POAC2021

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

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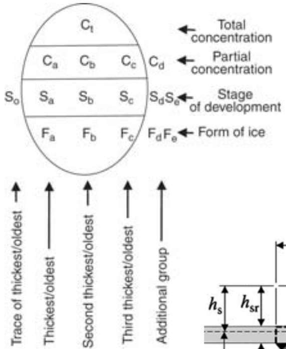
15 June 2021

Modelling of ice parameters in transit simulations

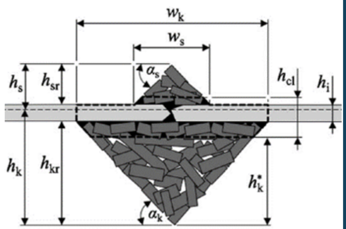
Ice parameters

(1) Geometrical



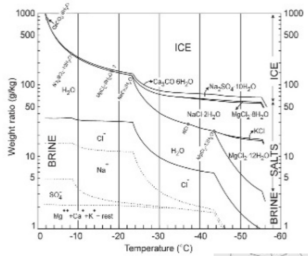
C , h_i , D_i ...

SIGRID-3 (2004)



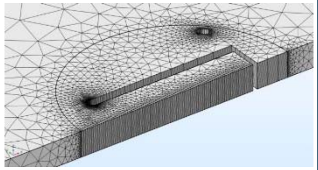
Milacovic et al. (2019)

(2) Physical and mechanical

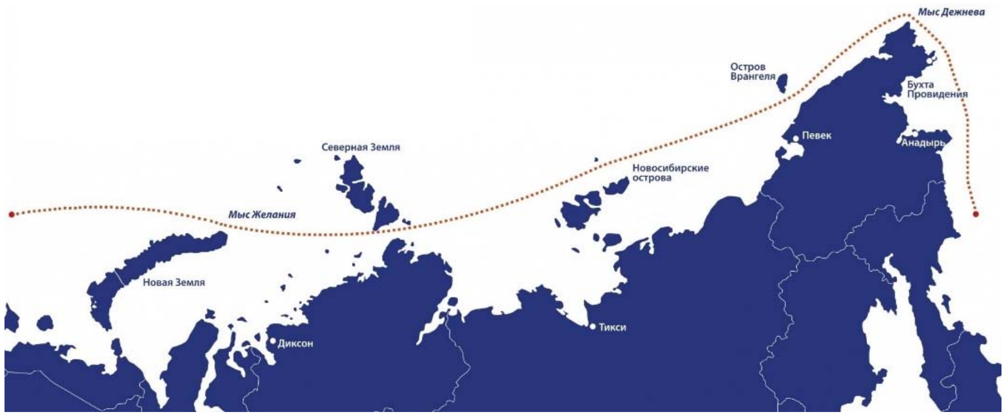


σ_f, E_i, μ_i ...

Thomas & Dieckmann (2010)

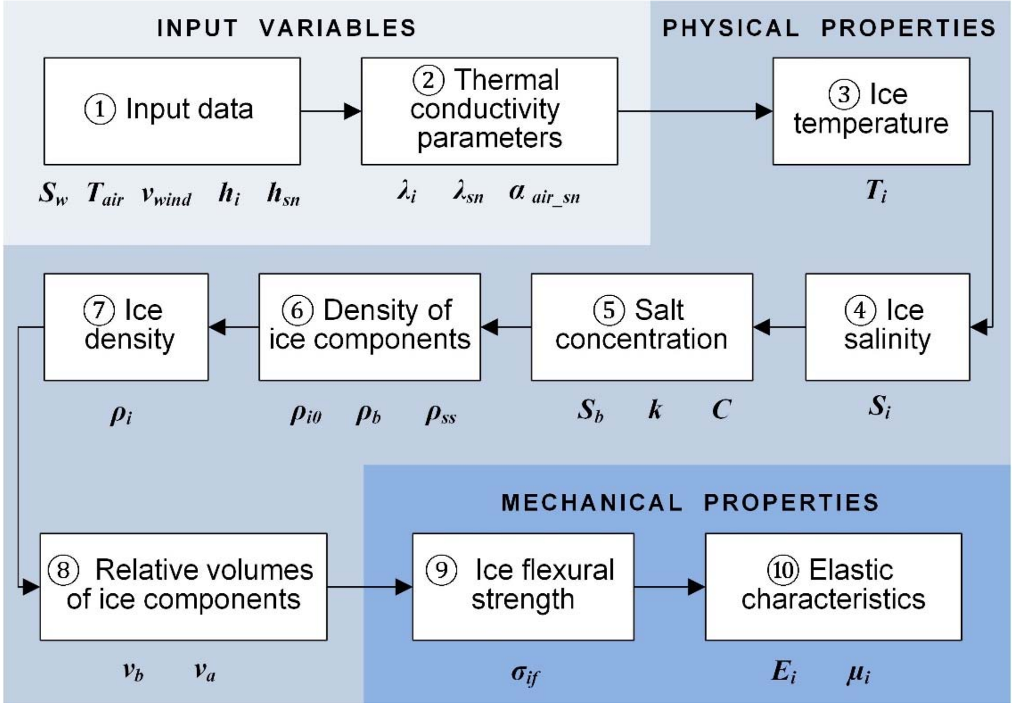


Karulin et al. (2019)

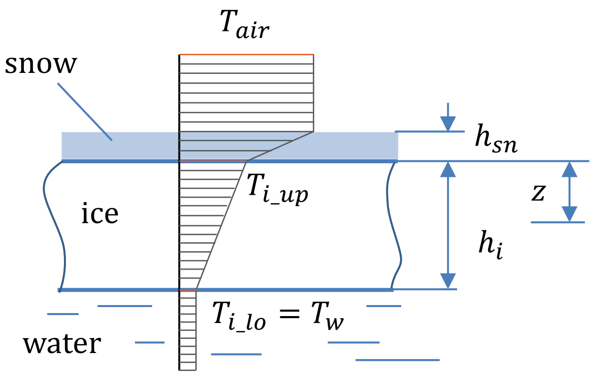


1. During year-round navigation in the Arctic, ships operate in different seasons and regions.
2. Practical experience shows that there is a systematic influence of the region and season on ice performance of a ship. We suggest that this is due to the dependence of mechanical properties of ice on the region and season.
3. In most studies and transit simulations, only the geometrical parameters are considered, while the mechanical properties of ice are usually taken by the nominal values.
4. This forms a research gap that we try to address in this study.

Algorithm to estimate the properties of ice



$\boldsymbol{S_w}$ – sea salinity
$\boldsymbol{T_{air}}$ – air temperature
$\boldsymbol{v_{wind}}$ – wind speed
$\boldsymbol{h_i}$ – ice thickness
$\boldsymbol{h_{sn}}$ – snow cover thickness
$\boldsymbol{\lambda_i}$ – thermal conductivity of ice
$\boldsymbol{\lambda_{sn}}$ – thermal conductivity of snow cover
$\boldsymbol{\alpha_{air\_sn}}$ – coefficient of heat exchange between air and snow
$\boldsymbol{\rho_i}$ – sea ice density
$\boldsymbol{\nu_a}$ – relative volume of air in sea ice
$\boldsymbol{\rho_{i0}}$ – density of air-free sea ice



Basic snow cover by Shalina & Sandven (2018):

$$h_{sn} = 0.069 \cdot h_i + 0.02$$

Linear change of ice temperature:

$$T_i(z) = T_{i\_up} + (T_{i\_lo} - T_{i\_up}) \cdot z/h_i$$

Ice salinity according to Ryvlin (1974):

$$S_i = S_w \cdot \left(\frac{1-b}{\exp\left(a \cdot \sqrt{h_i}\right) + b} \right)$$

Ice density by Cox & Weeks (1983):

$$\rho_i = (1 - \nu_a) \cdot \rho_{i0}$$

Flexural strength by Timco & O'Brien (1994):

$$\sigma_f = \frac{1760}{\exp\left(5.88 \cdot \sqrt{\nu_b}\right)}$$

Elastic modulus by ISO 19906 (2011):

$$E_i = E_{ifw} \cdot \left(1 - \sqrt{\nu_a + \nu_b}\right)^4$$

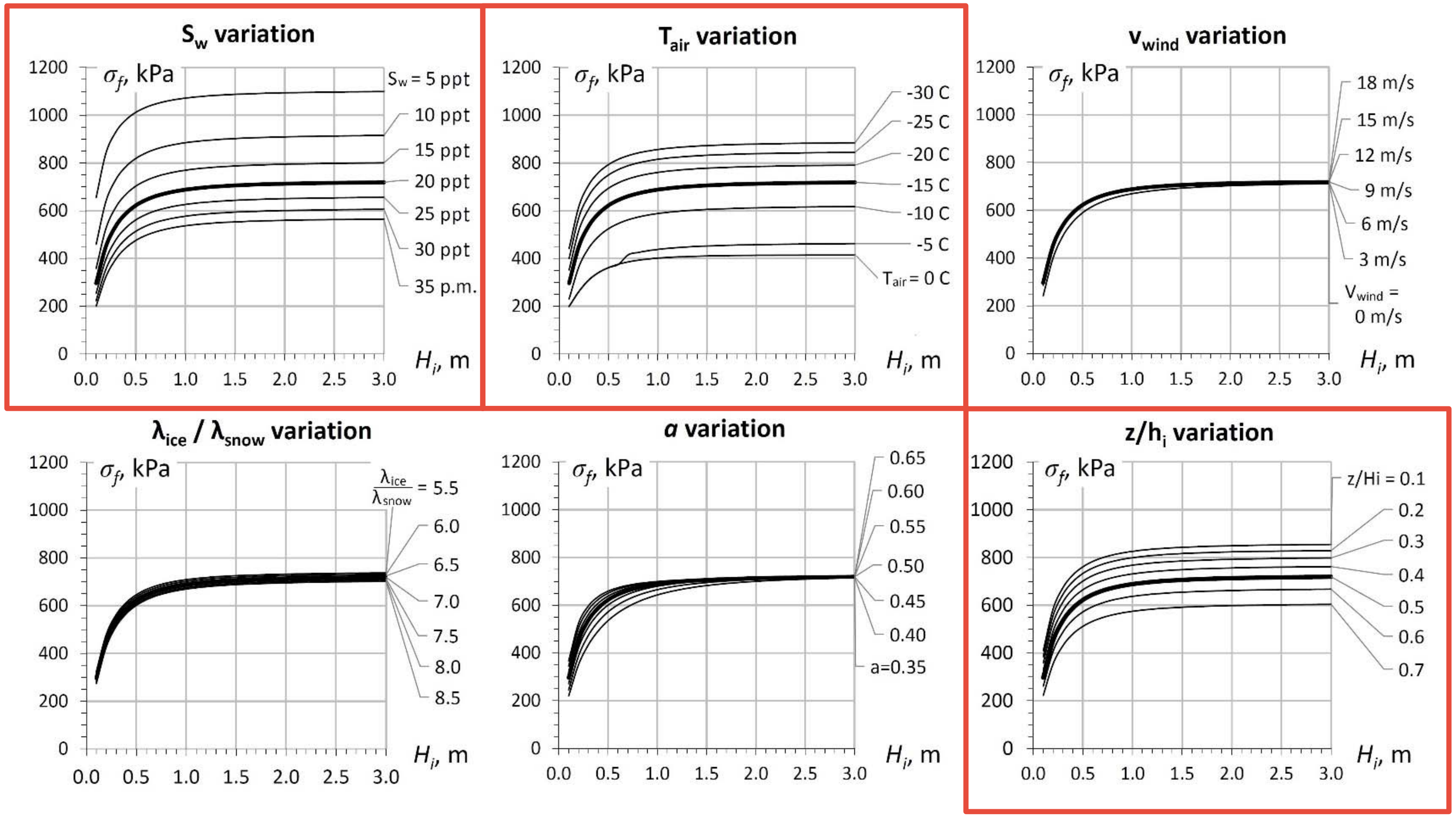
Poisson's ratio by Weeks & Assur (1967):

$$\mu_i = 1/3 + 6.105 \cdot 10^{-2} \cdot \exp\left(\frac{T_i}{5.48}\right)$$

Impact of various parameters on flexural strength of ice

Natural parameters

Internal variables



Parameter	Unit	Basic value	Variation parameters		
			Min	Max	Step
Seawater salinity S_w	‰ (ppt)	20	5	35	5
Air temperature T_{air}	°C	-15	-30	0	5
Wind speed V_{wind}	m/s	9	0	18	3
Ratio λ_i/λ_{sn}	-	7	5.5	8.5	0.5
Parameter a in Ryvlin's formula	-	0.5	0.35	0.65	0.05
Position of a design section z/h_i	-	0.5	0.1	0.7	0.1

Data on sea salinity and air temperature in the Arctic

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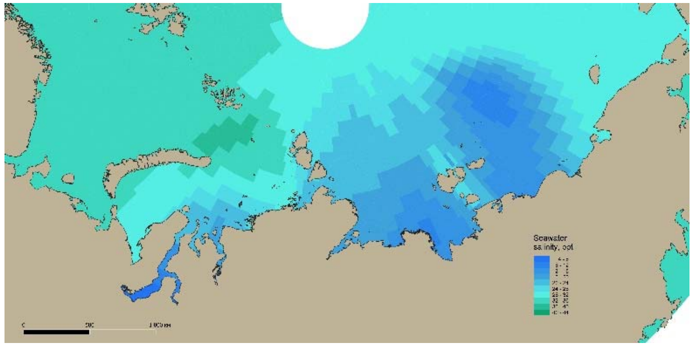
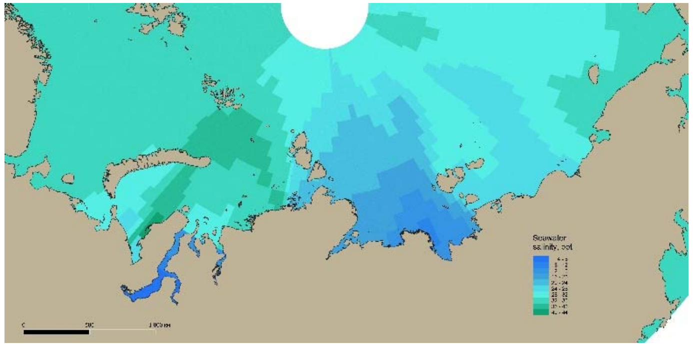
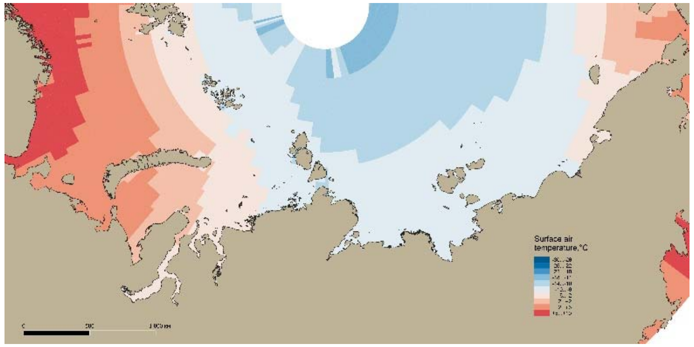
October | **March**

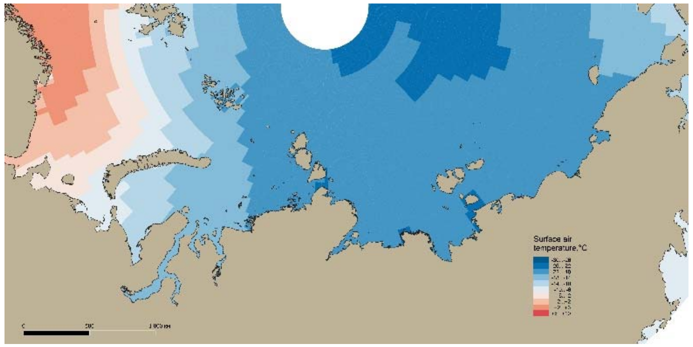
Sea salinity

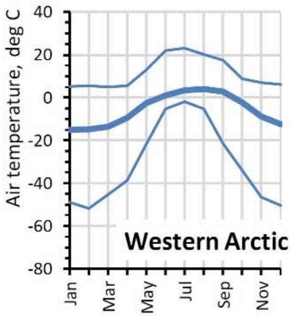


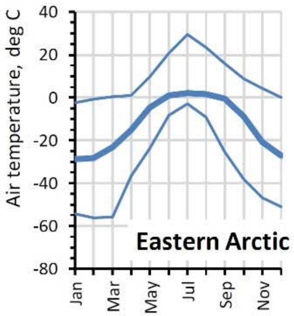


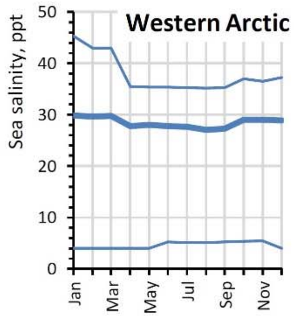
Air temperature

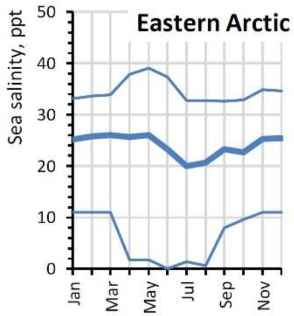












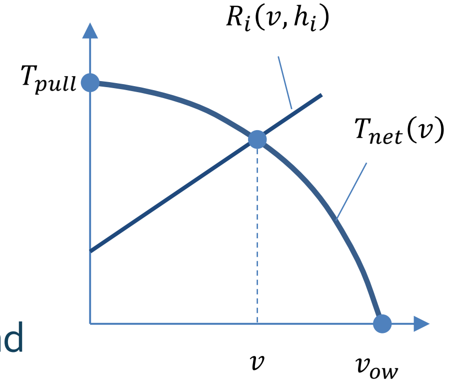
	Spring	Autumn
Eastern sector	–26.7 °C 25.7 ‰	+ 1.1 °C 21.3 ‰
Western sector	–14.5 °C 29.8 ‰	+ 3.4 °C 27.3 ‰

Data from (Boyer et al., 2012)

Estimation of ship performance in level ice

1. Attainable speed is estimated by equating a net thrust T_{net} to the ice resistance R_i:

$$R_i(h_i, v) = T_{net}(v), \qquad T_{net} = T_{pull} \cdot \left(1 - (1-\alpha)\frac{v}{v_{ow}} - \alpha\left(\frac{v}{v_{ow}}\right)^2\right)$$



2. Lindqvist's method is used as a basic approach to estimate ice resistance

$$R_i = (R_c + R_b)\left(1 + 1.4\frac{v}{\sqrt{gh_i}}\right) + R_s\left(1 + 9.4\frac{v}{\sqrt{gL}}\right)$$

3. We used scaling to obtain a strict correspondence between bollard pull T_{pull} and ice resistance at 2 knots and ice thickness equal to the nominal icebreaking capability of a ship h_{lim}. Scale factor k_{sc} was estimated as:

$$k_{sc} = \frac{T_{pull}}{\mathbf{R_{i0}}}$$

Ice resistance in nominal conditions:
$h_i = h_{lim}$, v = 2 knots, σ_f = 500 kPa,
ρ_i = 0.9 t/m³, E_i = 2.0 GPa, μ_i = 0.35

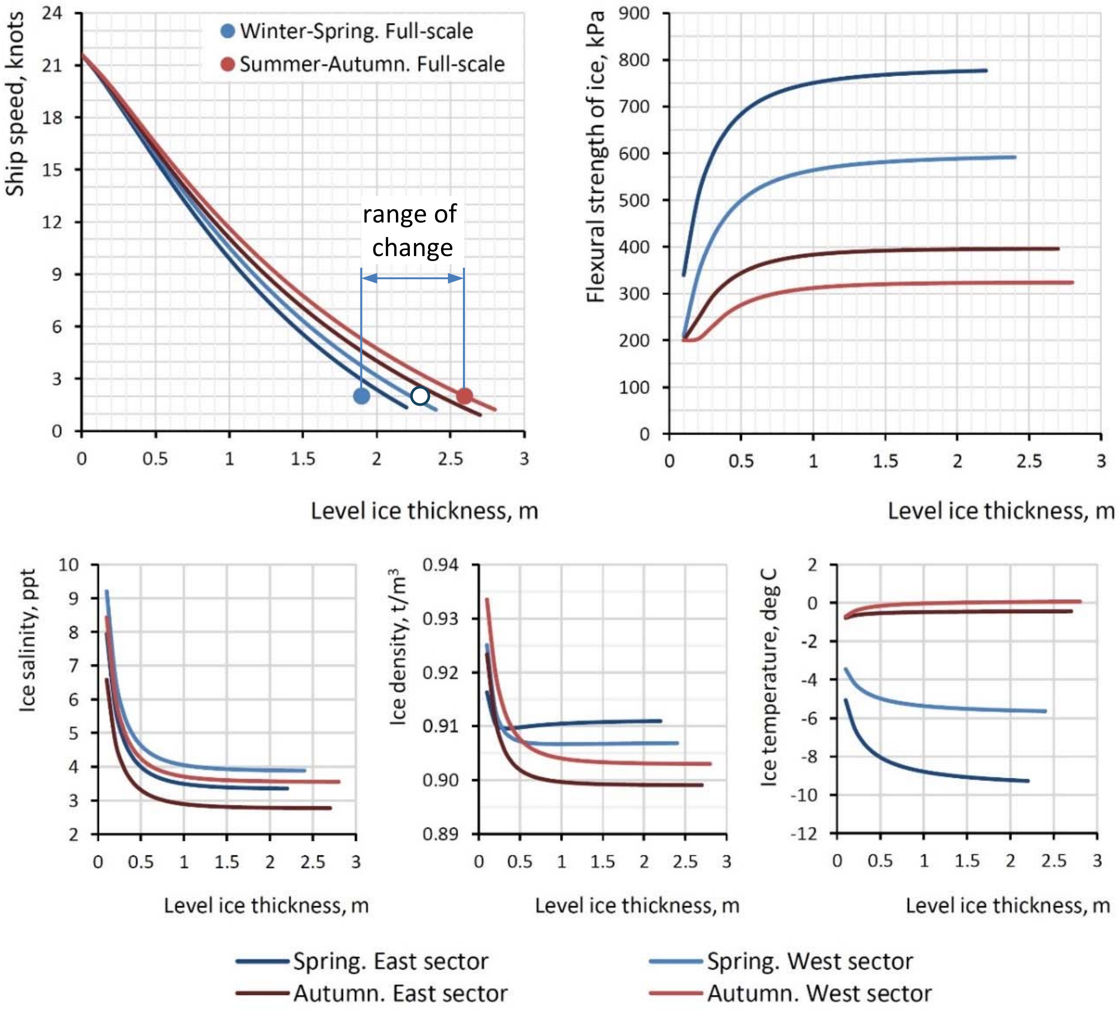
$$R_i(h_i, v) = k_{sc} \cdot \mathbf{R_i}$$

Ice resistance in given ice conditions:
h_i , v , σ_f , ρ_i , E_i , μ_i

4. IB Arktika (1972 built) was used as a sample ship

Length × Breadth × Draught	136.0 × 28.0 × 11.0 m
Displacement	23460 t
Total shaft power	48970 kW
Maximum open water speed v_{ow}	21.6 kn
Nominal icebreaking capability at 2 kn h_{lim}	2.3 m
Icebreaking capability in winter-spring	1.9 m
Icebreaking capability in summer-autumn	2.6 m
Bollard pull T_{pull}	4700 kN

Ice performance curve of a ship and properties of ice



1. Full-scale icebreaking capability ranges from 1.9 to 2.6 m, while our calculations give values from 2.05 to 2.6 m. This significantly deviates from the nominal value (2.3 m)
2. Calculated value of flexural strength of 1.5 m thick ice in the spring period is 580 - 770 kPa, while in the autumn it is 320 - 390 kPa
3. There is a systematic influence of seasonal and regional factors on ice performance of a ship.
4. Seawater salinity and air temperature can be used as main predictors of seasonal and regional variability of ship performance in ice.
5. The algorithm could be applied to consider the global trends of Arctic climate change

Thank you for your attention