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POLARIS-based Assessment of Operational Limitation in the Arctic Ocean for R/V Mirai II

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ABSTRACT

The Mirai II, currently under construction by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), is an icebreaker with an ice-class of the Polar Class 4 (PC4) designed to navigate the Arctic Ocean. For observation planning, the navigable range of the vessel must be predicted in advance based on its operational limitation and the operating conditions of its equipment in ice-covered water areas. Since the Arctic Ocean environment is continuously changing, we examined the operational limitation of Mirai II in the Arctic Ocean using sea ice and metocean data of recent years. The monthly changes in the capable areas were determined by POLARIS, a methodology for assessing operational limitation according to ice conditions proposed in the Polar Code established by the International Maritime Organization (IMO). As a result, Mirai II can navigate a wide area of the Arctic Ocean throughout the year, and it is expected to significantly expand the range of oceanographic surveys compared to conventional Japanese vessels. In addition, it was found that the classification of multi-year ice is essential for accurate estimation of navigation risks and that parameters such as ice age and ice thickness have a considerable impact on it.

KEY WORDS: R/V Mirai II; Operational Limitation; POLARIS; neXtSIM.

INTRODUCTION

The Arctic research vessel "Mirai II" currently under construction by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), is the first Japanese research vessel with icebreaking capabilities and is compliant with the Polar Class 4 (PC4) standard. Figure 1 shows the planned general arrangement, and Table 1 shows the planned general particulars of "Mirai II." Its design concept, onboard observation equipment, and onboard facilities such as laboratories are specialized for research activities and enable high-level Arctic surveys that were previously difficult to achieve with Japanese vessels.

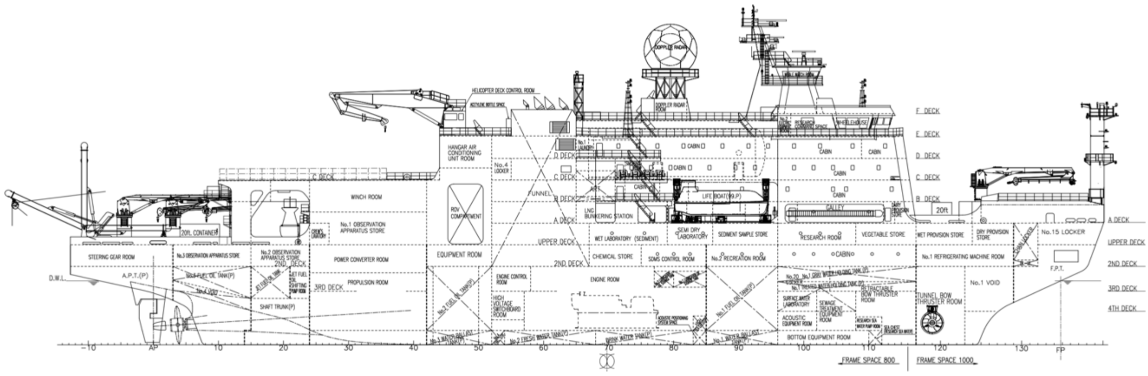


Figure 1. Planned general arrangement of “Mirai II”

Table 1. Planned general particulars of “Mirai II”

Item	Value
L_{OA} x B x D	128 x 23 x 12.5 m
Draft	8 m
Gross Tonnage	13,000 tons
Ice-breaking Capability	3.0 m thick level ice @ 3.0 knots
Ice Class	Polar Class 4 (PC4)
Propulsion Power	Approx. 5,600kW x 3 (Diesel) Approx. 2,600 kW x 1 (Dual fuel)
Accommodation	97 (34 crew, 63 scientists/engineers)

When the vessel is utilized as a research platform in the future, information regarding its navigation capabilities is fundamental to the research cruise's feasibility and planning. In this paper, we analyze the areas the vessel can navigate. This analysis utilizes a numerical analysis dataset for the Arctic ice and the navigability evaluation indexing system.

This study conducted a navigability analysis using the Polar Operational Limit Assessment Risk Indexing System, POLARIS, proposed by the International Maritime Organization, IMO, as a supplement to the Polar Code adopted in 2014 (IMO, 2015; IMO, 2016). POLARIS is a similar system to the Arctic Ice Regime Shipping System (Timco et al., 2005; Transport Canada, 2018) developed for Canadian water areas to determine the navigability corresponding to the ice condition. The Ice Regime System is designed for practical use, but it is already being used in many studies examining the navigability of actual ship routes.

METHODOLOGY AND DATA

Navigability Analysis

The POLARIS defines a coefficient matrix determined by the ice conditions and the vessel’s ice classes. Calculating an index value for the given ice conditions and the coefficients indicates whether or not navigation is possible. This system determines the Risk Index Outcome (*RIO*) by calculating an ice navigation risk index. The *RIO* is defined as a weighted sum of the concentration of each ice type, employing the following formula:

$$RIO = (C_1 \cdot RIV_1) + (C_2 \cdot RIV_2) + \cdots + (C_n \cdot RIV_n) \quad (1)$$

where C denotes the partial concentration (0-10) of a specific type of ice, with the subscript indicating the type of ice, the term *RIV*, or Risk Index Values, denotes a weighting system based on risk and is defined in a coefficient matrix. As shown in Table 1 (e.g., Zhang et al., 2017), the *RIV* is determined by the combination of ice type and vessel's ice class. In a calculation result, a positive *RIO* indicates that navigation is possible, while a negative *RIO* indicates that navigation is not possible.

Table 1. POLARIS's Risk Index Values. (Zhang et al., 2017)

Category	Ice class	Ice Free	New Ice	Grey Ice	Grey White Ice	Thin First-Year Ice 1st Stage	Thin First-Year Ice 2nd Stage	Medium First Year Ice	Medium First Year Ice 2nd	Thick First Year Ice	Second Year Ice	Light Multi-Year Ice	Heavy Multi-Year Ice
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	2	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	0	-1	-2	-3	-3	-3
C	IA Super	3	2	2	2	2	1	0	-1	-2	-3	-4	-4
	IA	3	2	2	2	1	0	-1	-2	-3	-4	-4	-4
	IB	3	2	2	1	0	-1	-2	-3	-3	-4	-5	-5
	IC	3	2	1	0	-1	-2	-2	-3	-4	-4	-5	-6
	Not ice strengthened	3	1	0	-1	-2	-2	-3	-3	-4	-5	-6	-6

Sea Ice Data

The POLARIS calculation requires information on the ice type and the partial concentration of each ice type. In this study, the ice data was derived from the Arctic Ocean Sea Ice Analysis and Forecast provided by the Copernicus Marine Service (Copernicus Marine Service, *online*, 2024). The ice parameters are the global analysis values for a 3 km square grid using the neXtSIM model (Williams et al., 2021), which includes the following variables:

- Sea ice concentration (*siconc*),
- Sea ice thickness (*sithick*),
- Surface snow thickness (*sisnthick*),
- Sea ice x velocity (*vxsi*),
- Sea ice y velocity (*vysi*),
- Sea ice albedo (*sialb*),
- Sea ice age (*siage*),
- Sea ice area fraction of multi-year ice (*siconc_my*),
- Sea ice area fraction of young ice (*siconc_young*),
- Sea ice volume fraction of ridged ice (*si_ridge_ratio*).

To map the neXtSIM variables to the POLARIS ice classes shown in Table 1, we use the definitions of ice types in the World Meteorological Organization (WMO) Sea Ice Nomenclature (WMO, 2014). Table 2 shows the assumed interpretation from the WMO classification to the POLARIS variables. To calculate the *RIO* for PC4, it is sufficient to divide the ice types into six categories. In addition, from the *RIV* setting for PC4, only multi-year ice reduces navigability, and it is essential to distinguish between them. Thus, the following three algorithms were investigated to observe the sensitivity of the parameters such as *siage*, *sithick* and *RIV*. Details can be found in the Appendix.

Algorithm I: Second-year ice is distinguished using *siage*, and light multi-year ice and heavy multi-year ice are distinguished using *sithick*.
Algorithm II: Only *sithick* is used to distinguish multi-year ice.
Algorithm III: The *RIV* of second-year ice is lowered by one level.

Table 2. WMO Sea Ice Nomenclature and POLARIS variables.

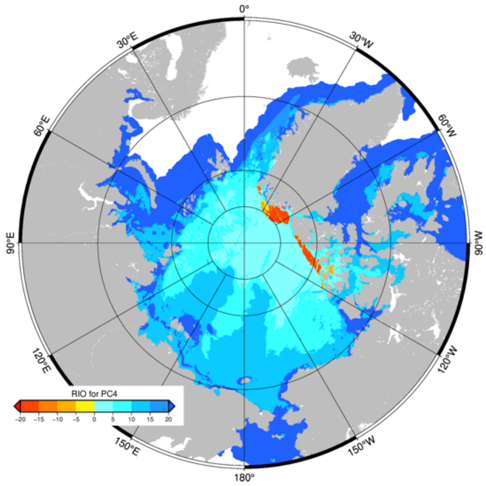
WMO Stage of Development		**Thickness**	**POLARIS Stage of Development**	***RIV* for PC4**
No ice	-		Ice free	3
New ice	Nilas; ice rind	< 10 cm	New ice	
Young ice	Gray ice	10-15 cm	Gray ice	
	Gray-white ice	15-30 cm	Gray-white ice	
Thin first-year ice	1st stage	30-50 cm	Thin first-year ice, 1st stage	2
	2nd stage	50-70 cm	Thin first-year ice, 2nd stage	
Medium first-year ice	1st stage	70-120 cm	Medium first-year ice, 1st stage	
	2nd stage		Medium first-year ice, 2nd stage	
Thick first-year ice		> 120 cm	Thick first-year ice	1
Old ice	Second-year ice		Second-year ice	0
	Multi-year ice		Light multi-year ice	-1
			Heavy multi-year ice	-2

ANALYSIS OF NAVIGABLE AREA IN THE ARCTIC

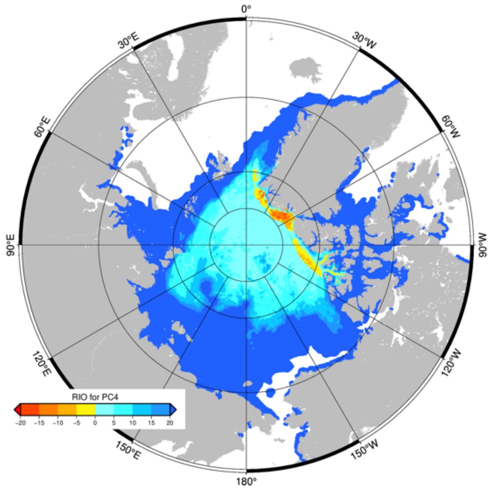
The analysis period is from 2020 to 2024. Figure 2 shows the results of calculating *RIO* for the ice class PC4 vessels for each of the three algorithms based on the neXtSIM monthly mean dataset in 2023 provided by the Copernicus Marine Service. Blue areas indicate positive *RIO*, which means that the area is considered navigable according to the POLARIS assessment, while yellow to red areas indicate negative *RIO*, which means that the area is considered difficult to navigate. May is the month with the most significant sea ice area in the Arctic Ocean, and October is the month with the smallest.

The different algorithms lead to very different judgments about the navigable areas. Navigating north of Greenland and the Canadian Arctic Archipelago is difficult, consistent with empirical knowledge. Algorithms I and II judge that navigating near the North Pole is possible if the timing is right, and it is even possible to sail the trans-Arctic route between Asia and Europe. On the other hand, Algorithm III is notably different from the other two in that even when the sea ice area in the Arctic Ocean is small, there are still broad and difficult areas in the high-latitude water area north of 80N.

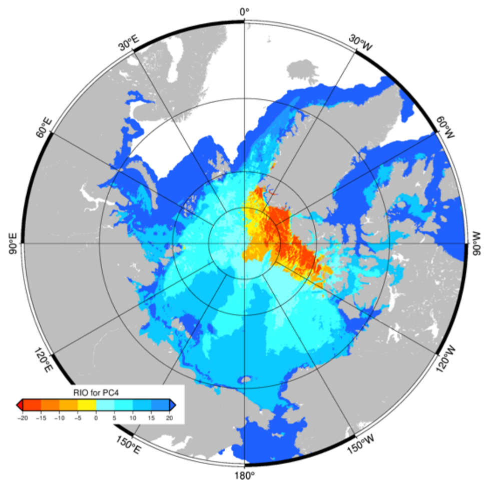
Figure 3 also shows the distribution of *siage* and *sithick* in May 2023, according to the neXtSIM.



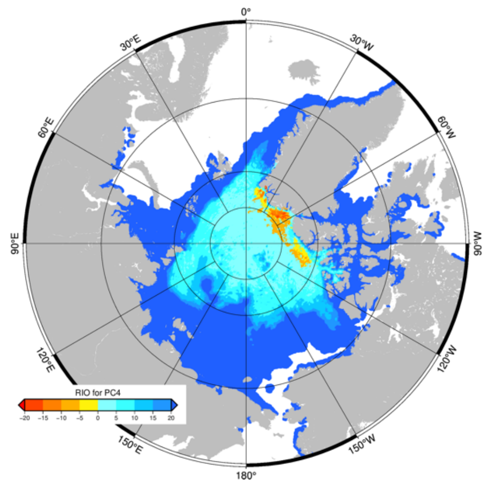
(a) Algorithm I: May 2023



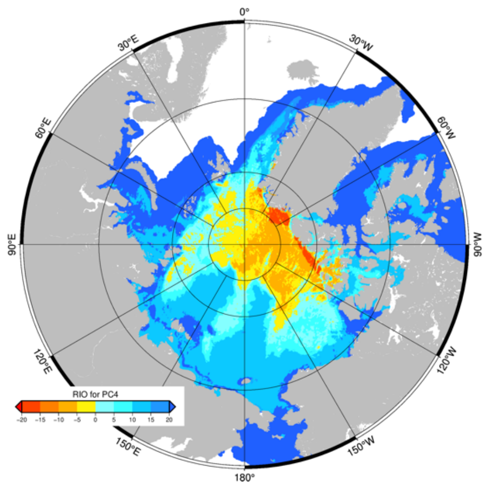
(b) Algorithm I: October 2023



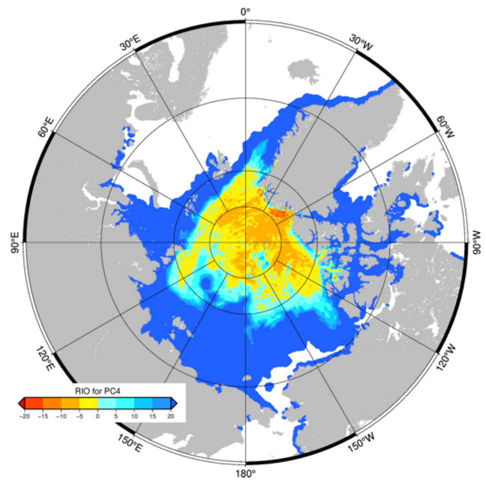
(c) Algorithm II: May 2023



(d) Algorithm II October 2023

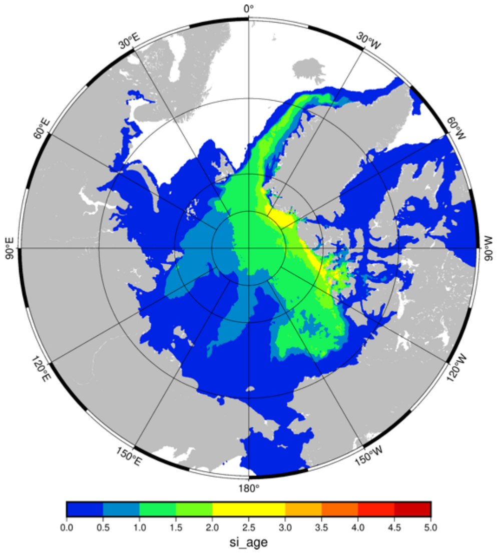


(e) Algorithm III: May 2023

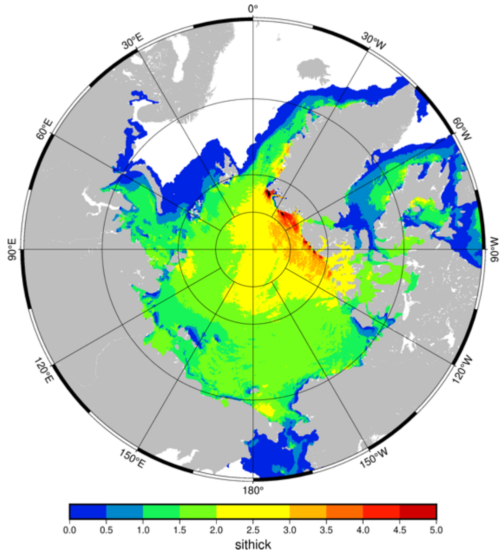


(f) Algorithm III: October 2023

Figure 2. POLARIS Risk Index Outcome calculated for PC4 ice class using neXtSIM monthly dataset in 2023.



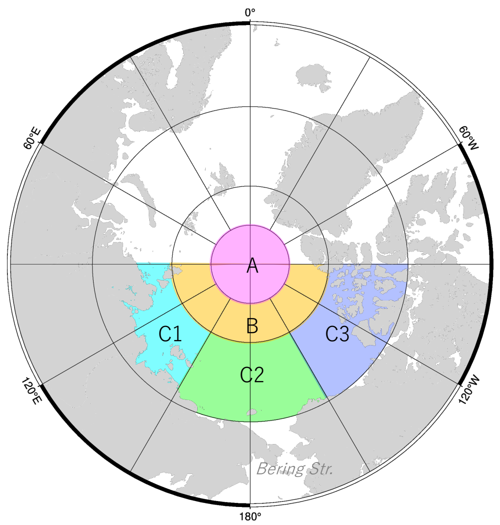
(a) Sea ice age (years) : May 2023



(b) Sea ice thickness (m) : May 2023

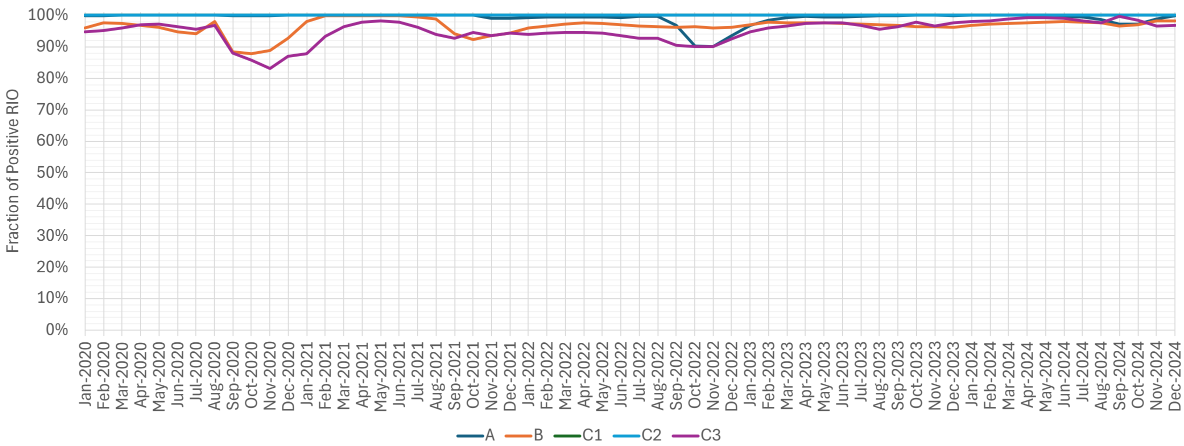
Figure 3. Distributions of neXtSIM ice parameters "sea ice age (years)" and "sea ice thickness (m)" in May 2023.

The area where Mirai II is active in the Arctic Ocean is assumed, as shown in Figure 4. Since Mirai II is considered to access the Arctic Ocean through the Bering Strait, the area was set mainly around 180E. Area A is around the North Pole, Area B is the high-latitude zone, and Area C is the low-latitude zone. Area C was divided into three sections from east to west. Here, the distribution of *RIO* was calculated for each month from 2020 to 2024, and the percentage of navigable area for the analysis area was calculated. Figure 5 shows the time variation of *RIO* for each area of interest.

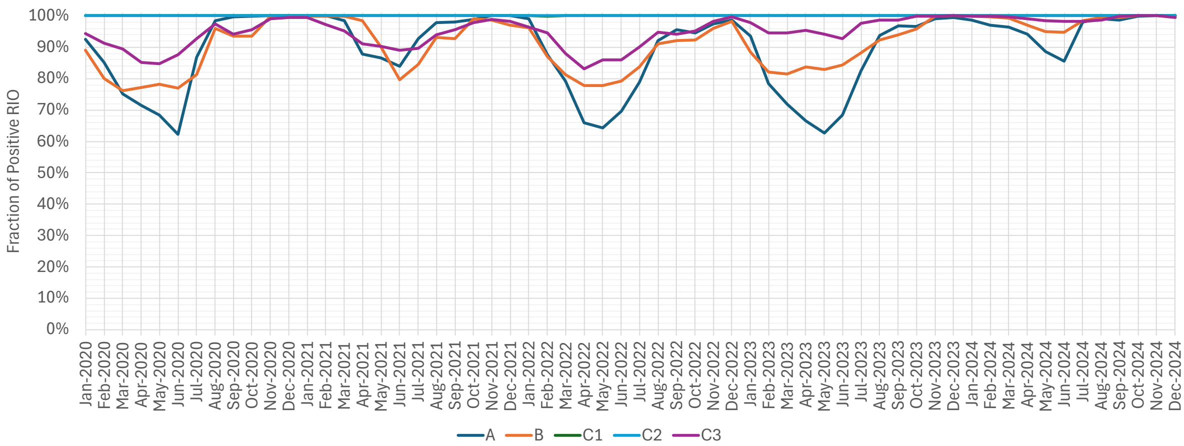


	Area	Latitude	Longitude
A	North Pole Area	85N < Lat	360°
B	High Latitude	80N < Lat ≤ 85N	90E ≤ Lon < 270E
C1	Low Latitude, East	70N < Lat ≤ 80N	90E ≤ Lon < 150E
C2	Low Latitude, Mid	70N < Lat ≤ 80N	150E ≤ Lon < 210E
C3	Low Latitude, West	70N < Lat ≤ 80N	210E ≤ Lon < 270E

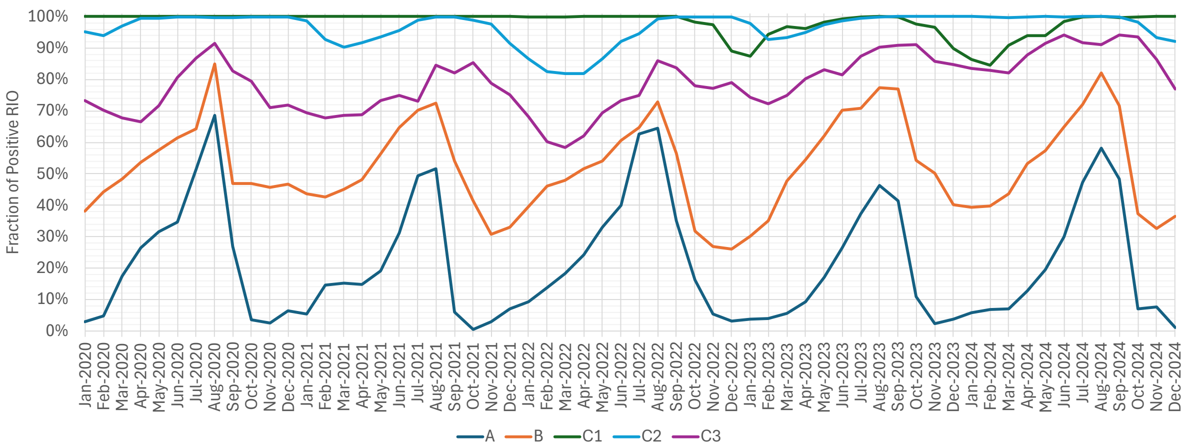
Figure 4. Definition of analysis areas for "Mirai II" navigability in the Arctic Ocean.



(a) Algorithm I



(b) Algorithm II



(c) Algorithm III

Figure 5. Time variation of positive POLARIS Risk Index Outcome fraction in assumed "Mirai II" cruise areas in the Arctic Ocean.

DISCUSSION

Trends by area

According to the neXtSIM, as seen in Figure 3 (a), multi-year ice is widely distributed, particularly in high-latitude waters. It is prominent in areas A, C3, and the Canadian side of B. Greenland and the northern Canadian archipelago always have large ice thicknesses, as described in Figure 3 (b). These areas are difficult for ships to enter. However, it is not necessarily the case that high latitudes are difficult, and negative *RIO* rarely covers the European side. Therefore, there are differences in trends between C1, C2, and C3, with C1 being the most calm and C3 being the most severe. If we focus on C3, even in the most severe case of Algorithm III, approximately 60% of the sea area is navigable. As there is a wide variety of sea ice in this water area, C3 can provide a good opportunity for ice observation.

Differences between algorithms

Algorithm I makes the most extensive use of the variables in the neXtSIM. However, even though multi-year ice exceeding 2m is widely distributed, the area where *RIO* is negative is minimal, and the severity seems underestimated. It is because the sea ice age is almost two years or less in such water areas, and *RIV* is 0 for second-year ice for PC4.

Algorithm II does not use ice age in the neXtSIM to determine the contents of multi-year ice but uses only ice thickness. The area where *RIO* is negative is slightly expanded, and the water areas where the ice conditions are severe are reasonably judged to be unsuitable for navigation. On the other hand, Algorithm III adjusts *RIV* to estimate the navigability of second-year ice as low. Still, this method is strongly affected by sea ice age greater than 1, and it is judged that navigating even in a wide area on the Russian side of the North Pole is impossible.

Benefits of Mirai II Operation

When comparing the sea ice age or sea ice thickness derived from the neXtSIM and the ice capability of Mirai II, the judgment of Algorithm III is convincing. However, changes to *RIV* will significantly impact POLARIS as a whole, and neXtSIM must be thoroughly validated for a wide variety of ice conditions before a quantitative evaluation of *RIO* can be made.

Mirai II's ability to enter high latitude waters, navigate in first-year ice, and approach multi-year ice will be very beneficial for validating POLARIS and numerical sea ice prediction models. For example, when measuring a ship's propulsive performance in ice, the ability to search for and reach suitable ice conditions can be expected to improve testing efficiency.

The selection of ice conditions would also improve the possibility of getting down on the sea ice and measuring the mechanical properties of the sea ice. This measurement is essential in engineering but has been difficult with conventional Japanese icebreakers. In contrast, Mirai II will be able to perform a variety of measurements comprehensively.

CONCLUSIONS

This paper examines the navigability of the Arctic research vessel Mirai II, currently under construction, based on ice condition data from 2020 to 2024. We used the IMO's proposed Polaris navigability index to evaluate the ship's navigability, and an objective analysis of the neXtSIM model was deployed for the ice condition data. Throughout the analysis period, we calculated the distribution of the Risk Index Outcome for the entire Arctic Ocean, and the percentage of navigable area for the assumed active area was analyzed as a time series.

As a result, it was found that Mirai II can enter and observe even the high latitude zone near the North Pole under certain ice conditions throughout the year. On the other hand, thick multi-year ice on the North Pole's Canadian side can prevent navigation even in the low-latitude water area.

We investigated the sensitivity of several algorithms to identify multi-year ice from the neXtSIM variables. We found that the second-year ice is more sensitive to the general distribution of the Risk Index Outcome.

The combination of the neXtSIM and the POLARIS need further validation based on measured data. Since Mirai II has access to various ice conditions, including near multi-year ice, it is beneficial to collect validation data. In particular, the ability to conduct performance tests in ice with a high capability is expected to lead to various developments in the icebreaker engineering field.

ACKNOWLEDGEMENTS

The following data were used in this study.
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APPENDIX

The POLARIS defines Risk Index Values (RIV_n) as multipliers to each sea ice type to calculate Risk Index Outcome (RIO). Although it is necessary to translate the neXtSIM parameters into sea ice types in POLARIS in this study, the neXtSIM parameters cannot represent the classification of multi-year ice. Therefore, as shown in Table A1, we have set three algorithms to relate the definition of C_n and the values of RIV_n for n = 4 to 6.

Table A1. Calculation algorithms of sea ice concentration with neXtSIM variables and assignation of POLARIS's Risk Index Values for Polar Class 4 vessels

(a) Algorithm I

n	C_n	RIV_n
1	$(1 - siconc) + siconc\_young$	3
2	$siconc - siconc\_young - siconc\_my$ where $sithick \leq 1.2$	2
3	$siconc - siconc\_young - siconc\_my$ where $sithick > 1.2$	1
4	$siconc\_my$ where $siage \leq 2$	0
5	$siconc\_my$ where $siage > 2 \cap sithick \leq 3.0$	-1
6	$siconc\_my$ where $siage > 2 \cap sithick > 3.0$	-2

(b) Algorithm II

n	C_n	RIV_n
1	$(1 - siconc) + siconc\_young$	3
2	$siconc - siconc\_young - siconc\_my$ where $sithick \leq 1.2$	2
3	$siconc - siconc\_young - siconc\_my$ where $sithick > 1.2$	1
4	$siconc\_my$ where $sithick \leq 2.0$	0
5	$siconc\_my$ where $2.0 < sithick \leq 3.0$	-1
6	$siconc\_my$ where $sithick > 3.0$	-2

(c) Algorithm III

n	C_n	RIV_n
1	$(1 - siconc) + siconc\_young$	3
2	$siconc - siconc\_young - siconc\_my$ where $sithick \leq 1.2$	2
3	$siconc - siconc\_young - siconc\_my$ where $sithick > 1.2$	1
4	$siconc\_my$ where $siage \leq 2$	-1
5	$siconc\_my$ where $siage > 2 \cap sithick \leq 3.0$	-1
6	$siconc\_my$ where $siage > 2 \cap sithick > 3.0$	-2