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Prediction Method of Polar Navigation Window Period Based on Risk Evaluation

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Abstract: With the increase of international trade activities and the gradual melting of the polar ice cap, the importance of the Arctic route for marine transportation has been emphasized. Prediction of the polar navigation window period is crucial for navigating in the Arctic route, which is of great significance to the selection of the route and the optimization of navigation. This paper introduces the establishment of a risk index system, determination of risk index weight, establishment of a risk evaluation model, and prediction algorithm for the window period. In addition, data sources of both environmental factors and ship factors are introducted, and their shortcomings are analyzed, followed by introduction of various methods involved in window prediction and analysis of their advantages and disadvantages. The quantitative risk evaluation and window period algorithm can provide a reference for the research of polar navigation window period prediction.

Key words: window period; risk evaluation; polar navigation; risk index

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0 Introduction

Climate warming has resulted in the gradual melting of Arctic sea ice, leading to the opening of the northeast polar summer route. The emergence of the Northeast Passage holds significant implications for global shipping and trade. Typically, navigation on the Northeast Passage commences in mid-to-late July and concludes in mid-to-late October, allowing for an average navigation period of approximately 90 days. However, during the years from 2005 to 2014, there was considerable fluctuation in the navigation period with no discernible stable trend[1]. The risk associated with polar navigation has not been consistent over the decade spanning from 2011 to 2020, posing a significant challenge for the accurate assessment of polar navigation safety[2]. Therefore, accurate prediction of the window period is of paramount importance as it directly impacts the safe navigation of the Northeast Passage.

Currently, there is limited research on the polar window period. Li et al[3] conducted a comprehensive analysis of the Arctic route's navigation environment, including meteorological, hydrological, geographical, traffic control, and navigational aid aspects. Wang et al[4] calculated the RIO of Yongsheng's first voyage through the Arctic Northeast Passage and identified the navigation window from 2011 to 2020. Over the past decade, the average navigation time of the Arctic Northeast Passage was 79 days. Liu et al[5] determined the

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window period for navigating through the polar Northwest Passage based on sea ice intensity data from the year 2006 to the year 2015 and found that its shortest navigation time was 69 days. Gu[2] established an ice state data analysis method based on the Egg Code rule system defined by the International Meteorological Organization (IMO), and studied the change rule of the navigation of the Northeast route in November. The study showed that the navigation safety was higher in 2011, 2012 and 2020 while the navigation risk was higher and it was not suitable for navigation During 2013–2016.

Most regulations do not cover whether ships can safely navigate specific routes within polar regions or assess potential risks involved. This paper presents a systematic introduction and analysis of the prediction method of window period based on risk evaluation.

1 Establishment of risk index system

1.1 Risk index system

The navigability of a shipping route in polar region is influenced by a multitude of factors, encompassing environmental, ship-related, human, and navigational technology factors. The environmental factors include sea ice thickness, sea ice concentration, channel depth, air temperature, visibility and wind speed. Ship-related factors include ship's anti-ice trapped ability, hull structure's anti-ice ability, propulsion system's anti-ice-loss ability, etc.. The human factors include the restriction of international laws, the legal constraints of coastal countries, the political environment of coastal countries, and the sovereignty dispute of the waterway. Navigation technology factors include route infrastructure, the number and capacity of icebreakers, ship navigation system and ice navigation technology.

In the actual risk evaluation, it is impossible to establish a risk evaluation model including all factors due to the availability of data and the impact of factors on the evaluation results. By taking into account the current situation of Arctic shipping routes and consulting relevant data, the risk factors shown in Fig. 1 are selected in this paper.

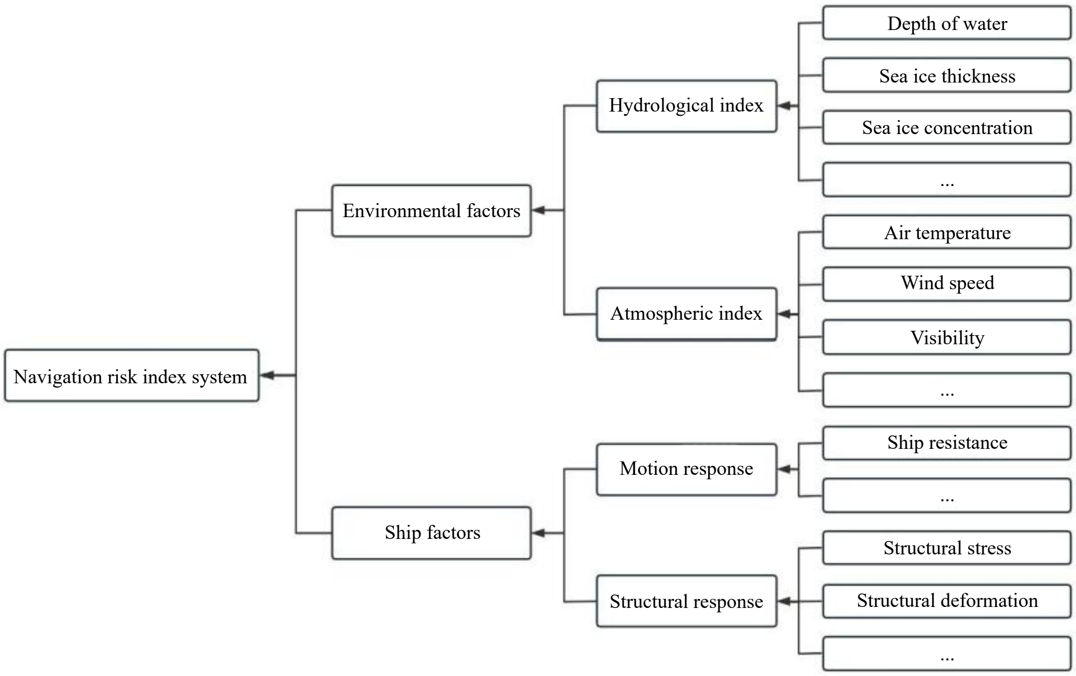


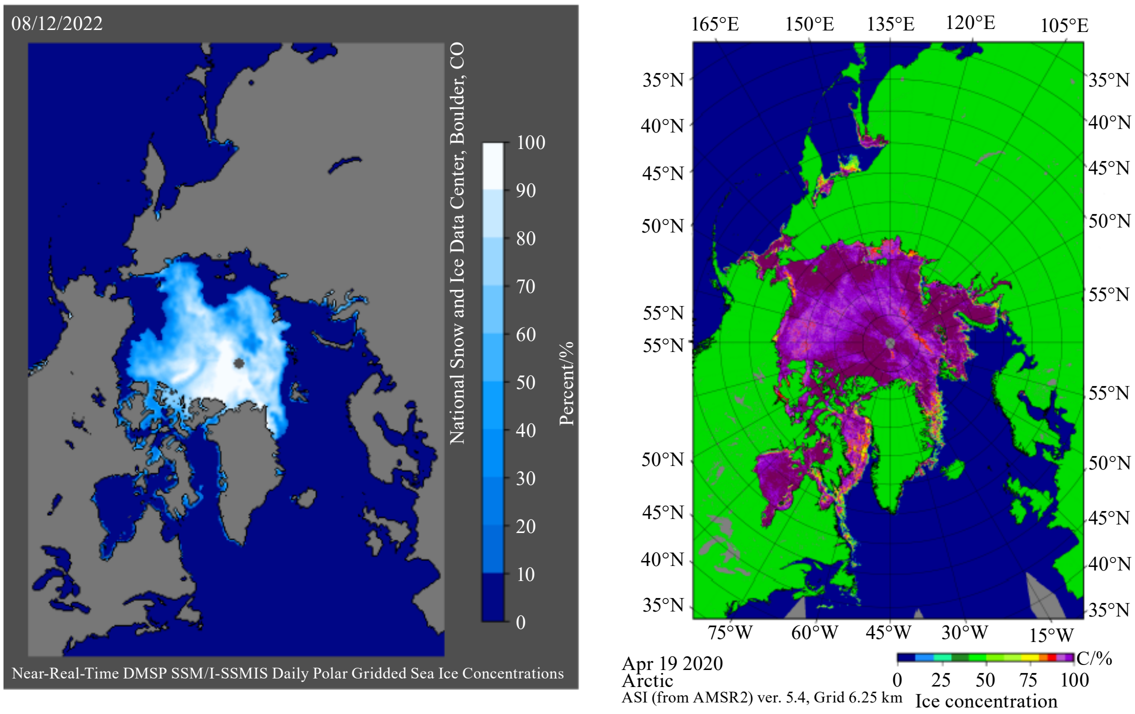
Fig.1 Risk index system

1.2 Environmental factors

The data of environmental factors are mainly obtained from the public data on the websites of various countries. In this paper, only the sea ice thickness, sea ice concentration and atmospheric data sources are introduced.

The main source of sea ice thickness data is SMOS sea ice thickness product, which is obtained based on Huntemann's empirical sea ice thickness inversion model[6]. The model is sensitive to thin ice with a thickness of less than 50 cm during the freezing period, which is in good agreement with the sea ice thickness data measured by air. The University of Bremen website provides daily SMOS sea ice thickness products with a resolution of 12.5 km.

Data on sea ice concentration come from the National Snow and Ice Data Center (NSIDC) and the University of Bremen in Germany, as shown in Fig. 2. SII sea ice concentration data from the NSIDC, retrieved using the NASATeam algorithm from Goddard Space Flight Center, include daily products, monthly average products and annual average products from October 26 th, 1978 to the present. The projection method is polar stereoscopic projection, and the spatial resolution is 25 km × 25 km. AMSR-E/2 Sea Ice concentration data from University of Bremen are obtained by inversion of ARTIST Sea Ice algorithm (ASI).



（a）NSIDC （b）AMSR-2

Fig.2 Arctic sea ice concentration distribution map

Air temperature and other atmospheric data sources are compiled by NCEP/NCAR reanalysis data, produced jointly by National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). NCEP/NCAR reanalysis data use advanced global data assimilation systems and well-established databases. Reanalysis data come from observation data from ground, ships, sounding instruments, balloons, airplanes, and satellites[7]. The sea surface air temperature and wind speed data used in this study are all from the isobaric surface data set. Other data source is the European Centre for Medium-Range Weather Forecasts (ECMWF). Visibility data come from the global weather sites of National Oceanic and Atmospheric Administration (NOAA).

The primary limitations of environmental factor data are as follows:

(1) Difficulty in obtaining meteorological data due to limited open sources and missing information.

(2) The data are mainly historical data with poor immediacy. The polar environment is meteorologically variable and historical data cannot be used for predicting future weather changes.

(3) Challenges in multi-source index data fusion, requiring interpolation to match spatial resolution and lacking time and space accuracy for research needs.

1.3 Ship-related factors

Ship-related factors refer to those that affect the ability to navigate, such as ship motion characteristics, structural response, etc.. There is a low availability of ship-related factors data, particularly for different ship types and hull structures. This paper specifically focuses on the data sources related to a ship's anti-ice trapping ability and hull structure's anti-ice ability.

The ability of a ship to prevent ice trapping is mainly predicted by ship resistance. The calculation of ship resistance can be based on empirical formula, calculation formula of rule and numerical simulation. These empirical formulas are derived from real ship observations and model experiments, and are suitable for predicting ice resistance in flat ice environments. The Lindqvist formula divides ice resistance into three components: squeezing-induced resistance, bending-induced resistance, and immersion-induced resistance. The Riska formula is an enhancement of the Lindqvist formula that disregards the interaction between water and ice. The Jeong formula is an empirical method for estimating the ice resistance of a standard icebreaker model based on the Spencer model and model experiments, with ice resistance comprising breaking resistance, floe ice resistance, and clearing force. The Edwards formula is derived from model and ship test results, re-analyzing and improving previous empirical formulas. The Finnish-Swedish formula originates from the Finnish-Swedish Ice Class Rules and is solely related to ship type and ice class, independent of ship speed. The empirical formulas above are mainly as follows.

Lindqvist formula:

$$R_{\text{ice}} = (R_c + R_b)\left(1 + 1.4\frac{V}{\sqrt{gh_i}}\right) + R_s\left(1 + 9.4\frac{V}{\sqrt{gL}}\right) \tag{1}$$

$$R_c = 0.5\sigma_f h_i^2 \frac{\tan\phi + \mu\cos\phi/\cos\psi}{1 - \mu\sin\phi/\cos\psi} \tag{2}$$

$$R_b = \frac{27}{64}\sigma_f B \frac{h_i^{1.5}}{\sqrt{\dfrac{E}{12(1-v^2)g\rho_w}}} \frac{\tan\psi + \mu\cos\phi}{\cos\psi\sin\alpha}\left(1 + \frac{1}{\cos\psi}\right) \tag{3}$$

$$R_s = (\rho_w - \rho_i)gh_i B\left(T\frac{B+T}{B+2T} + k\right) \tag{4}$$

$$k = \mu\left(0.7L - \frac{T}{\tan\phi} - \frac{B}{4\tan\alpha} + T\cos\phi\cos\psi\sqrt{\frac{1}{\sin\phi^2} + \frac{1}{\tan\alpha^2}}\right) \tag{5}$$

Riska formula:

$$R_{\text{ice}} = C_1 + C_2 V \tag{6}$$

$$C_1 = f_1 \frac{1}{\dfrac{2T}{B} + 1} BL_{par}h_i + (1 + 0.021\phi)(f_2 Bh_i^2 + f_3 L_{\text{bow}} h_i^2 + f_4 BL_{\text{bow}} h_i) \tag{7}$$

$$C_2 = (1 + 0.063\phi)\left(g_1 h_i^{1.5} + g_2 Bh_i\right) + g_3 h_i (1 + 1.2T/B)\frac{B^2}{\sqrt{L}} \tag{8}$$

Jeong formula:

$$R_i = 13.14V^2 + C_B \Delta\rho g h_i BT + C_C F_h^{-\alpha} \rho_i B h_i V^2 + C_{BR} S_N^{-\beta} \rho_i B h_i V^2 \tag{9}$$

$$F_h = \frac{V}{\sqrt{g h_i}} \tag{10}$$

$$S_N = \frac{V}{\sqrt{\dfrac{\sigma_f h_i}{\rho_i B}}} \tag{11}$$

Edwards formula:

$$R = \rho_w B g h_i^2 \left(4.24 + 0.05\frac{\sigma_f}{\rho_w g h_i} + 8.9F_h\right) \tag{12}$$

Empirical formula of Finnish-Swedish ice class rule:

$$R_{CH} = C_1 + C_2 + C_3 C_\mu (H_F + H_M)^2 (B + C_\psi H_F) + C_4 L_{\text{PAR}} H_F^2 + C_5 \left(\frac{LT}{B^2}\right)^3 \frac{A_{wf}}{L} \tag{13}$$

Taking a low ice class multi-purpose ship as an example, the resistance values are calculated using empirical formulas about at each speed for 1 m thick-ice, as shown in Fig. 3. Ship type parameters are as follows:

L is length of the ship between the perpendiculars, $L = 226.8$ m;

B is maximum breadth of the ship, $B = 32.26$ m;

T is actual ice class draughts of the ship, $T = 13.3$ m;

α is the angle of the waterline at B/4, $\alpha = 30.96°$;

Φ_1 is the rake of the stem at the centerline, $\Phi_1 = 90°$;

Φ_2 is the rake of the bow at $B/4$, $\Phi_2 = 90°$.

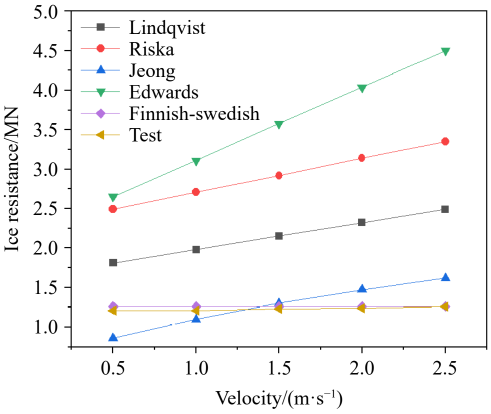


Fig.3 Calculation results of ice resistance with each formula

It is shown in Fig. 3 that the resluts of calculation formula of Finnish-Swedish ice class rule and Jeong are closer to the test value. There are accuracy differences between the empirical formulas at different ice thicknesses and speeds, which is due to the differences in the applicable sea area and calculation parameters of the empirical formulas. None of the existing formulas can independently and accurately predict the ice resistance of various ship types under different ice conditions[8]. Therefore, when using empirical formulas, attention must be fully paid to the application range of each empirical formula to obtain more accurate ice resistance prediction[9]. Based on this, for Norwegian Coast Guard ships, the selection criteria for ice resistance estimation formulas with speed less than 1 m/s or greater than 1 m/s and ice thickness less than 1 m or greater than 1 m are given[10]. The empirical formula of the Finnish-Swedish ice class rule is not related to the specific speed and ice thickness, but only to the ship class, so it cannot predict the ice resistance under different sailing ice conditions. It can be seen that the resistance estimation of each empirical formula or normative formula is suitable for the guidance of ship selection in the early stage of ship design, but there are certain limitations for the ice resistance risk evaluation of designated ships.

For the specified ship type, the finite element calculation can be carried out in ANSYS, ABAQUS and other softwares. The finite element model of the whole ship's outer contour is established.

The methodology defines the hull as a rigid body. The establishment of the ice field is conducted in the form of flat ice or crushed ice. Ship resistance is obtained through nonlinear contact calculations or fluid-structure interaction computations. A coefficient formula, with velocity and ice thickness serving as variables, is fitted to derive the ice resistance equation[11]. The numerical simulation method can be used to predict the ship resistance of different sailing ice conditions under the specified ship type. The ice resistance equation obtained by fitting is more concise, and the ice resistance equation in determining the ice thickness state can be referred to the following form for risk calculation.

$$F = a_1 C V^2 + a_2 V + a_3 \tag{14}$$

where C represents sea ice concentration, V reprensents velocity, and a_1,a_2,a_3 are coefficients.

The formula's data source is the ice resistance calculated by the finite element method based on a specific ship type and fixed ice thickness. However, it has limitations for different ship types and various ice thicknesses. When using different target ships, it is necessary to remodel the calculation and fit the coefficients a_1, a_2, and a_3.

The prediction of a ship structure's anti-ice ability is based on the stress and deformation of the ship structure, which are calculated by local ice load. The local finite element model of hull is established. The general research objects are bow, shoulder, midship and stern structure. The form of local ice load action can be concentrated force or uniform force. In the Finnish-Swedish ice class rule, the design ice pressure is applied in the form of a load plate at the place with the minimum bearing capacity of the structure, and the response of the ship structure is obtained through linear elastic calculation[12]. However, the design ice pressure cannot reflect the situation of different ice thicknesses and velocities. The form of local ice load can also be ice element, which is generally selected cube or half sphere, and the ship structure response is calculated by nonlinear contact collision. In addition, the estimated impact force of floating ice can be calculated by Eq. (15)[13] and the force is acted on the ship structure in the form of concentrated force.

$$F_{\mathrm{f}} = \frac{G_i \cdot V_w}{g \cdot t_z} \tag{15}$$

where F_{f} represents estimated impact force of floating ice on ships in N; G_i represents gravity of floating ice in kN; t_z represents ice impact time in s; V_w represents flow velocity in m/s; and g represents acceleration of gravity in m/s^2.

The main shortcomings of ship-related factors data include:

(1) Limited measured data availability requires significant numerical workload.

(2) Numerical calculations have strong pertinence to specific ship types and hull structures, resulting in low applicability across different ships.

(3) Ship response data obtained from existing empirical formulas or numerical simulations show poor coupling with sea ice thickness, velocity or other parameters.

1.4 Standardized values of evaluation index

Each risk index has different dimension levels and needs to be normalized. Therefore, this study standardizes each index by the method of extreme value standardization to achieve the purpose of eliminating the differences in different dimensions. The determination of standardized values of some evaluation indicators are shown in Tab. 1.

Tab.1 Determination of standardized values of each evaluation index

Evaluation index	Standardized value	Evaluation index	Standardized value
Sea ice thickness	$h^{\sim}=\dfrac{h-h_{\min}}{h_{\max}-h_{\min}}$	Visibility	$S^{\sim}=\begin{cases}1-\dfrac{S}{S_0}, S\leqslant 4000\\ 0, S>4000\end{cases}$
Sea ice concentration	$\rho^{\sim}=\dfrac{\rho-\rho_{\min}}{\rho_{\max}-\rho_{\min}}$	Ship resistance	$R^{\sim}=\dfrac{R-R_{\min}}{R_{\max}-R_{\min}}$
Air temperature	$T^{\sim}=\begin{cases}\left\lvert\dfrac{T-T_{\min}}{0-T_{\min}}\right\rvert, T\leqslant 0\\ 0, T>0\end{cases}$	Structural stress	$\sigma^{\sim}=\dfrac{\sigma-\sigma_{\min}}{\sigma_{\max}-\sigma_{\min}}$

2 Determination of risk index weight

The methods of determining the weight of risk index can be divided into subjective weighting method and objective weighting method. This chapter presents an introduction of the subjective and objective methods and an analysis of the advantages and disadvantages of each method.

2.1 Subjective weighting method

Subjective weighting methods cover analytic hierarchy process, Delphi method, grey relational degree method and so on. The subjective weight obtained by the subjective weighting method is also called artificial weight, which is obtained by the decision analyst according to the subjective importance of each indicator.

(1) Analytic hierarchy process (AHP): This method draws on expert knowledge to determine the weight of indicators. Expert opinions on the relative importance of each factor are gathered. Assuming that there are *n* risk factors in the indicator layer, $a(ij)$ is the relative importance of the i^{th} factor to the j^{th} factor, and the judgment matrix is given by Saaty's 1–9 scale method. Saaty's 1–9 scale method is shown in Tab. 2. The weights of each index are obtained by calculating the eigenvalues and the normalized feature vectors of the judgment matrix.

Tab.2 Saaty's 1-9 scale method

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between two adjacent judgments

Advantages of AHP: The complex problems are divided into different levels according to their importance, with a clear structure and high credibility.

Disadvantages of AHP: The construction of judgment matrix is influenced by subjective experience. When there are too many indicators, the data statistics are large and the weights are difficult to determine.

(2) Delphi method: The investigators draw up a questionnaire and consult the members of the expert group by correspondence, in accordance with established procedures. Members of the expert group exchange views anonymously. After many consultations and feedbacks, the opinions of the expert group gradually become converged. Finally, the collective judgment results with high accuracy are obtained.

Advantages of the Delphi method: Experts can modify or revise their opinions by eliciting feedback from the questionnaire, thus avoiding some shortcomings in group decision-making.

Disadvantages of the Delphi method: The process is complex and time-consuming. The anonymity of experts results in a lack of consistency in the evaluation criteria.

(3) Grey relational degree method: The value of multiple expert judgments is quantitatively compared with the maximum value of a certain expert judgment. Through the analysis of the magnitude of the differences between each other, the relational degree between the values is determined. The higher the relational degree is, the more important the index is in the whole index system.

The distance between each index column $X_1, \ldots, X_n$ and the reference data column X_0 is:

$$D_{0i} = \sum_{k=1}^{m} (x_0(k) - x_i(k))^2 \tag{16}$$

The weight of each index is:

$$w_i = \frac{1}{D_{0i}} \tag{17}$$

Advantages of the grey relational degree method: There is no requirement for sample size, and this method requires less computational cost. The results are in good agreement with those of qualitative analysis.

Disadvantages of the grey relational degree method: Data indicators and methodologies are subjective, leading to poor accuracy in quantitative analysis results.

2.2 Objective weighting method

The objective weighting method comprises the entropy weight method and variation coefficient method, also known as natural weight. The decision matrix is formed using actual index information, and the weight is determined through objective operations based on this matrix.

Entropy weight method: The entropy value can be used to judge the degree of discreteness of the indicator. A smaller information entropy value indicates greater discreteness of the index, signifying a larger impact on comprehensive evaluation and thus a higher weight. If an indicator has equal values, it will not contribute to composite evaluation.

Advantages of the entropy weight method: The influence of subjectivity on the decision result is reduced. The calculation is simple, intuitive and easy to implement.

Disadvantages of the entropy weight method: This method is prone to weight distortion. The dependence on the sample is large. A large amount of actual data is needed as a basis.

2.3 Combination method

In Arctic navigation risk evaluation studies where accurate environmental data is lacking, subjective weighting methods are commonly used or combined with objective methods to determine final weights.

If $\omega_{\mathrm{s}i}$ and $\omega_{\mathrm{o}i}$ are subjective weight and objective weight of index X_i, respectively, and ω_i is combined weight, then

$$\sum_{i=1}^{m} \omega_{\mathrm{o}i} = \sum_{i=1}^{m} \omega_{\mathrm{s}i} = \sum_{i=1}^{m} \omega_i = 1 \tag{18}$$

The linear weighted combination method is used to determine the weight of the evaluation index:

$$\omega_i = \mu \times \omega_{si} + (1 - \mu) \times \omega_{\mathrm{o}i} \tag{19}$$

The key to the linear weighted combination method is to determine the preference coefficients (μ) of subjective and objective weights. Considering the current lack of information on Arctic navigation routes, it is believed that subjective weight is more important. The preference coefficient is set as $\mu = 0.8$.

3 Establishment of risk evaluation model

Based on the risk index system and the weight of risk index, the risk evaluation model is established.

Risk evaluation methods include risk assessment index method, fuzzy comprehensive evaluation method, TOPSIS method, Bayesian network method and so on. This paper only introduces risk assessment index method and fuzzy comprehensive evaluation method.

Risk assessment index method: This is a method to determine the degree of risk reasonably by standardizing and weighting the value of a series of indicators. Risk assessment index method maximizes the weight and contribution of various indicators. The synthesis of each index adopts the weighted comprehensive evaluation method, and the formula is as follows:

$$R=\sum_{h=1}^{n} Q_h \times Z_h \tag{20}$$

where R is calculated value of risk, Z_h represents standardized value of the h-th indicator, Q_h represents weight of the h-th indicator, and n means number of indicators.

The risk index is calculated as the sum of the standardized values of each indicator multiplied by their respective weights. The average daily or monthly navigation risk index for key straits is determined using the standardized values derived from daily environmental and ship-related data in Chapter 1, along with the indicator weights in Chapter 2. A higher risk index indicates a greater level of risk, making it a standard measure for risk evaluation. This method is straightforward and yields highly precise results; however, it requires comprehensive channel data to be effectively utilized.

Fuzzy comprehensive evaluation method: This method makes a comprehensive evaluation by applying the principle of fuzzy transformation. It is suitable for the situation that the polar channel information is not comprehensive. The influencing factors of navigation safety are fuzzy.

The specific steps are:

(1) Establish a set of risk assessment factors, say $\boldsymbol{U}$, $\boldsymbol{U}$ = {sea ice thickness, sea ice concentration, visibility, temperature};

(2) Create a comment set, say $\boldsymbol{V}$, $\boldsymbol{V}$ = {very good, good, fair, poor, very poor};

(3) Determine the set of evaluation weights, say $\boldsymbol{A}$, $\boldsymbol{A}=\{a_1, a_2, \ldots, a_{\mathrm{n}}\}$;

(4) The membership degree of a single index to the safety of polar waterway is obtained by expert scoring method, $r_{\mathrm{i}}=\{r_{\mathrm{i}1}, r_{\mathrm{i}2}, \ldots, r_{\mathrm{im}}\}$;

(5) Construct the comprehensive evaluation matrix, say $\boldsymbol{R}$, $\boldsymbol{R}=\left\{\begin{matrix} r_{11} & r_{12} & \cdots & r_{1\mathrm{m}} \\ r_{21} & r_{22} & \cdots & r_{2\mathrm{m}} \\ & \cdots & & \\ & \cdots & & \\ r_{\mathrm{n}1} & r_{\mathrm{n}2} & \cdots & r_{\mathrm{nm}} \end{matrix}\right\}$;

(6) Calculate $\boldsymbol{B}$ according to the mathematical model $\boldsymbol{B}=\boldsymbol{A}\times\boldsymbol{R}$ and make a comprehensive evaluation based on the principle of maximum membership.

The fuzzy comprehensive evaluation method can assess the navigation risk of polar passages, producing a vector rather than a single point value as its result. This approach provides rich information that accurately portrays the object being evaluated and can be further processed to obtain reference information. Nevertheless, evaluations obtained through this method tend to be overly vague and general, lacking objectivity and spatiotemporal accuracy. As such, it proves challenging to assess the risk at specific dates within a strait location or discern patterns in how risks change over time. Consequently, the fuzzy comprehensive evaluation method is not suitable for window period assessment. It becomes evident that not all risk evaluation models are appropriate for window assessment purposes.

4 Prediction algorithm of window period based on risk evaluation

The prediction algorithm of navigation window period introduced in this paper is based on quantization risk value and evaluation threshold. The window-period prediction of a channel is obtained by the variation of the risk value of a single channel with the date, and the window-period prediction of the whole route is obtained by the variation of the risk values of several straits with the date. According to the number of evaluation indexes, the window period prediction algorithm can be divided into single index prediction and multi-index prediction.

4.1 Single index prediction

The first is the single index prediction, and the index with higher importance in Chapter 1 is selected according to the navigation environment. For example, considering sea ice concentration as an important index, predictions are made regarding its impact on the window period. Assuming a threshold of 40% sea ice concentration for safe navigation, a forecast for a single channel's window period can be derived from data sets showing variations in sea ice concentration over time (as shown in Fig. 4). For the entire route, if sections covering more than 90% have less than 40% sea ice concentration and remaining sections have less than 50%, it is considered safe for an ice-class ship to sail through. From this, the navigation window of the ice-class ship sailing in the Northeast Passage is extracted. In the case of the Sanikov Strait, the navigation window is from July 2nd to October 18th at the 40% threshold of sea ice concentration.

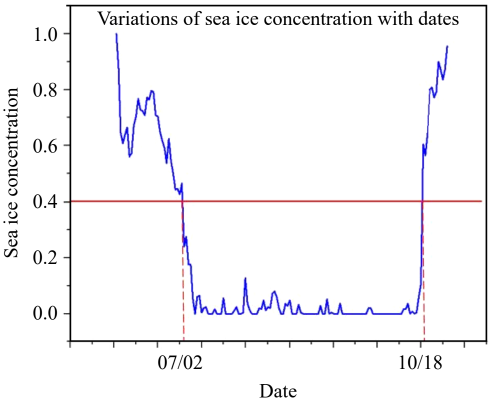
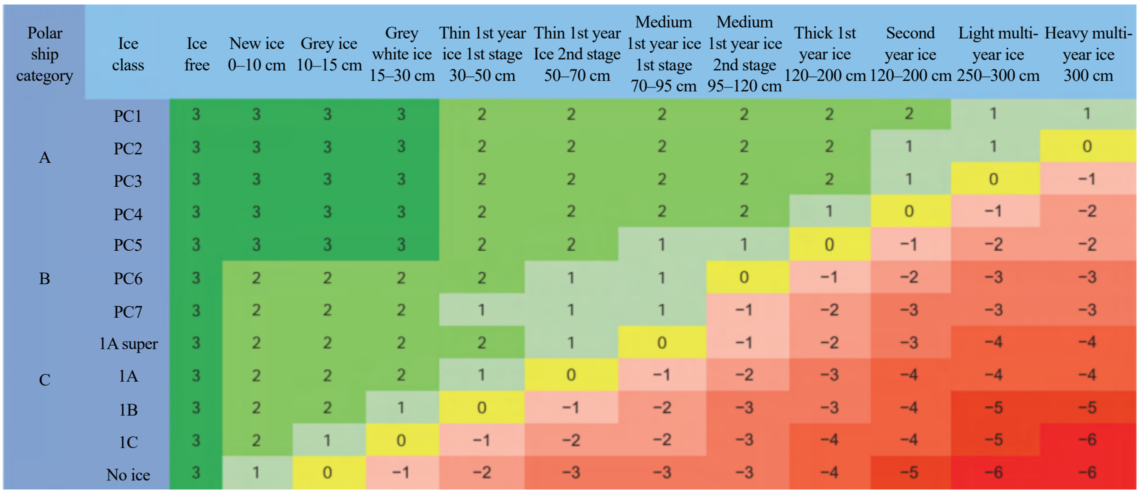


Fig.4 Sea ice density varying with dates in the Sannikov Strait

In addition to the indicators mentioned in Chapter 1, the *RIO* risk index can also be used as an indicator for window prediction[4]. The *RIO* Risk Index is calculated using the Polar Operational Limit Assessment Risk Indexing System (POLARIS) proposed by the International Maritime Organization (IMO)[14]. The risk index result is obtained by calculating the sum of *RIV*s corresponding to each ice type in the navigable waters multiplied by its concentration (*C*). The value of *RIV*s is shown in Fig. 5.



Polar ship category	Ice class	Ice free	New ice 0–10 cm	Grey ice 10–15 cm	Grey white ice 15–30 cm	Thin 1st year ice 1st stage 30–50 cm	Thin 1st year Ice 2nd stage 50–70 cm	Medium 1st year ice 1st stage 70–95 cm	Medium 1st year ice 2nd stage 95–120 cm	Thick 1st year ice 120–200 cm	Second year ice 120–200 cm	Light multi-year ice 250–300 cm	Heavy multi-year ice 300 cm
A	PC1	3	3	3	3	2	2	2	2	2	2	1	1
	PC2	3	3	3	3	2	2	2	2	2	1	1	0
	PC3	3	3	3	3	2	2	2	2	2	1	0	−1
	PC4	3	3	3	3	2	2	2	2	1	0	−1	−2
	PC5	3	3	3	3	2	2	1	1	0	−1	−2	−2
B	PC6	3	2	2	2	2	1	1	0	−1	−2	−3	−3
	PC7	3	2	2	2	1	1	1	−1	−2	−3	−3	−3
C	1A super	3	2	2	2	2	1	0	−1	−2	−3	−4	−4
	1A	3	2	2	2	1	0	−1	−2	−3	−4	−4	−4
	1B	3	2	2	1	0	−1	−2	−3	−3	−4	−5	−5
	1C	3	2	1	0	−1	−2	−2	−3	−4	−4	−5	−6
	No ice	3	1	0	−1	−2	−3	−3	−3	−4	−5	−6	−6

Fig.5 Values of *RIV*s for each ice type

$$RIO = (C_1 \times RIV_1) + (C_2 \times RIV_2) + \cdots (C_n \times RIV_n) \tag{21}$$

Referring to the *RIO* Criteria as shown in Tab. 3, when the *RIO* corresponding to a ship sailing in a single strait is greater than 0, the ship can operate normally in the strait. This indicates that the strait is navigable. For the entire route, if 90% or more sections of the route have an *RIO* greater than 0 and the remaining sections can safely perform high-risk operations or short-range icebreaking, then it is considered safe for an ice-class ship to navigate on this route. From this analysis, we can extract the navigation window for ice-class ships sailing in the Northeast Passage.

Tab.3 *RIO* criteria

<table>
<tr><th><i>RIO</i></th><th>PC1–PC7</th><th>Ice class other than polar class or no ice class</th></tr>
<tr><td><i>RIO</i>≥0</td><td colspan="2">Normal operation</td></tr>
<tr><td>−10≤<i>RIO</i><0</td><td>Elevated operational risk - operate only if measures in PWOM allow it and are followed</td><td>No entry</td></tr>
<tr><td><i>RIO</i><−10</td><td colspan="2">No entry</td></tr>
</table>

The method of predicting the window period based on the sea ice concentration index is simple. This leads to incomplete predictions. This is suitable for the early estimation of the window period. Using *RIO* risk index to forecast the window period yields relatively high precision but lacks intuitiveness. The window period cannot be correlated with data on ice conditions, sea conditions, and ship conditions, making it difficult to adjust in time.

4.2 Multi-index prediction

Accurate and timely prediction of polar navigation windows requires consideration of different attributes and characteristics specific to polar navigation. In a complex system such as this, a comprehensive evaluation based on most impact indicators is necessary for making correct decisions. Therefore, a multi-index prediction algorithm is needed for accurate prediction of window periods.

The specific method is to select environmental indicators and ship indicators as risk assessment indicators, and to build a comprehensive risk assessment system that integrates real-time ice conditions, sea conditions and ship conditions in Northeast Passage. The comprehensive risk assessment system is shown in Fig. 6. The methods of establishing the index system, determining the weight of the index, and establishing

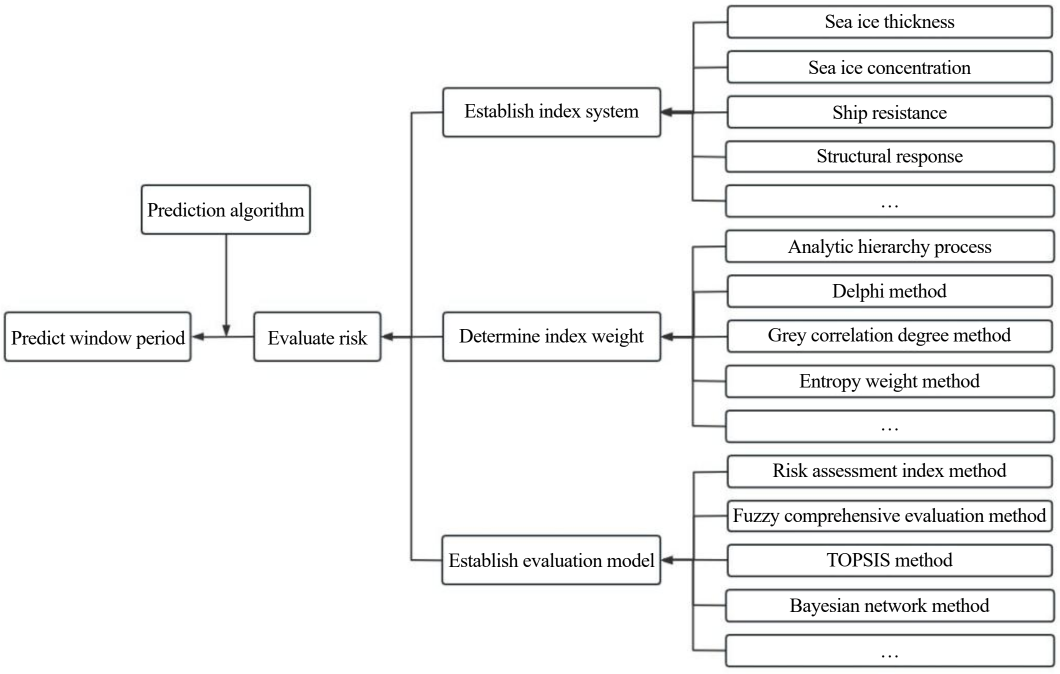


Fig.6 Comprehensive risk assessment system

the evaluation model have been introduced earlier. The risk index is calculated through the risk evaluation system. Combined with the characteristics of the index and the minimum standard of the navigable environment of the ship, the relationship between the standard of the passage of the ship through the strait and the risk index is determined, as shown in Tab. 4. The risk is divided into several levels with the corresponding evaluation value ranges and characteristic parameters for each level, and the determination method primarily relies on expert evaluation[15]. When a single strait's corresponding risk index falls within Class C range, it indicates that passage through that strait is feasible without difficulty; in other words, it is navigable. For an entire route, when 90% or more sections have a risk index falling within Class C while remaining sections fall within Class B, it is considered that the ice-class ships can safely operate on the route. The navigation window of the ice-class ships sailing in the northeast channel is extracted by this method.

The daily navigational risk value is calculated using the method described above. The change curve of the risk value with dates is shown in Fig. 7. In the case of the Vilkitskogo Strait, the navigation window is from July 21st to September 25th at the Risk Class C.

Tab.4 Relationship between the standard of the passage and the risk index

Risk class	Range of risk value	Level of passage
A	$R>0.4$	Not passable
B	$0.2<R<0.4$	Pass with difficulty
C	$R<0.2$	Pass without difficulty

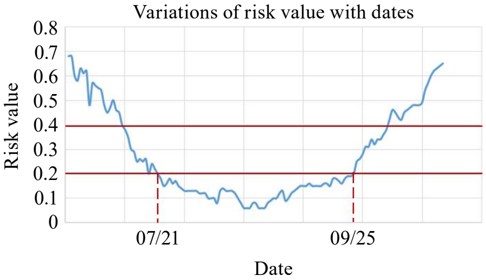


Fig.7 Variations of risk value with dates in the Vilkitskogo Strait

5 Conclusions

The prediction of navigation window period is one of the key issues affecting the safe navigation of the polar Northeast Passage. Three parts of risk evaluation and the prediction algorithm of window period are sorted in this paper, and the following conclusions are reached:

(1) With environmental factors and ship factors taken as risk indicators, the data sources of sea ice thickness, sea ice concentration, atmosphere, ship's anti-ice trapped ability and hull structure's anti-ice ability are analyzed. The main defects of natural factor data are difficulty in obtaining, poor immediacy, and low temporal and spatial accuracy. The main defects of ship factor data are large workload of numerical calculation, low applicability of ship type and poor parameter coupling. The standardized values of each risk index are given.

(2) This paper provides a detailed introduction to both subjective weighting method and objective weighting method. The subjective weighting method offers the advantage of minimal dependence on risk data but is influenced heavily by subjective experience. On the other hand, objective weighting is less dependent on subjectivity but relies more on available risk data. Considering the current situation of Arctic shipping route data, this paper proposes a combined approach that integrates both subjective and objective weighting methods to determine the weights of risk indicators.

(3) In this paper, a comprehensive overview of the risk assessment index method and fuzzy comprehensive evaluation method is presented. The risk assessment index method is characterized by its

simplicity and ease of use while yielding highly precise results suitable for window period prediction purposes. Conversely, the fuzzy comprehensive evaluation method lacks objectivity and has lower spatio-temporal accuracy, making it unsuitable for window period prediction.

(4) This paper introduces the navigation window period prediction algorithms including single index prediction and multi-index prediction approaches. The index of sea ice concentration is used to predict the window period, which is suitable for the estimation of the early window period. The *RIO* risk index is used to predict the window period, the accuracy is relatively high, but the real-time adjustment of the data is poor. Based on the integrated risk assessment system of real-time ice conditions, sea conditions and ship conditions of the Northeast Passage, this paper proposes a multi-index prediction algorithm for the window period, and finally determines the window period of the whole route according to the relationship between the ship's passage through the strait and the risk index.

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基于风险评估的极地航行窗口期预测方法

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摘要：随着国际贸易活动的增加和极地冰盖的逐渐融化，北极航道对于海运的重要性随之凸显，而极地航行窗口期的预测是北极航道能否通航的关键，对航道的选择和航行的优化有着重要意义。本文从建立风险指标体系、确定风险指标权重、建立风险评价模型、窗口期预测算法四个方面进行介绍，介绍指标数据来源并分析自然因素和船舶因素数据获取的缺陷，介绍窗口期预报涉及的各种方法并分析其优势和缺点。应用风险量化评价以及窗口期算法可以为极地航行窗口期预测的研究提供参考。

关键词：窗口期；风险评估；极地航行；风险指数

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