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An Investigation of POLARIS in the Ice-infested Northern Baltic Sea

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ABSTRACT

The Polar Operational Limit Assessment Risk Indexing System (POLARIS) provides a comprehensive framework for assessing operational risks in ice-covered waters, offering critical support for ensuring maritime safety in challenging environments. While POLARIS has been primarily employed in polar regions, such as the Arctic and Antarctic, the applicability in the ice-infested Northern Baltic Sea has yet been studied. This paper investigates its application and effectiveness in the wintertime Northern Baltic Sea, which features dynamic and demanding first-year ice conditions. The research examines how the risk index adapts to various ice types, concentrations, and vessel characteristics commonly encountered in this region. A key aspect of this study is the integration of icebreaker assistance records, enabling a unique comparison between POLARIS-assessed risk levels and actual icebreaker interventions provided to merchant vessels. This approach provides a practical validation of POLARIS's suitability for the Northern Baltic Sea, where detailed datasets and operational insights are more readily available than in polar environments. The findings offer insights into the system's performance, highlighting its strengths, limitations, and potential adaptations for non-polar ice conditions. This investigation contributes to the refinement of POLARIS and other risk assessment tools, emphasizing their importance for safe and efficient navigation in ice-prone regions.

KEY WORDS Ice Class; Ice Type; POLARIS; Risk assessment; Icebreaker.

INTRODUCTION

Maritime operations in polar regions pose significant challenges due to harsh and dynamic environmental conditions. To ensure acceptable risk levels under various ice regimes and operational scenarios, voyage planning must consider ship structural capabilities, vessel characteristics, operational type, and prevailing and forecasted ice conditions. To support risk mitigation and enhance navigational safety, the Polar Operational Limit Assessment Risk Indexing System (POLARIS) was developed as a standardized framework for assessing vessel-specific operational limits in ice-covered waters. Introduced by the International Maritime Organization (IMO) as part of the Polar Code (IMO, 2015), POLARIS provides guidelines for safe and environmentally responsible navigation in Arctic and Antarctic waters. It builds on earlier risk assessment systems such as Canada's Arctic Ice Regime Shipping System and Russia's Ice Certificate system, which includes pilot icebreaker support under the Rules of Navigation for the Northern Sea Route. POLARIS enables a risk-informed approach to voyage planning and operational decision-making in ice conditions.

Different research has focused on various aspects of POLARIS. Stoddard et al. (2016) studied maritime traffic using POLARIS. Kujala et al. (2019) demonstrated a validation on POLARIS utilizing full-scale measurement in the polar region. Bergström et al. (2022) highlighted a goal-based approach complementing IMO's POLARIS methodology for selecting a suitable Polar Class for an ice-going ship. Lee et al. (2021) and An et al. (2022) explored the POLARIS's role in route planning and sailing plans. Fedi et al. (2020) tried to map and analyze maritime accidents through the Polar Code and POLARIS. Browne et al. (2022) applied POLARIS as a regulatory guideline to assign structural safety constrains on ships and found that while POLARIS offered flexibility to operate in more severe ice conditions, it increases voyage time, fuel consumption, and the risk of vessel damage. Research and discussions on investigating and improving POLARIS are ongoing across various aspects to support its continuous application and validation.

The Northern Baltic Sea (NBS) is one of the busiest maritime areas affected by sea ice. Although it lies outside the Arctic region, it presents comparable navigational challenges for ships operating in ice-covered waters. Despite this, the applicability of the POLARIS framework in this region has received limited attention. This paper aims to address that gap by investigating the use of POLARIS in the ice-infested NBS, utilizing comprehensive datasets including ice forecasts, ship traffic, and icebreaker assistance records.

METHODOLOGY AND DATA

Polar Operational Limit Assessment Risk Indexing System (POLARIS)

POLARIS utilizes the Risk Index Outcome (RIO) to assess operational limitations in ice-covered waters. Risk Index Values (RIVs) are assigned based on a ship's ice class and the types of ice encountered, as outlined in Table 1. An additional row in Table 1 includes the corresponding ice thickness for each ice type, derived from the WMO nomenclature. For ice types 9 to 11, where standard thickness is not defined, expert judgment has been applied to assign representative thickness values. For each encountered ice regime, the RIVs are used to calculate the RIO, which serves as the basis for determining whether operations can proceed or need to be limited.

The RIO is determined by a summation of the RIVs for each ice type present in the ice regime multiplied by its concentration (expressed in tenths):

$$RIO = \sum_{i=1}^{n} C_i \cdot RIV_i \qquad (1)$$

Where C_i are the concentrations (in tenths) of ice types within the ice regime; and RIV_i are the corresponding Risk Index Values for each ice type.

Table 1. Risk Index Values

Ice Class	Ice Type 1	Ice Type 2	Ice Type 3	Ice Type 4	Ice Type 5	Ice Type 6	Ice Type 7	Ice Type 8	Ice Type 9	Ice Type 10	Ice Type 11	Ice Type 12
	0	0-10	10-15	15-30	30-50	50-70	70-100	100-120	120-150	150-200	200-250	250-
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
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
IAS	3	2	2	2	2	1	0	-1	-2	-3	-4	-4
IA	3	2	2	2	1	0	-1	-2	-3	-4	-5	-5
IB	3	2	2	1	0	-1	-2	-3	-4	-5	-6	-6
IC	3	2	1	0	-1	-2	-3	-4	-5	-6	-7	-8

Note: Ice Type 1 Ice-Free, 2 New Ice, 3 Grey Ice, 4 Grey White Ice, 5 Thin First Year Ice 1st Stage, 6 Thin First Year Ice 2nd Stage, 7 Medium First Year Ice (<1m thick), 8 Medium First Year Ice, 9 Thick First Year Ice, 10 Second Year Ice, 11 Light Multi-Year Ice (<2.5m thick), 12 Heavy Multi-Year Ice.

Ice Forecast Data

Ice information is generated by a Baltic Sea setup of the NEMOv4.2.1 ocean model. This model covers the Baltic Sea, including the transition areas towards the North Sea, such as the Danish Belts, the Kattegat, and Skagerrak. The ocean model is forced by Stokes drift data from the Baltic Sea Wave Forecast product. Satellite sea surface temperature, sea ice concentrations, and in-situ temperature and salinity profiles are assimilated into the model's analysis field. The model uses a regular horizontal grid with a step size of approximately 1 nautical mile (latitude: 0.017 degrees; longitude: 0.028 degrees). It employs a staggered Arakawa C-grid (see Figure 1). Scalar variables (temperature, salinity, sea level, ice, and biogeochemical parameters) are centered on the T points of the grid at the grid cell nodes, while velocity components are located halfway between adjacent grid cell nodes. These velocities are then de-staggered and interpolated to the T points in the delivered products (Bruggeman and Bolding, 2014; Neumann et al., 2021). The key parameters relevant to this study are ice concentration and ice thickness.

Ship AIS Data and Icebreaker Operation Records

The Automatic Identification System (AIS) serves as an information exchange platform between vessels and shore organizations, providing both static and dynamic data (Lu et al., 2021). For most maritime analyses, messages of Type 1–3 and 5 are typically utilized. Types 1–3 correspond to Class A Position Reports, which include essential navigational data. Specifically, the Type 1–3 data comprise the following information: the Maritime Mobile Service Identity (MMSI) number, which identifies the ship's radio station; latitude and longitude; speed over ground (SOG); course over ground (COG); heading (HDG); and rate of turn (ROT) (Lensu and Goerlandt, 2019).

In addition to AIS traffic data, icebreaker operation records are sourced from the Finnish Transport Infrastructure Agency. These records detail the assistance times and the ships that received help from icebreakers. By analyzing these records, the times at which merchant ships received assistance are identified, offering a comprehensive view of maritime operations in relation to ice conditions.

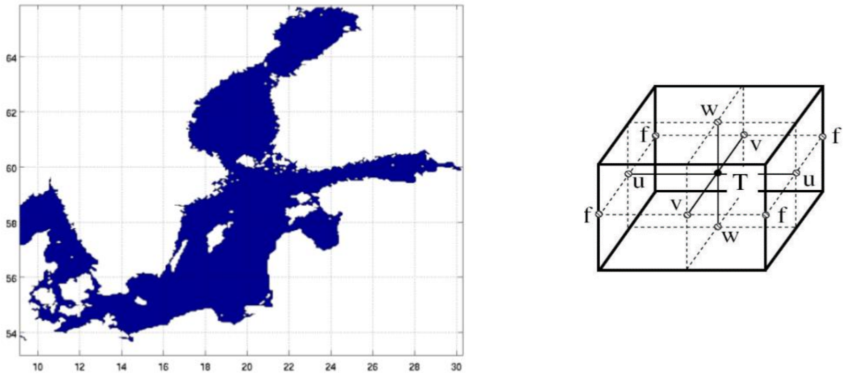

Figure 1. Domain, resolution and grid, Geographic coverage: North Sea – Baltic Sea: 53°N - 66°N, 9°E - 30°E

Investigation approach on POLARIS in the NBS

The overall approach for investigating and evaluating the applicability of the POLARIS method in the Northern Baltic Sea (NBS) is depicted in Figure 2. Ice forecast data, specifically ice thickness and concentration, are used to apply the POLARIS method across various ship ice classes, generating Risk Index Outcome (RIO) maps. Automatic Identification System (AIS) data and icebreaker operation records are then used to identify assisted vessels, from which their operational RIOs and corresponding profiles are extracted. The timing of a ship's request for icebreaker assistance is a critical indicator of the risk level perceived by the captain at that moment. By comparing this timing with the RIO values, valuable insights can be gained. Since the primary focus of this paper is on the timing of icebreaker assistance requests, the RIO values presented here does not consider the additional +10 RIO for icebreaker assistance.

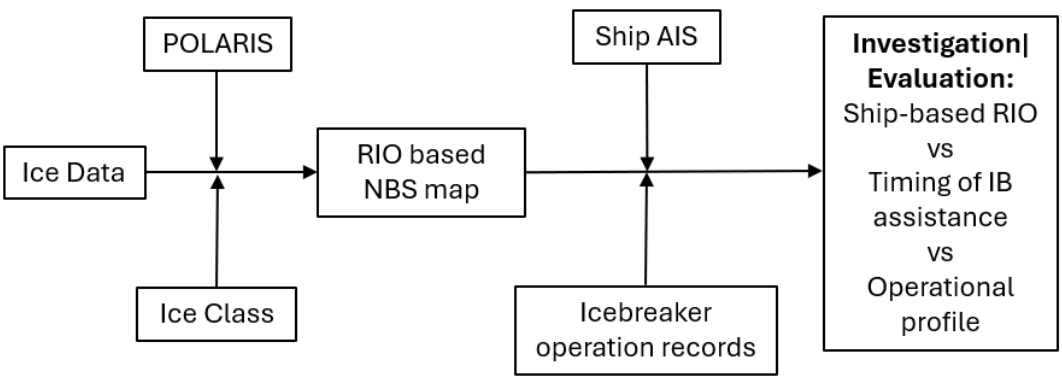

Figure 2. Overall approach for evaluation of POLARIS in the NBS

RESULTS

RIO maps

RIO maps for three different ice-class ships are generated by applying the POLARIS method to the ice data. It shows three risk levels RIO>0, -10<RIO<0, RIO<-10, representing normal operations, elevated operational risk and operations subject to special consideration. The investigation is conducted for April 20th, 2024. The icebreaker-assisted ships include three ice classes: IB, IA, and IAS. As expected, IB-class ships encounter larger risk areas than IA-class ships, and IA-class ships face more risk areas than IAS-class vessels.

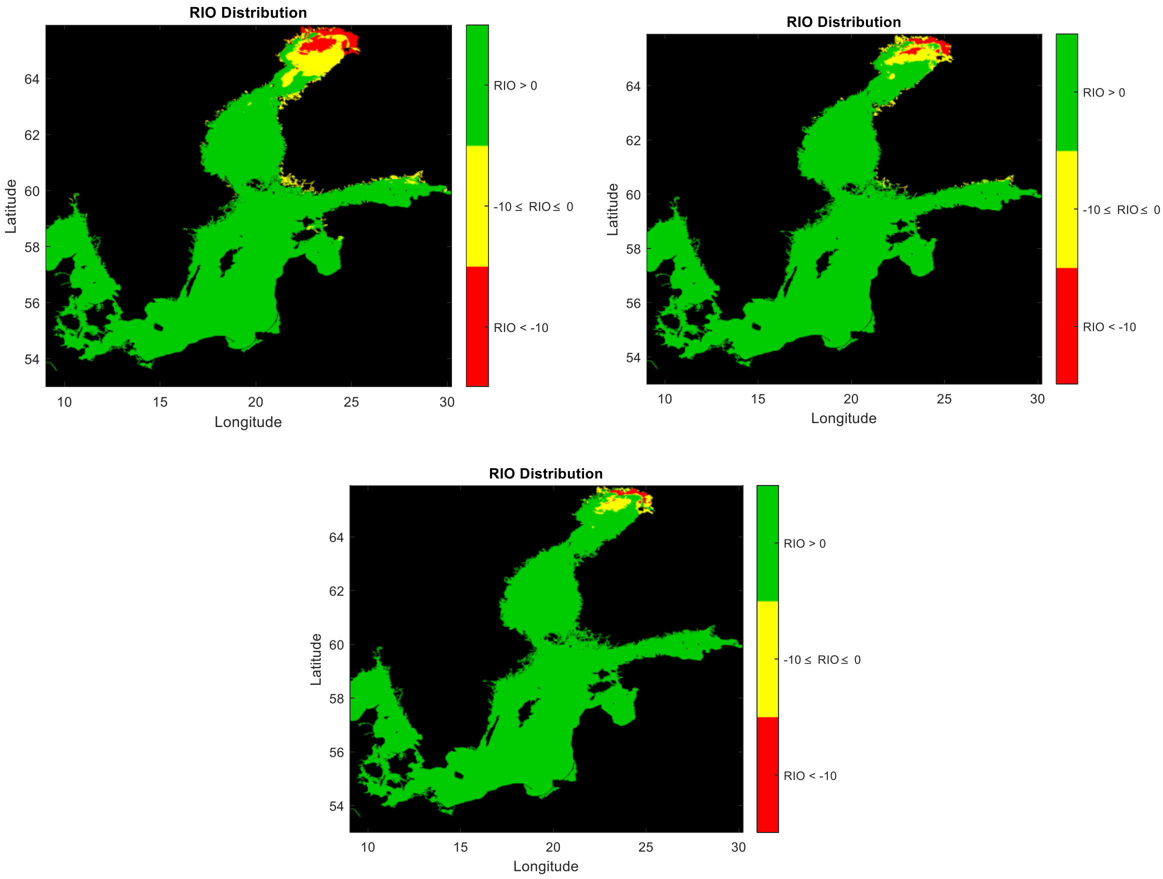

Figure 3. RIO map for IB, IA and IAS

Assisted ship records for the entire day were extracted, totaling 29 vessels, of which 24 were identified in the AIS data. Their trajectories were plotted together with the corresponding RIO map. It is evident that many ships navigated through high-risk regions with low RIO values. Consequently, a further investigation was conducted by extracting RIO values along the trajectories and analyzing the corresponding ship behaviors.

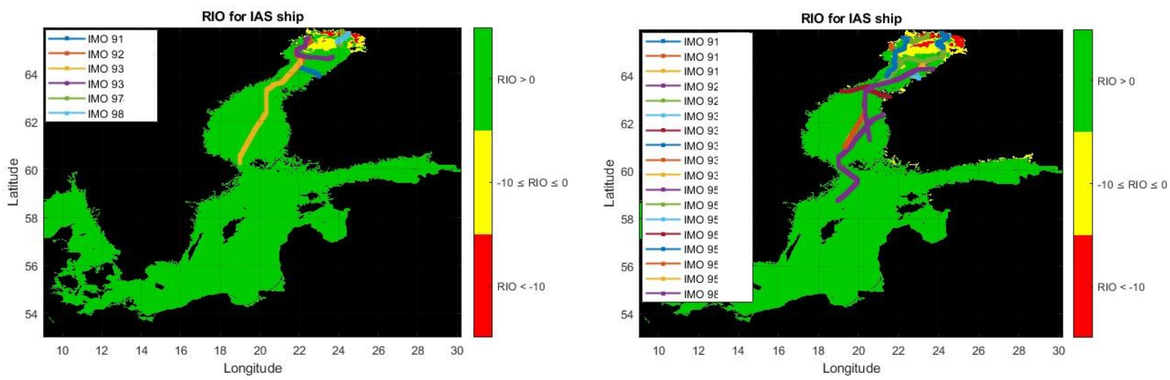

Figure 4. Assisted ship trajectory on RIO map

Correlation between RIOs and ship operational patterns

When RIO values fall below zero, it theoretically suggests that the ship should proceed with caution and reduce speed based on the prevailing conditions. Furthermore, if the ship encounters severe ice and the captain deems that independent navigation is not possible, icebreaker assistance is requested to ensure safe passage. To examine this relationship, ship speed (SOG) and RIO values are plotted together to assess the ships' operations.

Figure 5-8 display the calculated RIOs and the extracted ship speeds for the 24 assisted ships. In general, the correlation between ship speed and RIO values is not immediately clear. When the RIO value is low, the ship speed typically shows low or fluctuating characteristics. However, when RIO values are high, the ship speed does not necessarily increase. This could be understandable, as navigation speed is influenced by factors beyond ice conditions, such as weather and visibility. However, if the periods where the RIO is high and ship speed is zero last very long, it may also indicate mismatches. This could suggest that the local ice conditions are not as favorable as indicated by the RIO, implying the need for more accurate ice forecast data or the consideration of additional factors not addressed by the current RIO model.

Correlation between RIOs and the timing of icebreaker assistance

To further investigate the RIO values, we focus on cases with negative RIOs. A total of 8 ships encountered negative RIO values. The periods of icebreaker assistance are indicated by black rectangles, alongside the SOG and RIO records. The *start time of icebreaker assistance* is particularly important for the investigation, as it marks the moment when the ship's captain recognizes difficulties and risks in navigating independently. Once assistance begins, the RIO value is expected to increase by an additional 10, reflecting the assisted operation mode, according to the POLARIS method.

In the first case (Figure 5), there are three distinct assistance periods. In the first assistance, when icebreaker assistance begins, the ship's speed is zero while the RIO value is around 10, which can be understood to some extent as it occurs during the night, and the perceived risk may be higher than the actual conditions. At the start time of the second assistance, the RIO value is zero, and in the third assistance, the RIO is to -10. Zero and negative RIO values indicate elevated operational risk and conditions requiring special consideration. Therefore, icebreaker assistance requested under such conditions is generally justifiable. Therefore, the RIO values here seem reasonable in this context. In the second case (Figure 5), the icebreaker assistance occurs during a brief period, and the RIO is zero, which also makes sense for requesting icebreaker assistance.

In the third case (Figure 6), the first icebreaker assistance occurs at night, with a relatively high RIO value at the time the assistance is requested. Although such a RIO would not typically justify assistance, the request is understandable given nighttime visibility limitations. During the second assistance, the RIO value remains positive initially but soon drops to zero, indicating possible local variations in ice conditions. Similar fluctuations are observed during the third and fourth assistances.

In particular, for the fourth assistance, the RIO is positive at the start but quickly turns negative, supporting the need for icebreaker support. Following the start of assistance, the ship's speed remains relatively stable for several hours, while the RIO (without the additional +10 for icebreaker escort) continues to fluctuate. If the +10 adjustment is applied, most RIO values become positive, except for a brief period where the RIO remains negative. This raises the question of whether the standard +10 increment sufficiently reflects assisted operation conditions. Notably, in the later stage, when the original RIO drops to approximately -20, the ship's speed falls to zero even with icebreaker assistance, highlighting a potential match between the RIO value (with the +10 adjustment) and the actual operational difficulty experienced during icebreaker escort.

In the fourth case (Figure 6), all icebreaker assistance requests occur when the RIO is zero or negative, which supports the applicability of the POLARIS method. However, once the assistance begins, the ship's speed profile suggests difficulty advancing through the ice, while the RIO remains at zero or slightly positive even without the +10 adjustment. This may indicate that the actual local ice conditions are not accurately captured by the available ice data.

In the fifth case (Figure 6), an interesting observation is that the RIO is negative around midnight when the ship's speed drops to zero. Shortly after, the RIO unexpectedly rises to 10, even though the ship appears to remain beset in ice for an extended period. This highlights the importance of capturing local ice conditions and their dynamic changes. Notably, icebreaker assistance in this case is requested when the RIO is already positive, suggesting a possible mismatch. In contrast, the sixth case (Figure 7) shows assistance being provided when the RIO is around -10, which aligns well with the intended interpretation of the RIO metric.

In the seventh case (Figure 8), icebreaker assistance is requested when the RIO is zero, supporting the applicability of the RIO metric. Later, as the RIO drops significantly into negative values, even the icebreaker assistance appears to be suspended, suggesting particularly severe ice conditions. In the eighth case (Figure 8), the first assistance occurs during a period of negative RIO, which aligns with expectations. However, during the second assistance, despite a relatively high RIO value, the ship's speed does not improve, indicating a clear mismatch between the RIO and actual operational difficulty. This discrepancy likely stems from unaccounted or not captured local ice conditions in the ice data, or potentially from factors not currently included in the POLARIS framework.

Overall, there is generally good alignment between zero or negative RIO values and the timing of icebreaker assistance, though some mismatches are also evident. It is important to note that this detailed analysis focuses on eight cases with negative RIO values. However, there are still numerous cases where assistance was requested despite consistently positive RIO values.

DISCUSSION

The Northern Baltic Sea is a sub-Arctic region characterized by both seasonal sea ice and dense maritime traffic. Understanding the operational risk levels in such conditions is essential for ensuring maritime safety. This study aims to assess the applicability of the POLARIS methodology in this regional context. The availability of extensive maritime traffic data, ice forecasts, and icebreaker assistance records offers a strong foundation for analyzing various scenarios. In particular, icebreaker assistance records provide insight into perceived risk levels, as the decision to request assistance often reflects a captain’s assessment of navigational difficulty. Comparing these instances with calculated RIO values offers valuable perspective on POLARIS's performance. However, several important limitations and considerations must be acknowledged.

Firstly, POLARIS uses Risk Index Values (RIVs) based on ice types. In this study, ice types were translated into ice thickness values to match the format of available ice data. This necessary simplification may introduce deviations in calculated RIOs.

Secondly, ice information is a critical input for calculating RIOs, and its spatial and temporal resolution can significantly affect the accuracy of real-time assessments. In this study, the ice data has a spatial resolution of 1 nautical mile, which may not capture local ice features encountered by ships within each grid cell. Moreover, specific ice conditions such as ridges or compressive ice zones are not explicitly represented in the data and RIO calculations, potentially impacting the alignment between calculated RIOs and actual ship operations.

Thirdly, the comparison between RIO values and the timing of icebreaker assistance is theoretically meaningful. According to POLARIS, $RIO > 0$ indicates normal operations, $-10 < RIO < 0$ suggests elevated operational risk, and $RIO < -10$ implies conditions requiring special consideration. While these thresholds primarily reflect structural risk, in practice, a captain's decision to request assistance may also be influenced by other factors. As a result, assistance may sometimes be requested even under seemingly favorable conditions with relatively high RIO values.

CONCLUSION

This paper examines the applicability of POLARIS under the ice conditions of the Northern Baltic Sea. Ice forecast data is used to generate Risk Index Outcome (RIO) maps, and RIO values are extracted along the trajectories of ships that received icebreaker assistance. These are compared with assistance records and ship operational profiles. The analysis reveals both consistencies and discrepancies. Overall, the application of RIO in this region tends to underestimate the navigational challenges posed by ice. Two primary factors may contribute to this: first, the spatial and temporal resolution of the ice data may be insufficient; and second, although ice thickness theoretically accounts for features such as ridges, the current data may not fully reflect their localized effects. Moreover, other influencing factors such as ice compression may not yet be adequately incorporated into the POLARIS framework. Further investigations are planned as the project continues.

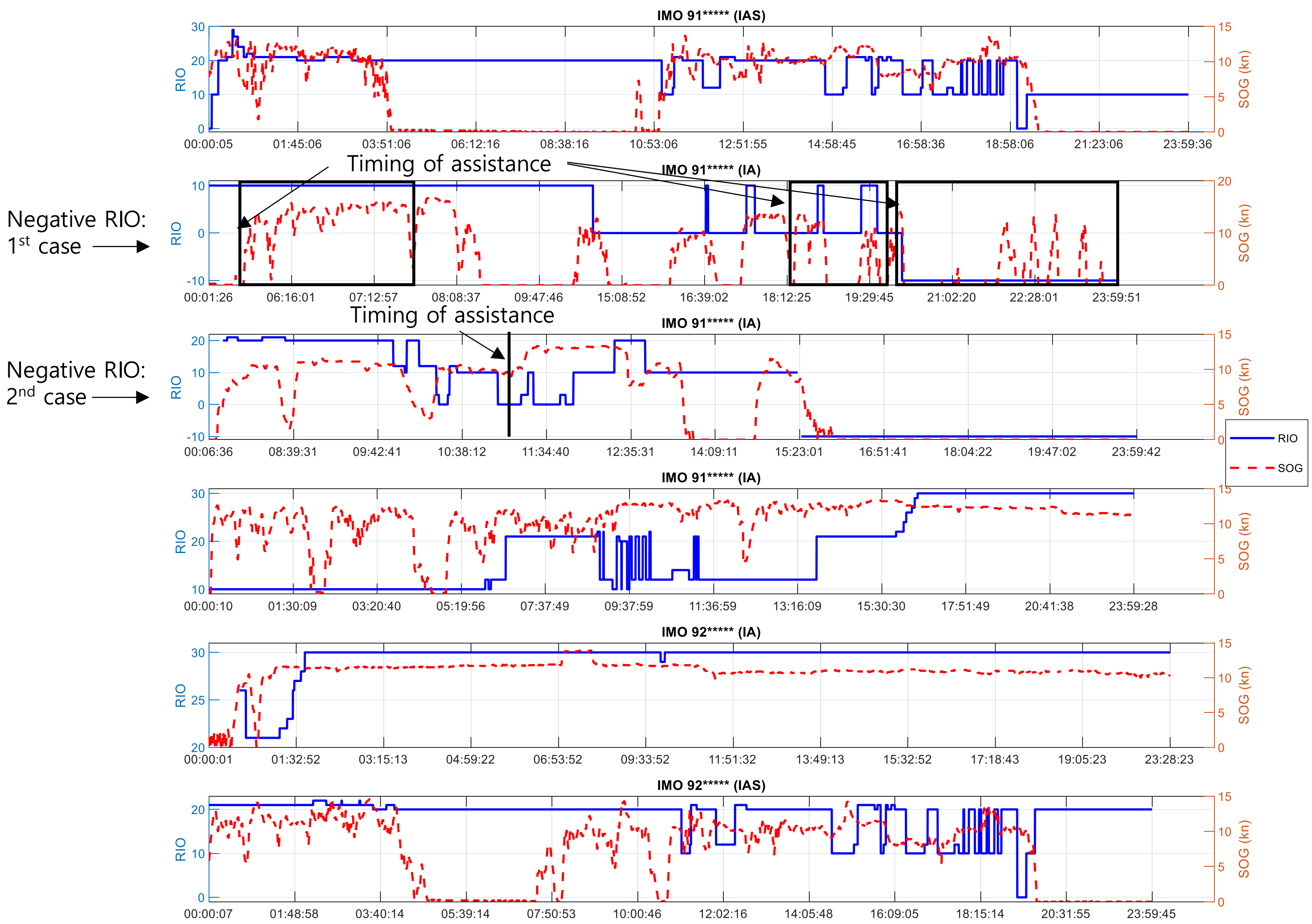

Figure 5. RIO values with icebreaker assistance and ship operational speed

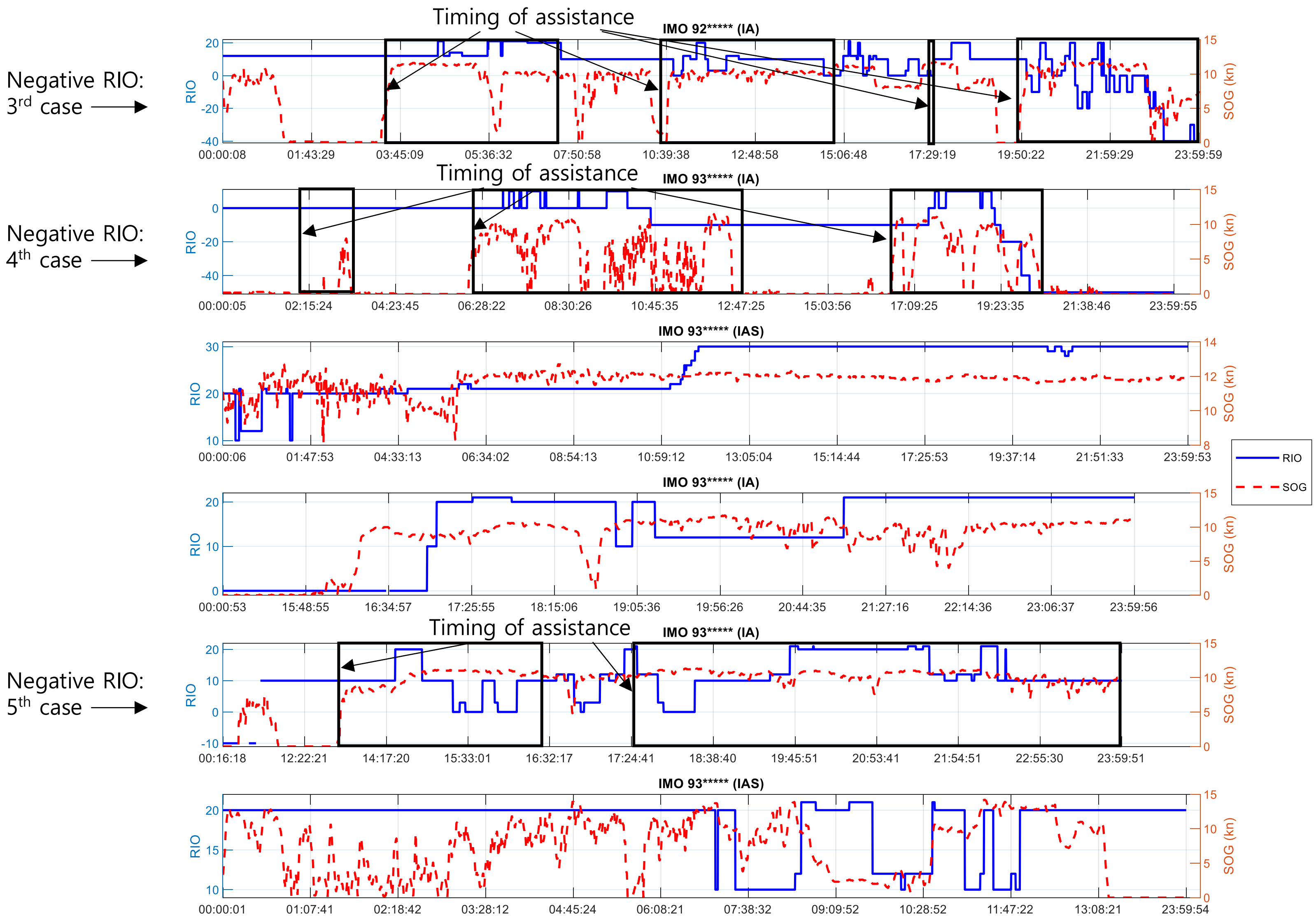

Figure 6. RIO values with icebreaker assistance and ship operational speed

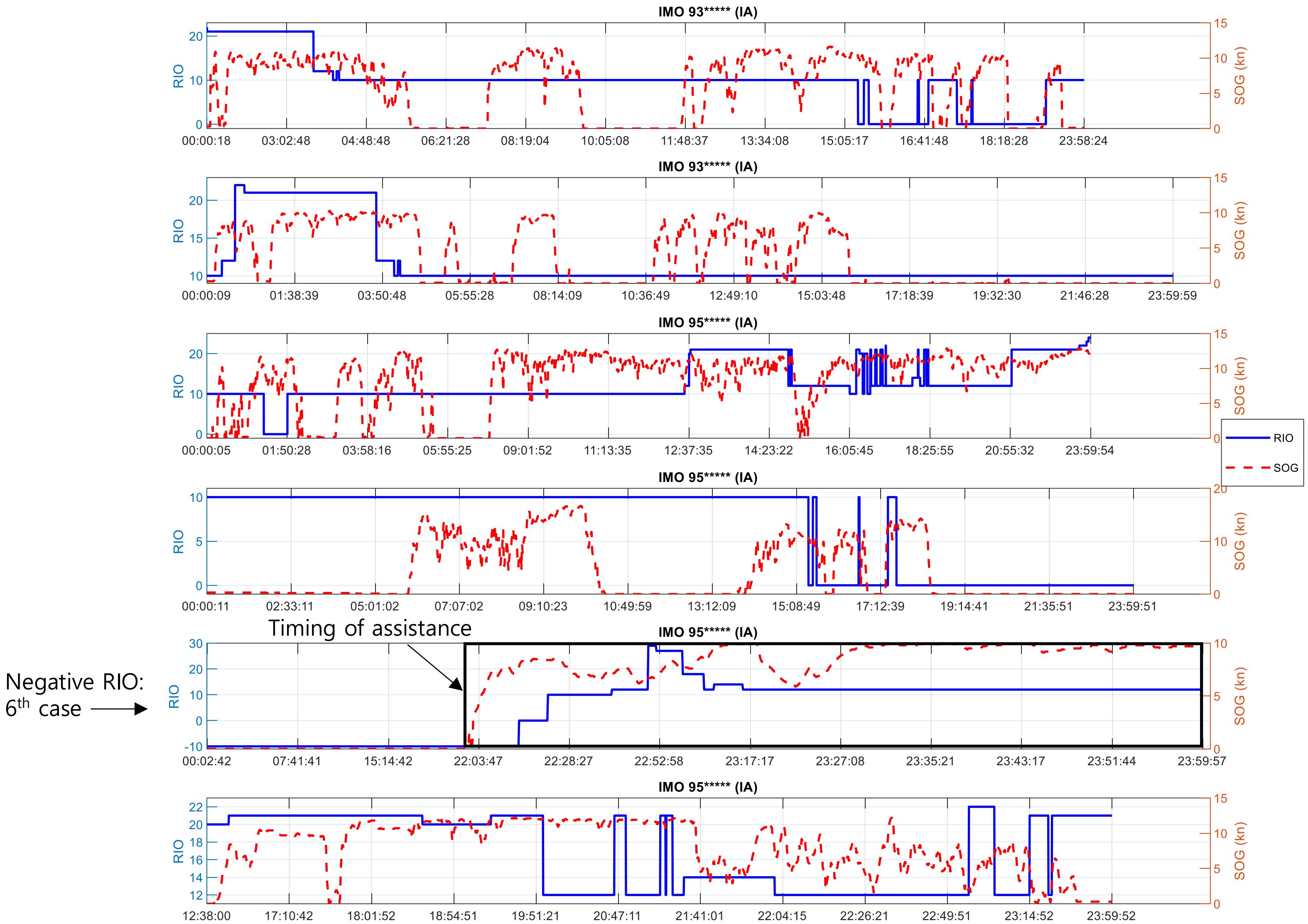

Figure 7. RIO values with icebreaker assistance and ship operational speed

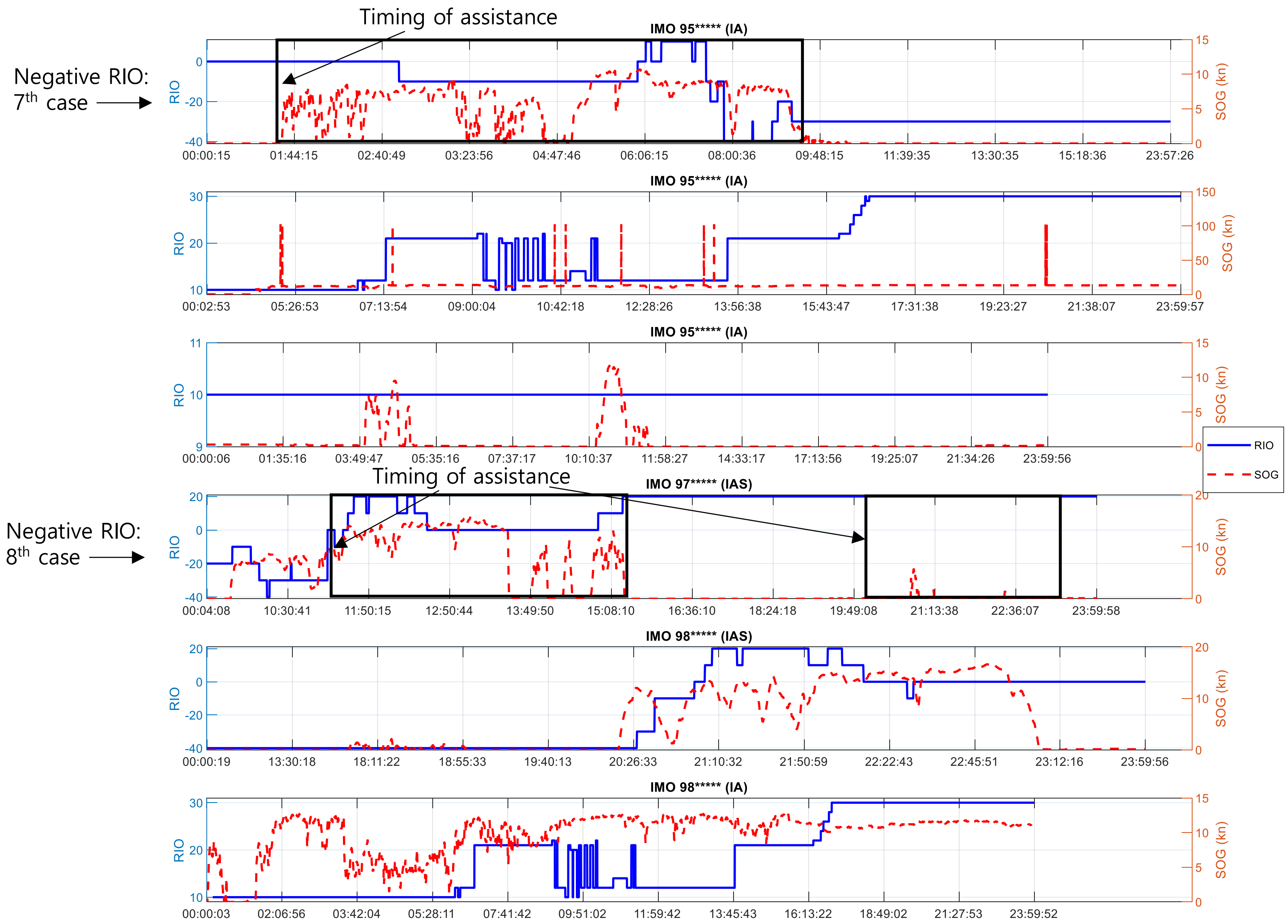

Figure 8. RIO values with icebreaker assistance and ship operational speed

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