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**Abstract.** Maritime traffic volume in the Arctic is growing for several reasons: climate change is resulting in less ice in extent, duration, and thickness; economic drivers are inducing growth in resource extraction traffic, community size (affecting resupply) and adventure tourism. This dynamic situation, coupled with harsh weather, variable operating conditions, remoteness, and lack of straightforward emergency response options, demand robust risk management processes. The requirements for risk management for polar ship operations are specified in the new International Maritime Organization (IMO) International Code for Ships Operating in Polar Waters (Polar Code). The goal of the Polar Code is to provide for safe ship operations and protection of the polar environment by addressing the risk present in polar waters. Risk management is supported by evidence-based models, including threat identification (types and frequency of hazards), exposure levels, and receptor characterization. Most of the information used to perform risk management in polar waters is attained in-situ, but increasingly is being augmented with open-access remote sensing information. In this paper we focus on the use of open-access historical ice charts as an integral part of northern navigation, especially for route planning and evaluation.

## 1. Introduction

Maritime traffic in the Canadian Arctic is expected to increase in coming years as northern communities grow, tourism increases, and large resource development projects enter into operation. As Arctic maritime traffic increases, a greater number of vessels are exposed to the navigational risks in Canada's Arctic. The vulnerability of a vessel to these navigational risks depends heavily on the type and class of ship, crew training and experience, and access to high quality information to support decision making. Efforts to improve our knowledge and understanding of the Arctic maritime domain are required to ensure the safety and sustainability of increased maritime activity in the Canadian Arctic.

Observation and monitoring of the changing environment is critical to achieving Maritime Situational Awareness (MSA) in the Arctic. Traditional efforts to achieve MSA have focused on building accurate and timely knowledge of anything within the maritime domain that could impact the security, safety, economy, or environment. In the Canadian Arctic, environmental factors strongly influence maritime activity, including but not limited to, extreme weather, ice conditions, and daylight [1]. The Arctic environment is not uniform; there are large seasonal variations in ice, light and weather and these factors vary greatly throughout the Arctic [2]. Characterizing these factors and their

impact of vessel activity in the Arctic presents a significant challenge due to the remoteness and vastness of the region. These challenges have driven major advancements in sensors and systems supporting MSA and the observation and monitoring of maritime traffic in the Arctic.

AIS (Automatic Identification System), LRIT (Long Range Identification and Tracking) and VMS (Vessel Monitoring System) now allow an observer to determine what types of ships are navigating, as well as their position at any time during their course [3,4]. These systems are now integral to the security and safety of the global maritime domain. Remote sensing systems also offer a very attractive tool for providing relevant and timely data from which a variety of shipping information products can be developed for decision makers.

Common applications of remote sensing in the Canadian Arctic include the characterization of ocean waves [5], coastlines [6], ocean currents [7-9], ice [10, 11], and shipping activity. Since the launch of the first civilian SAR satellite, SEASAT, there have been many research contributions to ship detection in SAR imagery [12-15]. Sensors such as RADARSAT-1, RADARSAT-2, ENVISAT, COSMO-SkyMed and Sentinel-1 have routinely been used to monitor the ice in the Arctic. These same sensors are also used to detect and monitor maritime traffic. The challenge we are now routinely faced with is how do we move past simply detecting and locating vessels and begin to achieve higher level sense-making of observed maritime activity. Increasingly, we must expand our awareness of non-traditional data sources and types to improve our understanding of maritime activity, and the risks it may pose.

In this paper we will introduce the Polar Operational Limitations Assessment Risk Indexing System (POLARIS). We will demonstrate how it can be used with open-access historical ice information to preform maritime risk assessment and subsequent risk visualization. Lastly, we will provide two examples of how POLARIS can be used to support both the planning and evaluation of maritime activity in the Canadian Arctic.

## 2. The Polar Code and POLARIS

The International Maritime Organization (IMO) has adopted the International Code for Ships Operating in Polar Waters (Polar Code) [16] and related amendments to make it mandatory under both the International Convention for the Safety of Life at Sea (SOLAS) [17] and the International Convention for the Prevention of Pollution from Ships (MARPOL) [18]. The Polar Code will aid Arctic marine transportation in a number of ways. Not only does it address safety of navigation and environmental protection from the mariner's point of view, but it also provides a way for classification societies and underwriters to appropriately assess the risks along a desired voyage and the readiness of the company, ship, master, and crew to embark on the journey. The Polar Code will establish new guidelines beyond those contained in the SOLAS and MARPOL conventions, helping to define customary behaviour in polar waters [19]. Associated with the Polar Code is a proposed methodology to determine a ships capabilities and limitations in ice, referred to as the Polar Operational Limitations Risk Indexing System (POLARIS).

### 2.1. Polar Operational Limitations Assessment Risk Indexing System (POLARIS)

POLARIS provides a risk assessment framework to assess navigational safety in a given ice regime, using observed or historical ice conditions and concentration and a polar ship classification [16, 20]. Many researchers may compare POLARIS to the Transport Canada Arctic Ice Regime Shipping System (AIRSS) [21], as discussed in [12-25]. A major difference is that POLARIS allows for the consideration of limited speed / escort operations, as well as the effects of seasonal ice decay on ice strength. The addition of limited speed operations reflects known feedback from operators in the Arctic where they met conditions they could operate in with due caution, although above the nominal limits given by AIRSS [26].

Both POLARIS and AIRSS rely on the use of an ice regime to describe an area with a number of relatively consistent ice types, including open water. The concentration of each ice type within an ice regime is reported in tenths. For each ice type there is an associated ice type score defined for each

particular polar ship classification. The ice type score is referred to as a Risk Value (RV), and a collection of RVs that correspond to a particular ice regime is referred to as a Risk Index Outcome (RIO). Using POLARIS, RIO is determined by summing the RVs for each ice type present in the ice regime encountered, multiplied by its concentration (equation 1):

$$(1) \qquad\qquad RIO = C_1RV_1 + C_2RV_2 + \ldots + C_nRV_n$$

Where $C_1$, $C_2$,..., $C_n$ are the concentrations (in tenths) of ice types within the ice regime and $RV_1$, $RV_2$,...,$RV_n$ are the risk values corresponding to each ice type and for a given ship ice class classification. The resulting RIO value is then evaluated to determine the appropriate polar ship operational limits in ice.

*2.2. Visualization of RIO Results using SIGRID-3 Ice Data*
Integral to the calculation of the RIO is the availability of accurate information of the ice regime. As was previously mentioned, an ice regime is used to describe an area with a number of relatively consistent ice types, including open water. The ice regime can be determined in two ways, (1) in-situ by a qualified ice navigator on the bridge of a ship operating in polar waters, or (2) using open-access historical Sea Ice data. Historical sea-ice charts covering the Canadian Arctic are available from the National Snow and Ice Data Centre (NSDIC). Weekly sea-ice charts are stored in the standard World Maritime Organization (WMO) ice chart archive vector format, Sea Ice Grid (SIGRID-3). Originally proposed in 1981 and adopted by the World Maritime Organization, the SIGRID format was designed to meet larger scale climate requirements, providing a computer-compatible sea-ice data bank [27]. The CIS SIGRID-3 vector format provides information about ice conditions in a specific geographic area.

   To facilitate the calculation and visualization of risk, a 1km x 1km rectangular mesh grid was generated for a defined Area of Interest (AOI) in the Canadian Arctic. This tessellation was chosen for its ease of calculation and simplicity of the resulting data structure. The resulting quantized AOI contained approximately 16 million grid cells at a 1 $km^2$ resolution. The AOI was further processed using a vector layer of the Canadian shoreline to delete gird cells that are outside of our AOI or inland. These spatial processing steps produced an AOI containing 4 million grid cells. Next, we filtered the CIS SIGRID-3 sea ice information to only include ice polygons within our AOI and associated this information with all intersecting grid cell from the quantized AOI. Now, for a given polar ship classification, we are able to determine the RIO for each grid cell. Six different statistical aggregations of RIO results have been generated using historical sea ice information from 2007 to 2014, including, (1) minimum RIO, (2) 25th percentile RIO, (3) average RIO, (4) median RIO, (5) 75th percentile, and (6) maximum RIO. Figure 1 provides a visualization of the Average POLARIS RIO from 2007 to 2014 for a Polar Class (PC) 6 vessel operating in the defined AOI during week 23.

**3. Arctic Maritime Traffic Analysis**
There have been many recent studies examining maritime traffic in the Canadian Arctic. Howell and Yackell provide an early example of a temporal and spatial assessment of ship navigation variability in the Canadian Arctic using historical ice information and the Arctic Ice Regime Shipping system (AIRSS) [22]. Etienne and Pelot discuss the development and use of a network graph model to determine shortest paths between an origin and destination in the Canadian Arctic, with consideration for historical ice conditions and ship capabilities in ice [25]. This model can be used to simulate maritime traffic in the Canadian Arctic. Somanathan et al. defined several alternative shipping routes through the Canadian Arctic, evaluating the relative economics of each route. By correlating ship speed to historical ice condition, and simulating year round transits of the North West Passage (NWP) - a sea route connecting the northern Atlantic and Pacific Oceans through the Arctic Ocean, along the northern coast of North America via waterways through the Canadian Arctic Archipelago - using the
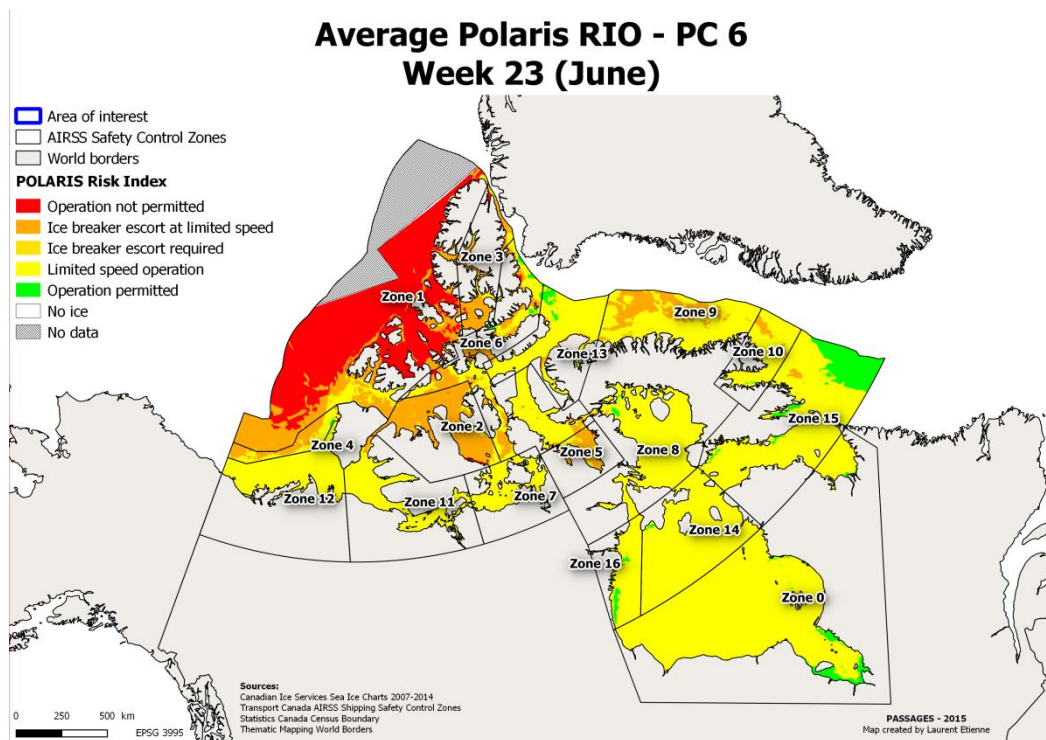
**Figure 1.** POLARIS scenario risk map for a PC 6 vessel operating in the defined AOI during Week 23, using the average RIO result from 2007 - 2014.

traffic simulation software Visual Simulation for Alternative Modelling (VSLAM™), the researchers were able to estimate a common measure of shipping performance, Required Freight Rate (RFR). The authors reasoned that continued thinning of Arctic ice will have the effect of increasing the economic benefit of taking the NWP when compared to conventional shipping routes [22]. Lastly, Smith and Stephenson examined the feasibility of new shipping routes through the Arctic based on the prediction of sea ice thickness and concentration from several leading Global Climate Change Models (GCMs) [24].

In this paper we will discuss the use of POLARIS and open-access ice information to evaluate the risk along a shipping route in the Canadian Arctic. We rely on the RIO to provide context when trying to make sense of erratic or unexpected kinematic behaviour along an executed route. We provide two examples, (1) Route evaluation with historical data, and (2) Route evaluation with near-real time data.

*3.1.1. Route Evaluation with Historical Data*
Passage planning for the Canadian Arctic region continues to be based on typical accepted standard navigational practice, with additional consideration placed on the expectation of ice presence and uncertain bathymetric charting information. Many factors influence route planning, including, operating area remoteness, locations of nearby support, extreme weather, daylight, presence of multi-year and glacial ice, and location of historical incidents [28]. For the purposes of this example we will evaluate and visualize the expected Risk Index Outcome (RIO) along a planned route. Using our AOI grid containing pre-computed RIO values, we are able to assess the risk along the route using the POLARIS evaluation criteria. Figure 2 provides an overview of the three types of visualizations that can support route planning and evaluation for a Polar Ship Ice Class 1A (IA), as defined in [18].

Figure 2 (a) provides a strategic appraisal of the RIO for a given ship class and voyage week, in this case it is an IA vessel transiting the AOI during week thirty using the median RIO value. Using this image, a planner can assess their route visually, using the median RIO results for the area they intend to transit in a particular week. Figure 2 (b) simply colour codes the route based on the median
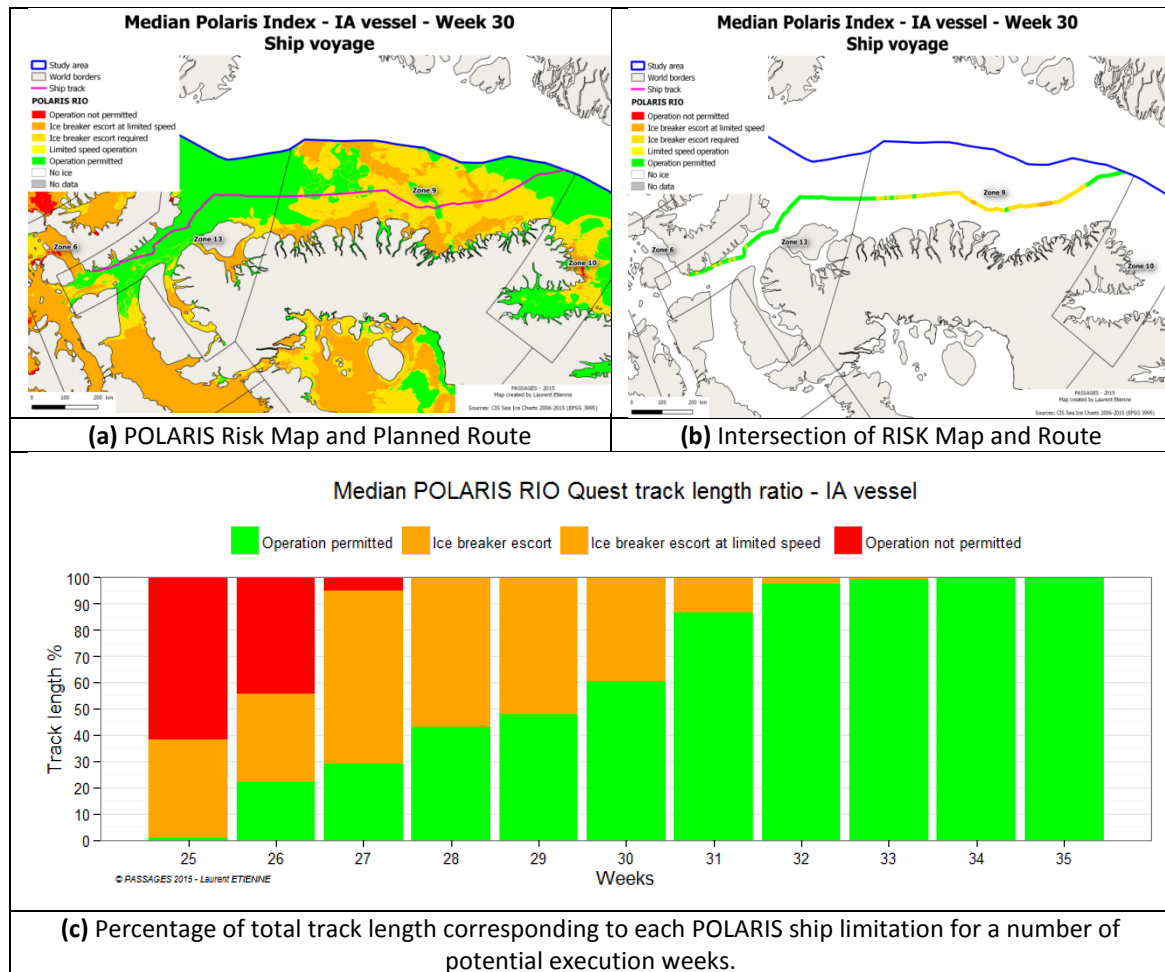
**(a)** POLARIS Risk Map and Planned Route

**(b)** Intersection of RISK Map and Route

**(c)** Percentage of total track length corresponding to each POLARIS ship limitation for a number of potential execution weeks.

**Figure 2.** Route planning and evaluation visualizations for an IA vessel enter the defined AOI during week 30 using the median POLARIS RIO score.

RIO results. This simplified view can be used to quickly identify the portions of the route that are higher risk. Lastly, figure 2 (c) provides a route summary based on the proportion of the planned route that corresponds to each of the POLARIS RIO evaluation criteria. In this case we see that for an IA ship executing this planned route during week 30 that roughly 60% of the route is GREEN (operations permitted), while the other 40% may require ice breaker escort, based on median POLARIS RIO results. Of interest is that if the trip was to be be moved from week 30 to week 31 we see that conditions are much more favourable, with 86% of the track is GREEN (operations permitted), while only 14% may require ice breaker escort.

When interpreting the results shown in figure 2 one must always consider both the sea ice variation – the natural spatiotemporal variation in sea ice conditions, and the ship limit (RIO) uncertainty – the degree of precision with which ship limitations (RIO) can be measured, assessed, or evaluated. The inter-annual variation of sea ice conditions throughout the Canadian Arctic has been studied ever since Arctic-wide data for the extent of sea ice was first computed in 1979 [29]. This inter-annual variability provides a significant challenge to effective route planning and evaluation in Arctic waters. In response, figure 3 provides a box plot visualization that can be used to examine the impact of sea ice variation (inter-annual) on each of the RIO categories. The variation is expressed in terms of the percentage of the total surface area of a given TC zone associated with a particular RIO category, for each of the 52 weeks of the year. The box plot visualization shown in figure 3 was constructed for an IA vessel operating in TC zone 13, using CIS multi-year sea ice information from 2007 and 2014.
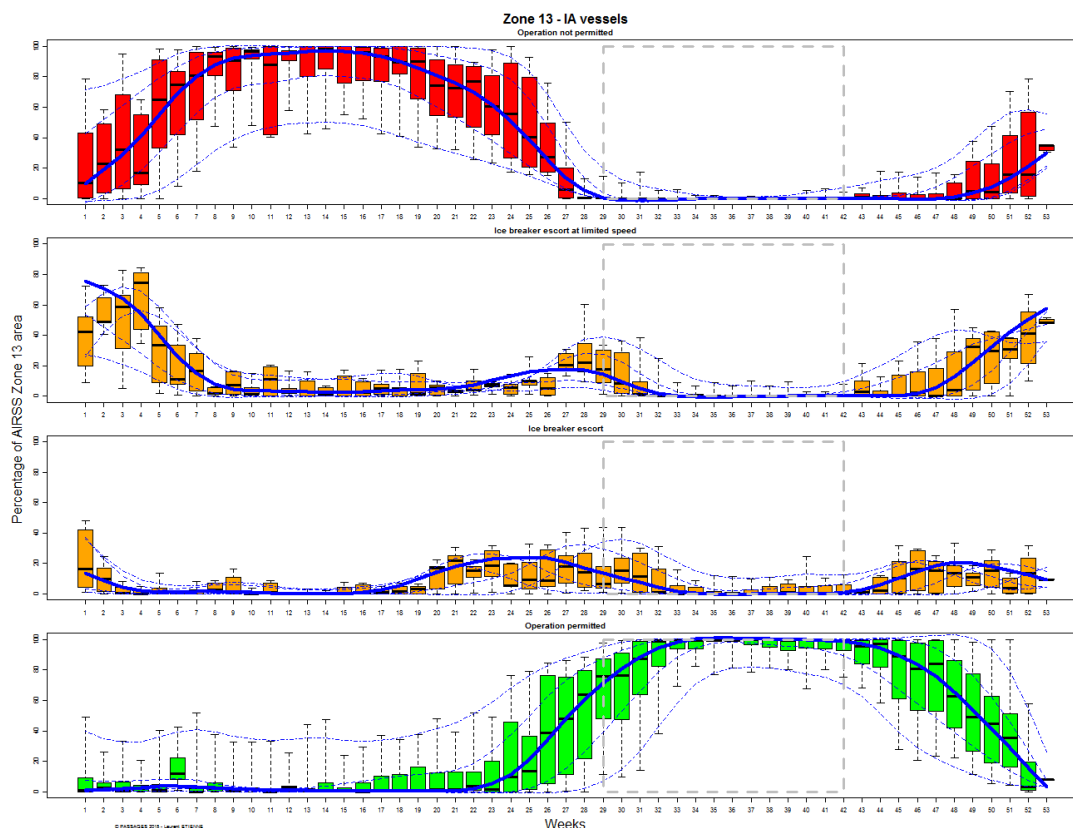
**Figure 3.** Box plot visualization of variability in RIO for Zone 13 using CIS ice information from 2007 - 2014. Interpolation lines are given for the minimum, 1$^{st}$ quartile, mean (thick blue), median, 3$^{rd}$ quartile, and maximum RIO value.

### 3.1.2. Route Evaluation with Near - Real Time Data

When presented with a recently executed or planned route it is possible to assess this route using the ice chart most closely matched in time. The approach can be used to determine the expected impact of ice along a ship route. The resulting POLARIS risk map will highlight areas were unusual kinematic ship behaviour may be observed due to the presence of ice. In figure 4 we show a POLARIS scenario risk map for a particular IA vessel observed operating in the Canadian Arctic during week 30 of 2012. The pink line represents the ships track, as reported by an on-board Global Positioning System (GPS). Using the corresponding 2012 week 30 sea-ice information from the CIS SIGRID-3 ice database we can associate this vessel route with reported ice conditions. Instead of simply displaying the reported ice conditions, we use our knowledge of the vessels polar classification to determine the ships RIO (and associated operational limits in ice) and visualize the result over the entire AOI. Using the resulting visualization, we can associate unusual kinematic behaviour along the executed route with the ship operational limits determined using POLARIS. The two black boxes shown in figure 4 highlight areas along the route where erratic kinematic behaviour was observed, and expected, due to the presence of ice.

## 4. Discussion

In the previous section we illustrated the use of POLARIS to evaluate a route. The significance of this work is that it allows an observer of maritime activity, such as the Canadian Coast Guard, to identify areas along a route where unexpected kinematic behaviour may occur due to the presence of ice. This approach takes in to account the complex interaction of ice type, ice concentration, and ship design
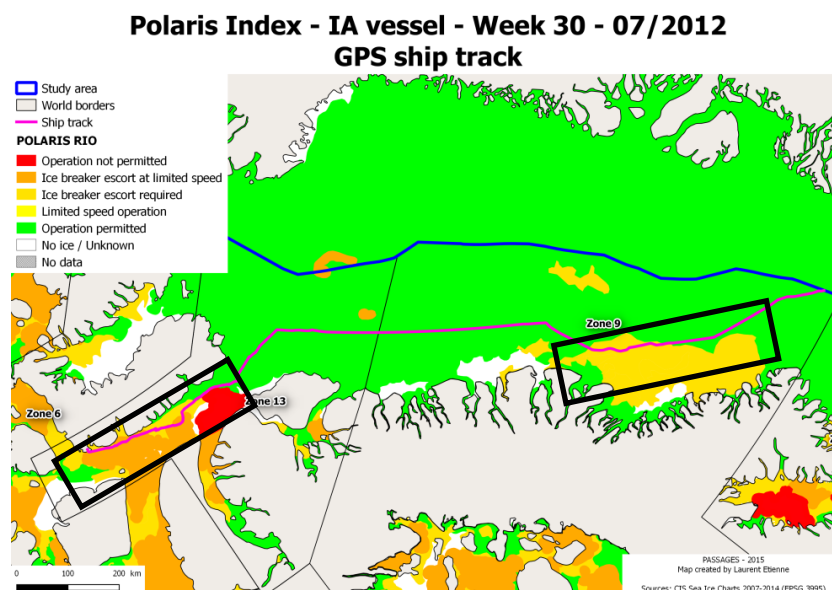
**Figure 4.** POLARIS Scenario risk map for 2012 week 30 for a 1A vessel operating in the Eastern Arctic.

limitations; ultimately providing a rich visualization of ship operational limits. This information can potentially be used to support three functions, (1) monitoring of vessels to ensure they remain safely within their operational limitations in ice, (2) aid in route planning and evaluation using historical ice information, and (3) identification of vessels exhibiting unexpected kinematic behaviour.

## 5. Conclusion

The use of POLARIS with open-access sea-ice information has made it easy to assess and visualize ship operational limits in ice over a large area of interest or along a particular route. The resulting POLARIS scenario risk maps provide a user-friendly visualization of the RIO for a particular polar ship ice classification. We have generated several statistical aggregations of RIO results from 2007 to 2014, supporting a more rigorous assessment of the available historical sea-ice information. We have also shown how using a sea-ice chart that most closely matches a series of observations from an executed route can help make sense of observed vessel kinematic behaviour. The use of the POLARIS scenario risk map in this case allows the user to understand how ice may influence a particular vessel's behaviour.

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