We will not focus here on a variety of formulas to estimate the flexural strength of ice and refer an interested reader to the review, e.g., of Timco & Weeks (2010). However, we would note that after analyzing various indirect indicators and comparing the resulting ice performance of a vessel determined based on Lindqvist's (1989) method (see Section 4), we decided that it is best to use the empirical dependence of Timco & O'Brien (1994). This dependence is also recommended by international standard ISO 19906:

$$\sigma_f = \frac{1760}{\exp\left(5.88 \cdot \sqrt{\nu_b}\right)} \ge 200 \ \text{[kPa]} \tag{15}$$

Equation (15) can be applied in a wide range of values ν_b, from 0 to 0.25. However, as a rule, sea ice with a high specific content of brine $\nu_b > 0.12$ has a flexural strength approximately equal to 200 kPa (Doronin & Kheysin, 1975). Therefore, we took 200 kPa as a lower limit of possible values of σ_f.

At the last, tenth ⑩ step, the elasticity characteristics of sea ice are calculated: elasticity modulus E_i and Poisson's ratio μ_i. There are also many empirical formulas to calculate E_i, but in this study after some analysis we chose the formula recommended by international standard ISO 19906 as revised in 2010:

$$E_i = E_{ifw} \cdot \left(1 - \sqrt{\nu_a + \nu_b}\right)^4 \ \text{[GPa]} \tag{16}$$

where $E_{ifw} = 6.1 \cdot (1 - 0.012 \cdot T_i)$ is a true modulus of elasticity of freshwater ice according to Lindgren & Gold formulas from (Bergdahl, 1977).

Equation (16) gives the values of E_i significantly lower than those ones described in the literature for true modulus of elasticity (from 6 to 9 GPa). Nevertheless, this equation was accepted due to the following reasons. First, the basic value of elasticity modulus in Lindqvist's method is equal to 2 GPa that is also significantly less than the available estimates and rather corresponds to the effective modulus of elasticity under static load. We assume that the use of values of E_i close to 6…9 GPa will not be entirely correct in Lindqvist's method due to the peculiarities of the method itself. Second, equation (16) allows us to consider both the porosity of ice (i.e. brine and air volumes) and its temperature that is important in this study. In general, it can be noted that the absolute values of mechanical characteristics of ice, as well as methods for their experimental determination are still a subject for discussions (Karulina et al., 2019). Therefore, the methods applied in this study mainly correspond to the authors' opinion.

The true value of the Poisson's ratio of sea ice μ_i is fairly steady. It can be determined as a function of ice temperature T_i using the empirical expression from (Weeks & Assur, 1967):

$$\mu_i = 1/3 + 6.105 \cdot 10^{-2} \cdot \exp(T_i/5.48). \tag{17}$$

Based on the presented approach, other mechanical parameters of sea ice (e.g., compressive strength, crushing strength, shearing strength, etc.) that depend on brine and air relative volumes, ice temperature, its density, and other physical properties can be assessed.

2. IMPACT OF VARIOUS PARAMETERS ON FLEXURAL STRENGTH OF ICE

The algorithm presented in the previous section allows us to evaluate various mechanical parameters of ice; however, it is known that the flexural strength σ_f affects ice performance of a vessel most of all. It is obvious that the method applied to calculate σ_f will significantly impact the results. As shown in (Karulina et al., 2019), the values of σ_f determined based on various semi-empirical formulas can differ significantly, especially for the ice of low salinity. Nevertheless, in this study, we do not analyze the influence of the calculation method and focus on the analysis of natural factors taking the formulas from Section 1 as a basis.

To perform such an analysis, we did a series of calculations in accordance with the plan shown in Table 1. Each factor varied separately when other ones were equal to the basic values. Ice thickness varied from 0.1 m to 3.0 m with a step of 0.1 m, and snow thickness was taken according to equation (1). Fig. 2 shows the obtained results.

Table 1. Factors to analyze the sensitivity of the algorithm for determining σ_f

Parameter	Unit	Basic value	Variation parameters		
			Min	Max	Step
Seawater salinity $\boldsymbol{S_w}$	‰ (ppt)	20	5	35	5
Air temperature $\boldsymbol{T_{air}}$	°C	-15	-30	0	5
Wind speed $\boldsymbol{v_{wind}}$	m/s	9	0	18	3
Thermal conductivity ratio $\boldsymbol{\lambda_i/\lambda_{sn}}$	-	7.0	5.5	8.5	0.5
Parameter $\boldsymbol{a}$ in Eq. (9) for ice salinity	-	0.50	0.35	0.65	0.05
Position of a design section $\boldsymbol{z/h_i}$ in Eq. (4)	-	0.50	0.10	0.70	0.10

As it can be seen, seawater salinity S_w and air temperature T_{air} have the greatest influence on the value of σ_f. Seawater salinity change from 35 ppt up to 5 ppt at ice thickness of 1.5 m leads to a change in σ_f from 550 kPa to 1090 kPa. Under the same ice thickness, a change in air temperature from 0°C to –30°C leads to an increase in σ_f from 410 kPa to 870 kPa. In other words, there is a double change in ice flexural strength when seawater salinity and air temperature vary in ranges that are typical for natural conditions. The wind speed v_{wind} has a negligible effect on ice flexural strength; therefore, it can be ignored further.

The ratio between the thermal conductivities of ice and snow λ_i/λ_{sn} also affects ice strength a little due to the relatively small thickness of snow cover. The internal parameter a, which is used to calculate ice salinity in equation (9) and varies from 0.35 to 0.65, affects σ_f in general insignificantly. Noteworthy differences are observed only at ice thickness lower than 0.7-1.0 m; therefore, for the simplicity of a model, it seems possible to take the average value a = 0.50. As for the parameter z/h_i, which reflects the relative position of a design section along the thickness of ice cover, its influence turns out to be significant. This is because z/h_i affects the calculated ice temperature and, in other words, reflects the uncertainty of ice temperature value. Moreover, ice temperature is non-linear by ice thickness and depends on the dynamics of daily average air temperatures, which introduces additional uncertainty. Therefore, we have no way other than to accept a certain constant value z/h_i = 0.50 and note a significant uncertainty of ice temperature factor.

Thus, it could be said that air temperature and seawater salinity are the key parameters to estimate the influence of seasonal and regional factors on the ice performance of a vessel.

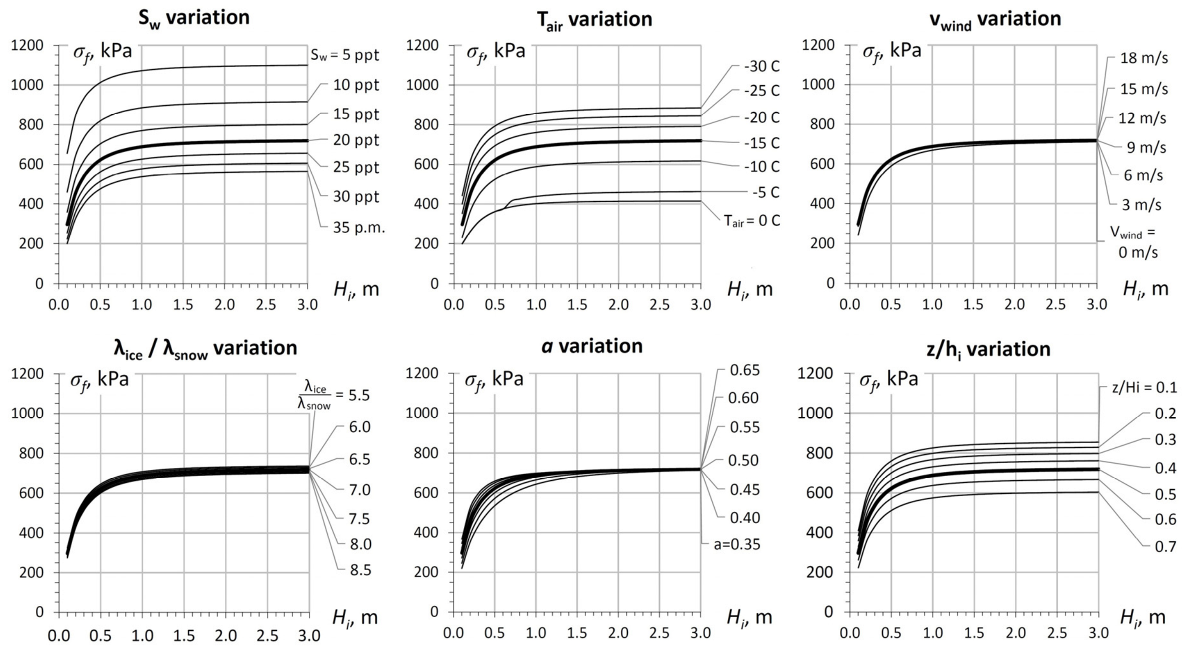

Figure 2. Sensitivity analysis of the model for calculating the physical and mechanical properties of ice to various factors

3. DATA ON SEAWATER SALINITY AND AIR TEMPERATURE IN THE ARCTIC

The possibility to use the presented algorithm when modeling ship movement across the entire Arctic is based on one important assumption, which we applied here without formal justification. It lies in the fact that ice drift does not significantly affect its physical and mechanical properties. Therefore, such properties can be predicted in each geographic region based on the average values of seawater salinity and air temperature in this region. To assess how strongly the latter factors can vary, we analyzed the dynamics of temperature and salinity within the Russian Arctic based on the data from (Boyer et al., 2012). Fig. 3 shows an example of monthly average values of air temperature and seawater salinity in March.

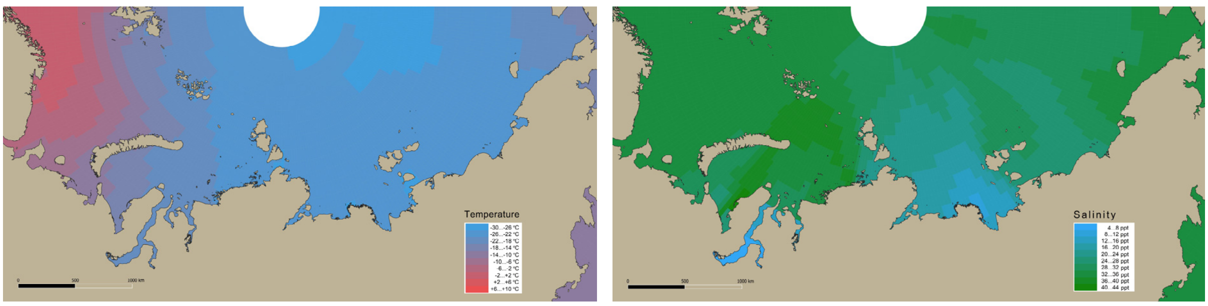

Figure 3. Example of monthly average air temperature (left) and seawater salinity (right) in the Arctic in March based on the data from (Boyer et al., 2012)

Obviously, different areas of the Arctic have different temperatures and salinities in both space and time. Spatial and temporal variability of temperature and salinity is significant. However, we think that in practice it will never be possible to reveal true values of air temperature and seawater salinity that influence ice during the period of its life from formation to melting, as well as during its drift. This factor will always be a source of significant uncertainty. Therefore, we assumed that ice parameters at any point of the Arctic correspond to the monthly average climatic values of air temperature and seawater salinity at this point. This approach allows us to consider the fundamental features of each water area of the Arctic when modeling the movement of ships along the Northern Sea Route.

For further sample calculations in this study, we took the integrated estimates of air temperature and seawater salinity for the Western and Eastern sectors of the Arctic. The border between the sectors runs along the Vilkitsky Strait. Fig. 4 shows the dynamics of mean, minimum, and maximum monthly average air temperature and seawater salinity on shipping routes within the averaging period from 1997 to 2020. For calculations, we distinguished two time periods: winter-spring (from January to March) and summer-autumn (from July to September). The averaged values of air temperature and seawater salinity on shipping routes are the following:

- Winter-spring navigation & Western sector of the Arctic: T_{air} = –14.5°C, S_w = 29.8‰
- Winter-spring navigation & Eastern sector of the Arctic: T_{air} = –26.7°C, S_w = 25.7‰
- Summer-autumn navigation & Western sector of the Arctic: T_{air} = + 3.4°C, S_w = 27.3‰
- Summer-autumn navigation & Eastern sector of the Arctic: T_{air} = + 1.1°C, S_w = 21.3‰

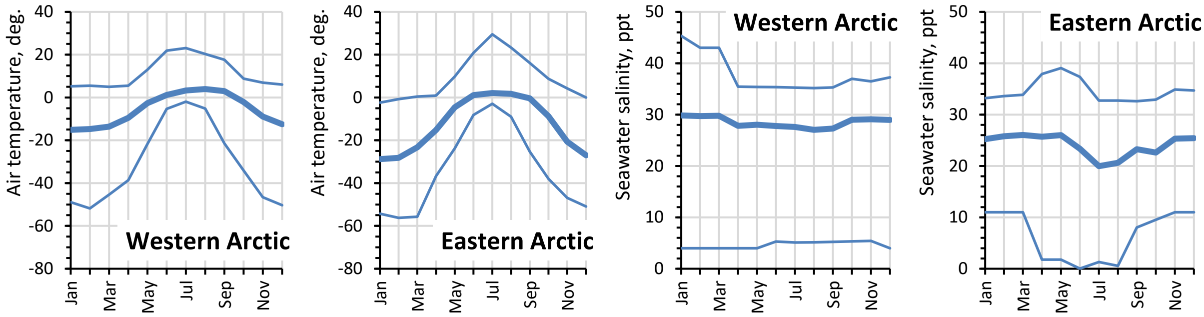

Figure 4. Air temperature and seawater salinity in the Western and Eastern sectors of the Arctic for the period 1997-2020. Monthly averages are shown in each graph as follows: mean values (middle line), minimum values (bottom line), and maximum values (top line)

4. CASE STUDY OF SHIP PERFORMANCE IN LEVEL ICE IN DIFFERENT CONDITIONS

We chose the case of level ice to perform test calculations of ship performance considering seasonal and regional variability of ice properties. As an example, we took the Arktika-type icebreaker (see Table 2) launched in 1972. This is basically the only vessel, for which there are some data on its ice performance in various natural conditions. In particular, Adamovich et al. (1995) indicated that the icebreaking capability of this vessel is 1.9 m in winter and 2.6 m in summer, while its nominal value under standard conditions is 2.3 m.

Table 2. Main particulars of Arktika-type icebreaker (built in 1972)

Length on waterline $\boldsymbol{L_{wl}}$	136.0 m
Breadth on waterline $\boldsymbol{B_{wl}}$	28.0 m
Draught at midship $\boldsymbol{d_{wl}}$	11.0 m
Mass displacement $\boldsymbol{\Delta}$	23 460 t
Total shaft power $\boldsymbol{N_{\Sigma}}$	48 970 kW
Maximum open water speed $\boldsymbol{v_{ow}}$	21.6 kn.
Nominal icebreaking capability at 2 kn. $\boldsymbol{h_{lim}}$	2.3 m
Bollard pull $\boldsymbol{T_{pull}}$	4 700 kN

We built ice performance curves for this icebreaker in level ice using a standard approach, i.e. by equating the ice resistance R_i to the net thrust T_{net} (i.e. to the available thrust):

$R_i(h_i, v) = T_{net}(v)$ [kN] (18)

where $T_{net} = T_{pull} \cdot (1 - (1 - \alpha) \cdot v/v_{ow} - \alpha \cdot (v/v_{ow})^2)$ is an approximate net thrust according to (Ryvlin & Kheysin, 1980), where coefficient α is assumed to be 0.66.

Ice resistance R_i was determined using Lindqvist's method. We adopted this method due to its versatility and applicability in a wide range of ship dimensions, as well as its relative simplicity. The same as any semi-empirical method, Lindqvist's method can give significant errors (see, e.g., (Erceg & Ehlers, 2017)). As a result, the calculated value of icebreaking capability h_{lim} (at 2.0 kn.) may not correspond to the real ice performance observed in full-scale conditions. To compensate for this, we used scaling. It was done in such a way that the calculated resistance at a speed of 2.0 kn. in the ice of thickness $h_i = h_{lim}$ and under nominal values of physical and mechanical ice parameters corresponded to the bollard pull T_{pull} of a ship. Due to scaling, the calculated resistance in ice with σ_f = 500 kPa strictly corresponds to the known nominal icebreaking capability of a ship. So, the expression to determine ice resistance R_i can be written as follows:

$R_i(h_i, v) = R_i \cdot k_{sc}$ [kN] (19)

where $k_{sc} = T_{pull}/R_{i0}$ is an ice resistance scale factor; R_{i0} is an ice resistance determined by Lindqvist's method under the following values of input parameters: $h_i = h_{lim}$, v = 1.029 m/s (i.e. 2.0 kn.), σ_f = 500 kPa, ρ_i = 0.9 t/m^3, E_i = 2.0 GPa, μ_i = 0.35; R_i is an ice resistance determined by Lindqvist's method under the actual values of ice thickness h_i and ship speed v, as well as for relevant physical and mechanical parameters of ice (σ_f, ρ_i, E_i, μ_i) estimated based on the algorithm from Section 1.

In case of Arktika-type icebreaker, the scale factor k_{sc} is equal to 1.712, i.e. Lindqvist's method underestimates the real resistance of an icebreaker in thick ice by 71.2%.

Fig. 5 shows the examples of calculating ice performance curves according to the scenarios described in Section 3. Snow thickness was taken according to equation (1). This figure illustrates the systematic influence of seasonal and regional factors on ice performance of a ship. Comparison of calculation results with the full-scale data from (Adamovich et al., 1995) shows a good agreement between them. The full-scale variations of icebreaking capability are from 1.90 to 2.60 m, while according to our calculations, they range from 2.05 to 2.60 m, which is ±10…13% of its nominal value equal to 2.30 m. The obtained concave shape of ice performance curves also well corresponds to the shape of full-scale curves given, e.g., in (Riska et al., 1997).

The calculated value of flexural strength of 1.5 m thick ice in winter-spring period is 580-770 kPa, while in summer-autumn period it is 320-390 kPa. When analyzing the change in ice properties depending on ice thickness, it should be borne in mind that for each curve the air temperature and seawater salinity are constant. As it could be seen, when increasing ice thickness, ice salinity and ice density decrease, while ice strength grows up. This is close to the real pattern, because in thick ice the brine flows down through cracks, and the density of such desalinated ice becomes lower, whereas its flexural strength increases. Ice temperature also decreases with increasing ice thickness and asymptotically approaches a certain value. The form of this dependence is due to the influence of snow cover and ratio between the thicknesses of snow and ice.

CONCLUSIONS

Seasonal and regional variability of physical and mechanical properties of ice has a significant impact on ice performance of a ship. Therefore, it should be considered when simulating year-round operation of ships in the Arctic. The algorithm proposed in this study can be used to predict the parameters of vessel movement in ice-covered water areas considering the navigation region and season, as well as taking into account the global trends of Arctic climate change. To do this, it is required to know the distribution of monthly average air temperature and seawater salinity on each shipping route. The obtained results are in a good agreement with the available fragmentary full-scale data. However, the volume of such data is insufficient. Therefore, the proposed computational model needs further analysis and comparison with the full-scale values.

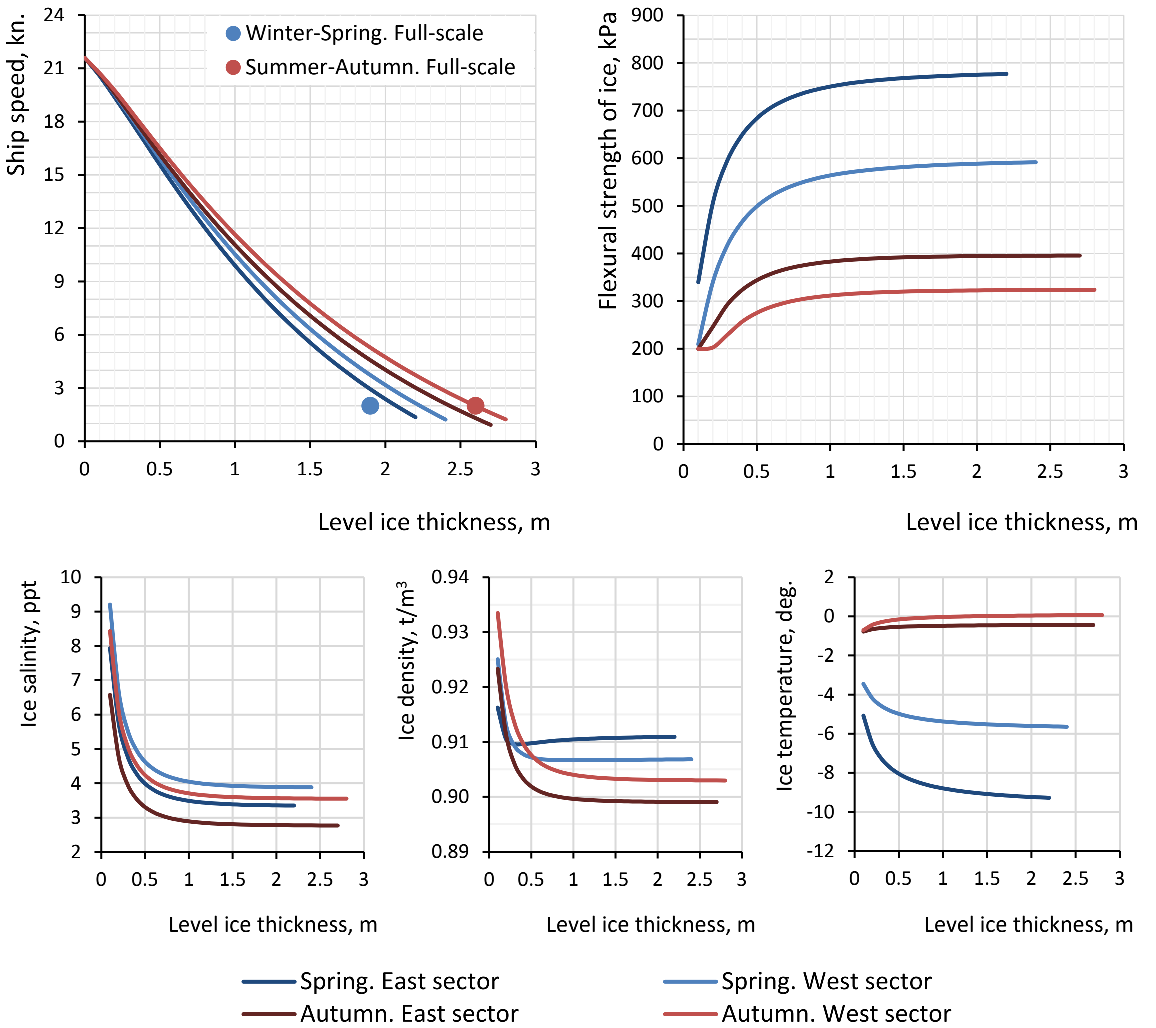

Figure 5. Calculated ice performance curves of Arktika-type icebreaker in various conditions (upper left figure) and calculated values of ice parameters (other figures)

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