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# Chapter 12

## Making Sense of Marine-Based Search and Rescue Response Time Using Network Analysis



Mark A. Stoddard, Ronald Pelot , Floris Goerlandt ,  
and Laurent Etienne 

**Abstract** Navigation in polar waters follows standard navigational practice, with special consideration for the presence of sea ice and its expected impact on safe ship operation. Experienced polar ship operators rely on timely access to authoritative sea ice analysis and knowledge of the safe operational limits of their ship to determine the navigability of polar waters. Several sea ice risk assessment frameworks exist to assist ship operators with onboard decision-making, most notably, the Polar Operational Limit Assessment Risk Indexing System (POLARIS). The result from POLARIS is referred to as the Risk Index Outcome (RIO). By adjusting ship speed in response to the RIO value, it is possible to account for sea ice risk in the estimation of ship transit time in polar waters. In this chapter we discuss the use of network analysis techniques to generate the fastest route between two locations in the Arctic and to compute surface ship incident response service areas (IRSA) and incident response isochrones (IRI) for different times of year and ship ice classes. The use of IRSA and IRI to support area-based management (ABM) tools that aim to formally incorporate historical observations of shipping activity into quantitative assessments is also discussed. Incorporating IRSA and IRI results into ABM tools would provide decision-makers with a useful tool to possibly help plan and coordinate incident response in polar waters and support ABM of commercial vessel operation and search and rescue provision.

**Keywords** POLARIS · Service area · Isochrone · Network analysis · Optimization

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## 12.1 Introduction

Reductions in sea ice due to climate change continue to affect navigability in the Canadian Arctic and other polar regions (Smith & Stephenson, 2013; Melia et al., 2016). Many of the maritime areas experiencing changes in sea ice conditions are becoming more accessible for longer periods, resulting in increased maritime activity and higher volumes of shipping traffic. As accessibility improves, global interest in Arctic maritime activity from various economic sectors will likely continue to increase (Arctic Council, 2009). Increases in Arctic shipping will put new pressures on the limited infrastructure and services supporting Arctic shipping, especially the search and rescue (SAR) capabilities of many Arctic nations. While Arctic states continue to build infrastructure and response capacity, polar ship operators must continue to demonstrate a high degree of self-reliance and sound decision-making. The International Maritime Organization (IMO) International Code for Ships Operating in Polar Waters (Polar Code, 2014/15) also provides mariners with guidance to reduce operational risks in polar waters via safety and environmental prevention measures (Fedi et al., 2018). Currently, the Polar Code requires that all vessels operating in polar waters be prepared to wait at least 5 days for SAR resources to arrive on scene (Polar Code, 2014/15). The combination of the remoteness of the Canadian Arctic and lack of SAR infrastructure has the potential to push maritime-based SAR response well beyond 5 days, and in some cases the incident location may be inaccessible by available maritime-based SAR assets.

Accessibility in the Arctic can be assessed using navigability and expected ship transit times as proxy indicators. Navigability is commonly determined using risk-based methods to identify go/no-go areas for a particular polar ship class, on the basis of the ice risk present in an area of operations (Mudryk et al., 2021). Ice risk is typically determined by ship bridge watch officers and/or qualified ice navigators using a variety of frameworks developed by transportation authorities and ship classification societies. The Polar Code currently recommends the use of the Polar Operational Limit Assessment Risk Indexing System (POLARIS). A ship operator can use POLARIS to assess the navigability of an area of operation by converting observed sea ice conditions into a Risk Index Outcome (RIO). The RIO result is specific to a ship's polar class (Fedi et al., 2020). The more positive the RIO value, the more navigable the area of operation. POLARIS is already widely used by researchers to support a variety of analyses that involve Arctic navigation and navigability, such as trans-Arctic routing (Melia et al., 2016; Aksenov et al., 2017), economic analysis of polar routes (Lloyds of London, 2014; Smith & Stephenson, 2013), and modelling and simulation of shipping activity (Wei et al., 2020; Wang et al., 2022).

In this chapter we examine how variable sea ice conditions in the Canadian Arctic affect the fastest route between two locations and expected transit time. The method to compute the fastest route between two points in the Arctic accounts for changes in the navigability along a route due to sea ice risk. The method to compute transit time integrates sea ice risk assessment and knowledge of expected ship

speeds in different ice regimes. The result is a transit time estimate that accounts for changes in ship speed due to varying levels of sea ice risk encountered along the route. By combining these two methods, we are now able to compute incident response service areas (IRSA) and incident response isochrones (IRI) for different times of year, different polar class vessels, and locations of interest. IRSA and IRI are analysis tools that are used to determine the reachable areas of a geographic area within a maximum response time cut-off (MRTC). All figures presented in this chapter were produced by the authors.

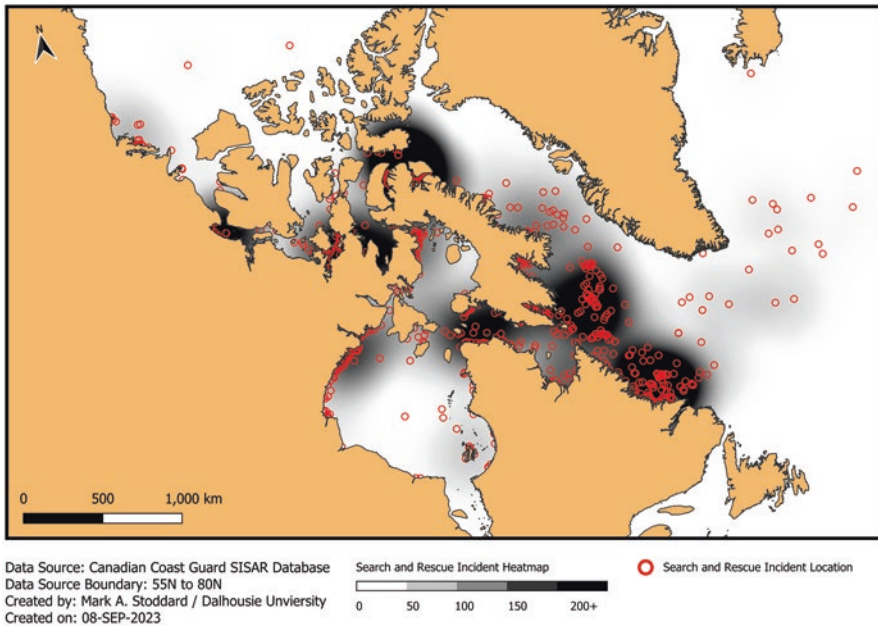
The use of IRSA and IRI simplifies the analysis of expected transit time from an arbitrary location in the Arctic to a point of interest, such as a SAR incident location and coastal community or area-based management (ABM) location of interest. This allows one to quickly assess and visualize many of the complex navigational challenges associated with maritime mobility in Arctic waters, supporting a variety of ABM applications. One focus of the discussion here is on the potential to apply IRSA and IRI concepts to a previous effort conducted by the National Research Council of Canada (NRC) that examined exposure time until recovery at fixed locations in the Arctic (Kennedy et al., 2013). The goals of the NRC study were to identify and assess key factors that influence exposure time and to use the results to strengthen policy and regulations relating to operational requirements and life-saving appliance testing conditions. The discussion here demonstrates how IRSA and IRI concepts could be used to better quantify the potential contribution of vessels of opportunity (VOO) in the analysis of marine-based SAR response.

## 12.2 Theoretical Background

### 12.2.1 Incident Response and Maritime SAR

In Canada, SAR is one of the primary responsibilities of the Canadian Coast Guard (CCG). Through the effective use of dedicated SAR resources, the CCG responds to approximately 6000 maritime incidents per year (DFO, 2022). Following each response operation, incident reports and logs are entered in a database known as the Search and Rescue Program Information Management System (SISAR) (Stoddard & Pelot, 2020). SISAR incident data is one of the primary data sources used to capture statistics relating to maritime SAR cases to inform demand for programme services and the achievement of outcomes (DFO, 2022). SAR incident data provides a rich multivariate spatiotemporal dataset that can support a wide range of analysis. This chapter focuses only on the location of historical maritime incidents to provide a basic understanding of the spatial distribution of historical incident locations in the Canadian Arctic, broadly supporting the ABM objectives of the CCG. Figure 12.1 provides an overview of historical maritime incidents which occurred between 2001 and 2020. Much of the analysis in this chapter is focused on the Baffin Bay region. Baffin Bay was selected for discussion for two reasons: (1) it

### Canadian Arctic Maritime Search and Rescue Incident Response (2001 to 2020)



**Fig. 12.1** Spatial distribution of SISAR incident data collected between 2001 and 2020

is an area of high incident occurrence, and (2) it presents a very challenging navigational environment throughout the year, especially during the yearly sea ice free-up and break-up.

### ***12.2.2 Route Planning and Transit Time Estimation in Variable Sea Ice Conditions***

Navigation risk assessment tools, such as POLARIS, are widely used to assess sea ice risk and determine its impact on safe ship operations (Fedi et al., 2018). The POLARIS assessment can be applied over wide areas using national sea ice analysis charts from the United States National Ice Center (USNIC) and Canadian Ice Service (CIS) to determine the accessibility of maritime locations in the Arctic. Accessibility is a crucial element in incident response operations, especially when considering remote maritime locations that lack supporting infrastructure in the Canadian Arctic. POLARIS is a useful tool to determine the navigability in an intended area of operations, but it does not provide extensive guidance on the selection of safe ship speeds in different RIO categories. The current guidance is limited to recommended ship speeds for polar class ships operating on RIO values between

0 and  $-10$  (IMO, 2014a). No speed recommendations are specified in the POLARIS framework outside of this RIO value range.

Due to the spatial variability of sea ice conditions and the navigational complexity of the Arctic archipelago, standard approaches to calculate travel distance and time, such as Euclidean and Manhattan distance, are not feasible or even practical. One approach is to determine transit distance and time using network analysis methods, relying on the computation of total network distance and travel time along predefined arcs in an undirected graph (Siljander et al., 2015). Several network analysis algorithms exist to compute the shortest/fastest path between a source node and destination node in a graph, such as Dijkstra's shortest path algorithm (Dijkstra, 1959).

Smith and Stephenson (2013) demonstrated the use of network analysis methods to study new trans-Arctic shipping routes. Their method successfully combined the Transport Canada Arctic Ice Regime Shipping System (AIRSS) navigability assessment (similar to the POLARIS methodology) and sea ice data from different coupled atmosphere-ocean general circulation models (GCM) to compute trans-Arctic shipping routes and expected transit times using a terrain sensitive least-cost path algorithm. The optimal route was the route that accumulated the lowest possible travel time between origin and destination along the network arcs. The total transit time is the linear sum of the travel time of each arc in the graph that was traversed (Smith & Stephenson, 2013). Wang, Zhang, and Qian (2018) provide a complementary example of combining AIRSS with GCM outputs, to generate routes in the Arctic using a modified A\* network optimization algorithm. More recently, Wei et al. (2020) generated Arctic shipping routes using a two-step process: (1) calculate the technical accessibility of a grid cell by an ice class ship, and (2) find the fastest route. Technical accessibility of a grid cell was determined using AIRSS with forecasted ice properties (thickness and concentration) from the output of a GCM. The cell-based least-cost path algorithm in a geographical information system was then used to determine the optimal path from origin to destination.

A good estimate of ship speed in different RIO categories is critical to improve the estimation of travel time and related metrics such as fuel consumption and emissions. Much research has been devoted to improving our understanding of the complex relationship between ice conditions, ship design, and operating characteristics. McCallum (1996) provided an early approach to predict expected ship speed in ice using a polynomial fit between minimum and maximum expected ship speeds for several Canadian Arctic Class (CAC) ships in different ice risk regimes. Ice risk was determined using AIRSS. Similarly, Somanathan, Flynn, and Szymanski (2006) also discuss the use of AIRSS to create a relationship between the AIRSS ice numeral and ship ice class to calculate a speed through ice. Kotovirta et al. (2009) examined the use of a mathematical relationship between ship net thrust and ice thickness/resistance. Automatic information systems (AIS) data was used for statistical validation of the transit times calculated by their method. More recently, researchers have begun to directly associate AIS data collected in polar regions with daily sea ice analysis to gain new insight into expected ship speed. Loptien and

Axell (2014) examined the relationship between AIS reported speed over ground and sea ice forecasts in the Baltic Sea to produce a mixed-effects model to predict vessel speed from forecasted ice properties, such as ice concentration, ice thickness, and ridge density. Lensu and Goerlandt (2019) and Goerlandt et al. (2017) provide two more recent examples of combining AIS and sea ice data for the Baltic Sea area to obtain insights in their relationship with operational ship speeds in ice for different types of ship operations. Lastly, Tremblett, Garvin, and Oldford (2021) used shore-based AIS data collected in the North American Great Lakes region between 2010 and 2019 to examine the distribution of observed vessel speeds in different RIO risk categories derived from CIS sea ice charts produced for the Great Lakes region. The authors do caution that POLARIS does not currently provide risk values (RV) for lake ice conditions or provide a mapping of sea ice equivalence, so great care must be taken when interpreting the results from this study.

### ***12.2.3 Service Areas and Isochrones***

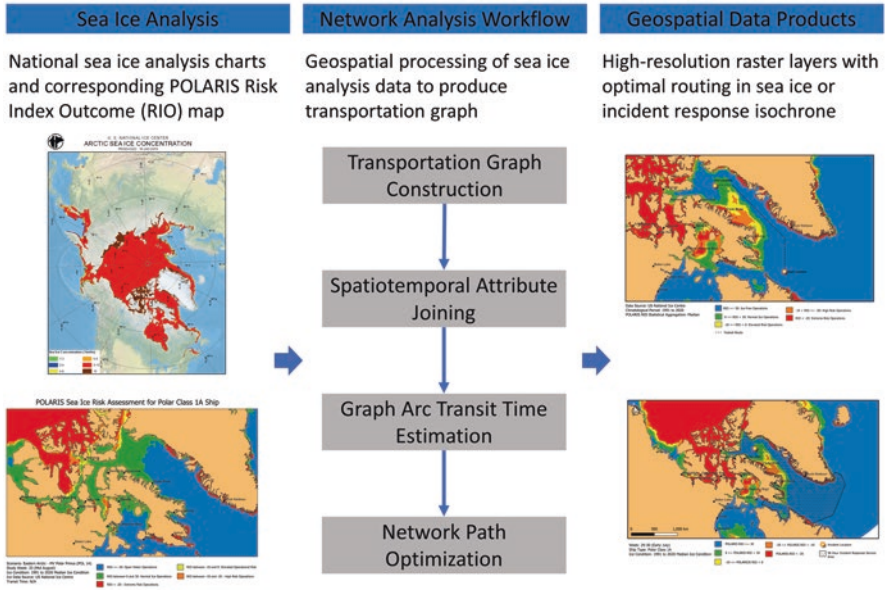
An “isochrone” is defined as the line joining the equal travel time distances from any given location and has been used to understand the relationship between movement and time for more than 130 years (Dovey et al., 2017). A service area is defined as all geographic points within the polygon created by the isochrone. In this chapter we introduce the use of service areas and isochrones to study the relationship between ship movement and transit time in the Arctic. Isochrones and service areas are an effective tool to examine accessibility and mobility simultaneously, which is highly desirable when studying Arctic transportation. Determining the accessibility of and mobility in polar waters is one of the primary motivations for using the POLARIS assessment. POLARIS is used to determine if an area is accessible, meaning it is safely navigable, and to enable risk-based decisions related to safe ship speeds in ice.

The focus here is on the use of service areas and isochrones to better understand marine-based SAR response at different locations in the Arctic and response time cut-offs. Reference is made to service areas as IRSA and isochrones as IRI. IRSA and IRI have several potential uses in support of maritime ABM, but the focus here is on their use for marine-based SAR response in polar waters.

## **12.3 Methods**

In this section we discuss data sources and analysis workflows used to produce the geospatial products presented and discussed throughout this chapter. Bi-weekly sea ice analysis data from the USNIC was used as the basis for the POLARIS calculations discussed here. POLARIS was used to compute and visualize navigational risk, and the expected transit time was determined by combining POLARIS





**Fig. 12.2** Geospatial data processing workflow for producing optimal ship routes in ice and ISRA

RIO results with expected ship speeds in different RIO result categories as reported by Stoddard et al. (2023). Dijkstra’s algorithm was used to perform network optimization and compute the fastest path between two points in a undirected transportation graph. Service area isochrones were produced by computing the concave hull of all nodes in the transportation graph from which an incident location can be reached by the fastest path within a given service level target, specified in hours. Figure 12.2 provides an overview of the geospatial data processing workflow for producing the fastest routes in ice, transit time, and incident response service areas and isochrones.

**12.3.1 Sea Ice Analysis**

Several authoritative sources of sea ice analysis exist, including USNIC, CIS, Danish Meteorological Institute, Icelandic Meteorological Office, and the Norwegian Meteorological Institute. To promote interoperability and data exchange, all national ice centres publish sea ice charts in a standard World Meteorological Organization (WMO) ice chart archive vector format known as Sea Ice Grid (SIGRID-3) (NSIDC, 2022). Operational sea ice charts show ice regimes as distinct polygons within a mapped region. An ice regime is defined as an area with a relatively consistent distribution of any mix of ice types, including open water. Ice analysts working for national ice centres have access to a variety of high-resolution data



sources to estimate the partial ice concentrations of various ice types in an ice regime and encode the information according to a WMO standard (IOC/UNESCO, 2004).

Bi-weekly sea ice charts for the Arctic from the USNIC were selected for this study because of their circumpolar coverage and historical date coverage range. USNIC sea ice charts are produced through a detailed analysis of available in situ remote sensing and model data sources. The USNIC digital ice analysis charts (hemispheric, regional, and daily) have two main components: the shapefile containing the ice analysis ice information (ice polygons and related attributes) and the metadata describing the ice analysis data (NSIDC, 2015). Both components of the USNIC sea ice charts were used in this study.

### 12.3.2 Navigational Risk Assessment in Polar Waters Using POLARIS

POLARIS provides a quantitative framework to assess navigational risk in polar waters. Each polygon in a USNIC sea ice analysis chart is used to describe an area with a relatively consistent distribution of one or more ice types and may include open water. The concentration of each ice type (determined by observed stage of development and thickness) is reported in tenths. POLARIS specifies a RV for each ice type and polar class ship type. The output of the POLARIS assessment is referred to as RIO. The RIO is determined by calculating the linear sum of the RVs associated with each ice type present in a given ice polygon, multiplied by the respective ice type concentration (in tenths):

$$RIO = C_1RV_1 + C_2RV_2 + \dots + C_nRV_n \tag{12.1}$$

where  $C_1, C_2, \dots, C_n$  are the concentrations of the ice types present in an ice regime and  $RV_1, RV_2, \dots, RV_n$  are the risk values provided by POLARIS. The RIO value is then evaluated, and a series of decision rules are applied to determine an appropriate operational limitation due to the presence of sea ice in the area of operation (IMO, 2014b). The decision rules applied in this study are shown below in Table 12.1.

It is possible to use POLARIS to compute and visualize the RIO for each polygon in the USNIC sea ice analysis chart for a chosen POLARIS scenario. The

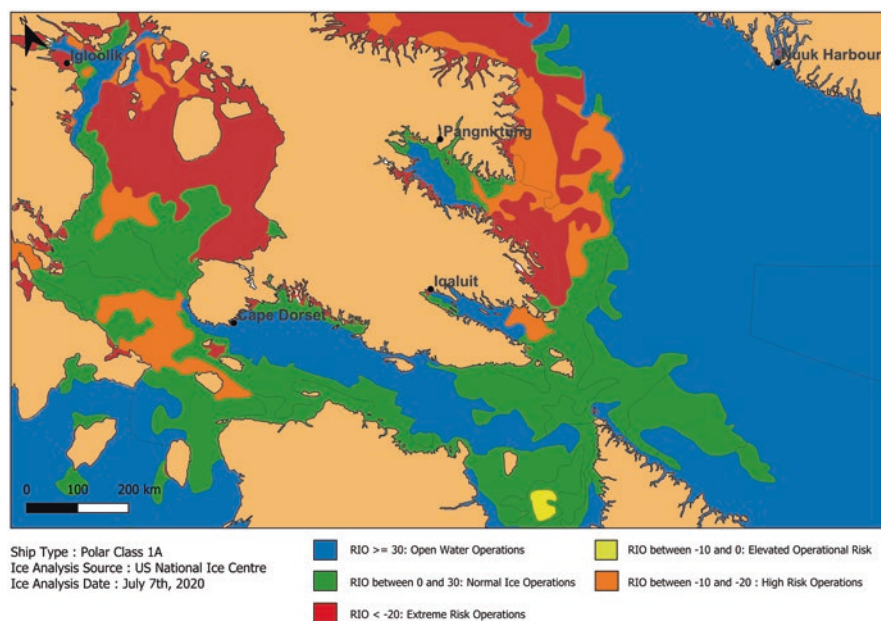
**Table 12.1** POLARIS RIO results decision rules and associated risk level descriptions used for this study

Decision rule	Risk level
$RIO > = 30$	Open water operations
$0 < = RIO < 30$	Normal ice operations
$-10 < = RIO < 0$	Elevated operational risk
$-20 < = RIO < -10$	High risk operations
$RIO < -20$	Extreme risk operations

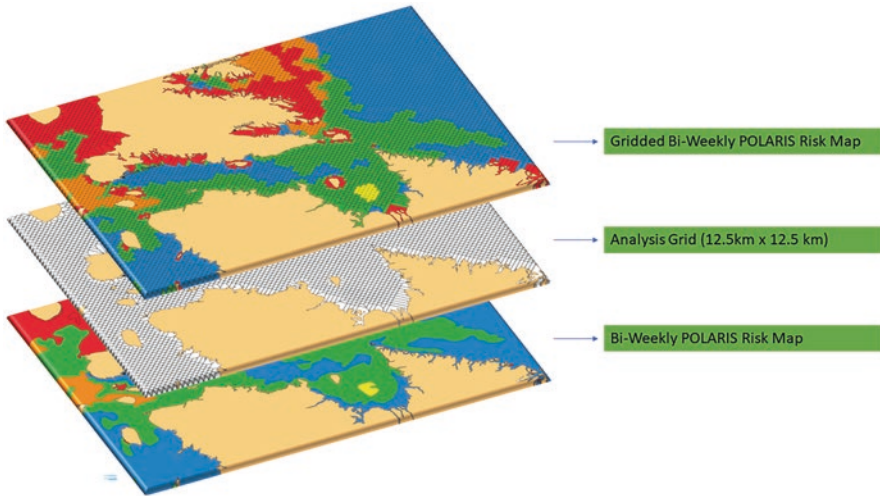
POLARIS scenario refers to the selection of ship polar class and the decision rule used to determine the different RIO result categories. The result is a new sea ice analysis product we refer to as the single chart POLARIS scenario risk map. A POLARIS scenario risk map is unique to each polar class ship type and selection of decision rule. Figure 12.3 provides an example of a POLARIS scenario map for a Polar Class 1A ship.

For strategic navigation planning, it is often necessary to plan routes based on the ice conditions expected to be encountered during a future voyage. Stoddard et al. (2016) demonstrated how statistical aggregations of historical POLARIS RIO results can be used to support strategic navigation planning in polar waters. Using gridded CIS daily sea ice analysis charts from 2007 to 2014, the authors computed six statistical aggregations of historical RIO results throughout the Canadian Arctic including (1) minimum RIO, (2) 25th percentile RIO, (3) average RIO, (4) median RIO, (5) 75th percentile, and (6) maximum RIO.

This study focuses on the use of gridded USNIC bi-weekly sea ice analysis charts that cover the climatological period from 1991 to 2020 to compute the median POLARIS RIO value. In total, 1295 USNIC bi-weekly sea ice analysis charts were first gridded, resulting in 4,212,296 georeferenced grid cells containing the sea ice analysis attributes from each chart. The median RIO value for each grid cell was then computed on a bi-weekly basis, resulting in a final output of 26 gridded bi-weekly POLARIS scenario risk maps. Figure 12.4 shows how the features of the



**Fig. 12.3** Single chart POLARIS risk map for a Polar Class 1A ship operating in the eastern Arctic on 7 July 2020



**Fig. 12.4** Geospatial processing of map layers to generate the gridded bi-weekly POLARIS scenario risk map (top layer)

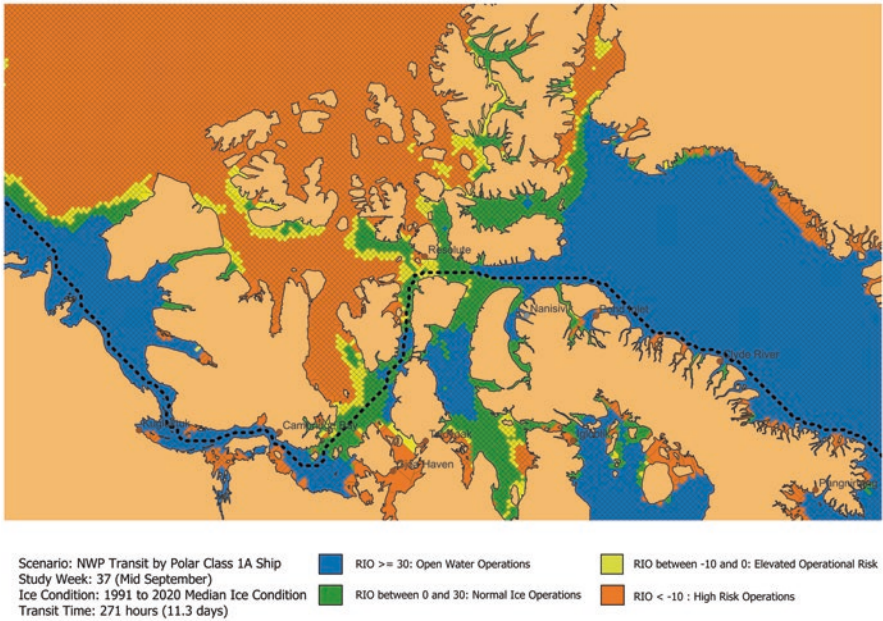
bi-weekly POLARIS scenario risk map are spatially joined with the analysis grid to produce the gridded bi-weekly POLARIS scenario risk map. This process is repeated for all USNIC bi-weekly sea ice analysis charts produced within the climatological period, and then a median RIO value is computed for each grid cell.

### 12.3.3 *Transportation Graph and Transit Time Estimation*

In order to utilize network optimization algorithms to compute the fastest route through an area of operations, we constructed an undirected graph for each bi-weekly analysis period, consisting of 137,494 nodes and 1,099,952 arcs. A node was created at the centroid of each grid cell in our analysis grid, with each node inheriting the sea ice analysis and POLARIS RIO attributes from the associated grid cell. Arcs were created by connecting adjacent nodes by straight line segments. The RIO value for each arc was computed by averaging the RIO value of the start and end node. The transit time for each arc was determined by dividing the arc length (km) by the expected ship speed in each RIO category (km/h). The ship speeds shown in Table 12.2 were first reported by Stoddard et al. (2023) and were derived from the visual inspection of a histogram of AIS reported vessel speed over ground in different RIO result categories observed over a 2-year period. Since the speed is specified based on the RIO result category, it is not necessary to consider the polar class of vessel when determining the appropriate ship speed along an arc. This is because the polar class of the vessel is already considered when computing the RIO value for each polar ship ice class. The fastest path is therefore the path from a start

**Table 12.2** Ship speed versus RIO category

RIO category	Ship speed (km/h)	Ship speed (kts)
RIO >= 30	26	14
0 <= RIO < 30	16	8.5
-10 <= RIO < 0	9	5
-20 <= RIO < -10	5.5	3
RIO < -20	0	0

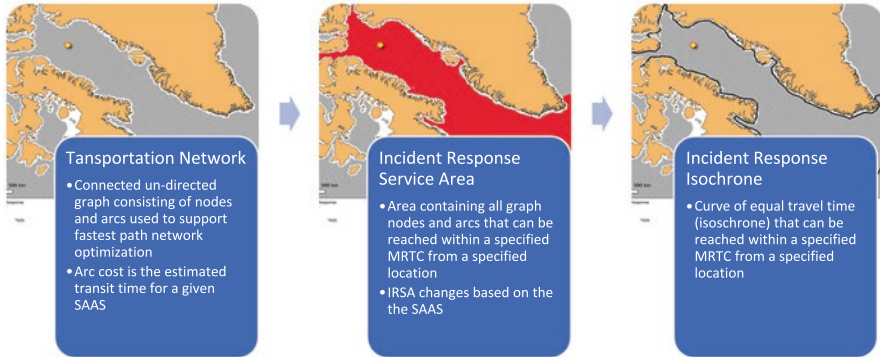


**Fig. 12.5** Segment of a computer-generated trans-Arctic route from Southwest Greenland to Chukchi Sea, Alaska, for a Polar Class 1A ship in week 37 using the expected ship speed in the median RIO value observed over the climatological period from 1991 to 2020

location to an end location that minimizes the total transportation cost (total transit time).

To compute the fastest path between two points in our network, we utilized the QGIS software implementation of Dijkstra’s algorithm (Dijkstra, 1959). The fastest path is the selection of arcs in the graph that minimizes the total transit time, computed by summing the transit cost of all selected arcs that form the path from start to end location. Figure 12.5 shows a computer-generated fastest route through the Canadian Arctic archipelago. This route represents the fastest route for a Polar Class 1A ship in week 37–38 (mid-September) using the 1991–2020 median RIO value.

In addition to computing the fastest path, we are also interested in computing IRSA and IRI in the Canadian Arctic. To simplify the following discussion, we first introduce the concept of the service area analysis scenario (SAAS). The SAAS



**Fig. 12.6** Relationship between transportation network, incident response service area, and incident response isochrone

refers to the selection of (1) polar class ship type, (2) analysis time period, (3) RIO value statistic, (4) expected ship speed in each RIO result category, (5) MRTC, and (6) a specified geographic location of interest. The IRSA contains all the nodes and arcs of the transportation network that can be reached for a given SAAS. The IRI is a curve of equal travel time (isochrone) formed at the furthest locations in the network that can be reached for given SAAS. Mathematically, the IRSA is the concave hull formed from all nodes in the transportation graph that can be reached within the specified time cut-off. Figure 12.6 illustrates the relationship between the transportation graph, incident response service area, and incident response isochrone.

The methods discussed here are applied below to examine several different aspects of incident response in the Baffin Bay region of the Eastern Arctic. The emphasis will be on generating results that can help guide discussion related to incident response in polar waters, as well as introducing the concept of ISRA and IRI to support SAR response operations and ABM more generally. While the results shown below are focused on a notional incident in Baffin Bay, the methods are applicable throughout the Arctic region. Computational results have been produced for a variety of polar class ships, bi-weekly analysis periods, and MRTC to help draw attention to the factors that influence ISRA and IRI and their interpretation.

## 12.4 Results

In this section we apply the methods discussed above to examine incident response in the eastern Arctic. All results were produced using the same incident location (central Baffin Bay) to simplify the comparison of results and follow-on discussion. All POLARIS risk maps, ISRA, and IRI have been computed for an International Association of Classification Societies (IACS) Polar Class 1A ship, with some exceptions for the comparison of modelling results for different ship classes. The



1A ship ice class was chosen because it is one of the most common ship ice classes found operating in the Canadian Arctic during the navigable summer season. In practice, the methods discussed in the previous section, and shown in this section, can be produced for any incident location, time of year, ship ice class, and selection of RIO value summary statistic. The three primary results presented and discussed in this section include:

1. Fastest route in polar waters
2. Incident response service areas
3. Incident response isochrones

### ***12.4.1 Fastest Route in Polar Waters***

The fastest path is the route that minimizes the total transit time from a start node to an end node in our Arctic transportation graph. Figure 12.7 provides an overview of the fastest route between a start and end location in the eastern Arctic for a Polar Class 1A ship during each bi-weekly analysis period. The 1991–2020 median RIO value was used to assess the navigational risk throughout the year. The figure shows how the route and the corresponding transit time change throughout the year depending on the POLARIS RIO results at the time of operation. We also observe that for a significant portion of the year, there is no feasible route for a Polar Class 1A ship between the start and end location due to the severity of the sea ice conditions. This would indicate that the severity of sea ice conditions exceeds the safe operating limits of a Polar Class 1A ship during that time.

It is also possible to compare expected transit time results for different polar ship classes. In Fig. 12.8 we compare the year-round estimated transit time for a Polar Class 1A and Polar Class PC5 ship using a multi-line plot. For awareness, a Polar Class 1A is capable of summer/autumn operation in thin first-year ice (ice thickness from 30 to 70 cm), while a Polar Class PC5 is capable of year-round operation in medium first-year ice (ice thickness from 70 to 120 cm). The enhanced ice operating capabilities of the PC5 vessel allow it to operate safely over a much wider range of sea ice conditions than a 1A vessel. The result is twofold: (1) a PC5 vessel can typically operate at higher speed when sea ice is present when compared to a 1A vessel, and (2) a PC5 vessel has a longer operating season when compared to a 1A vessel.

Using the start and end location from the eastern Arctic transit scenario shown in Fig. 12.7, we computed the fastest route and expected transit for Polar Class 1A and PC5. Figure 12.8 shows the expected transit time results as a multi-line plot. For a large portion of the year, there is no feasible route between the start and end location for the Polar Class 1A vessel, that is, starting in late January/early February (week 5) and ending in late June (week 25). Periods where no feasible route exists appear as areas of discontinuity in the line plot. Notable observations from the comparison of Polar Class 1A and PC5 vessels are summarized in Table 12.3.

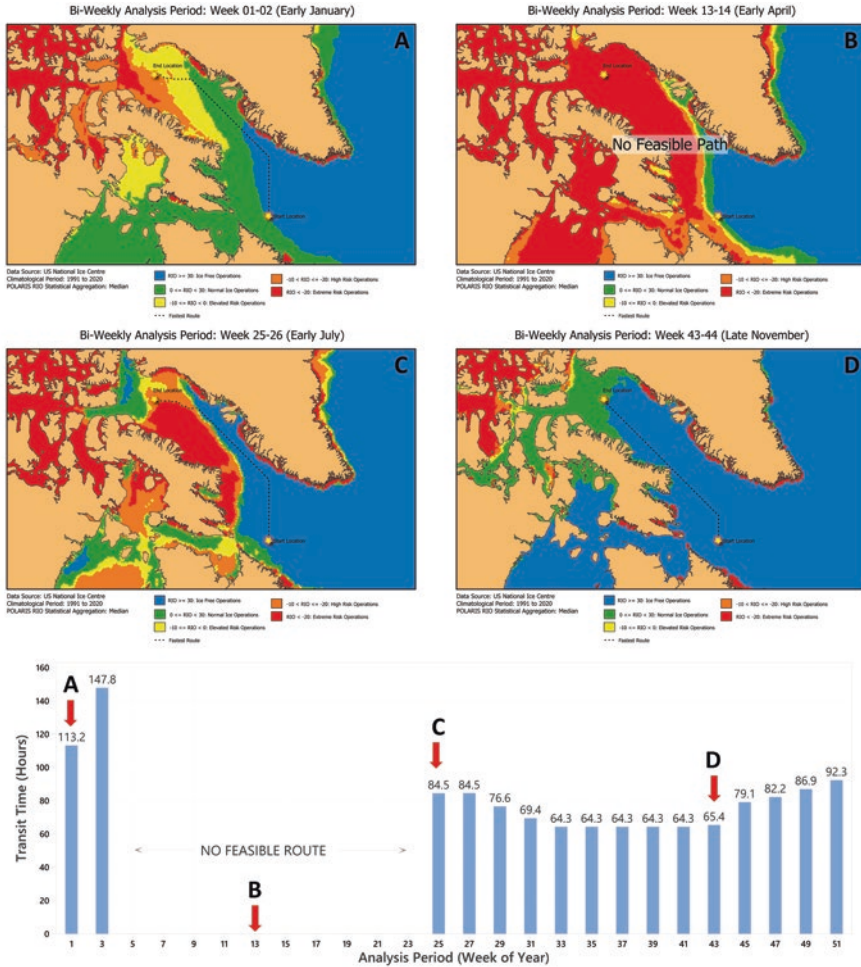
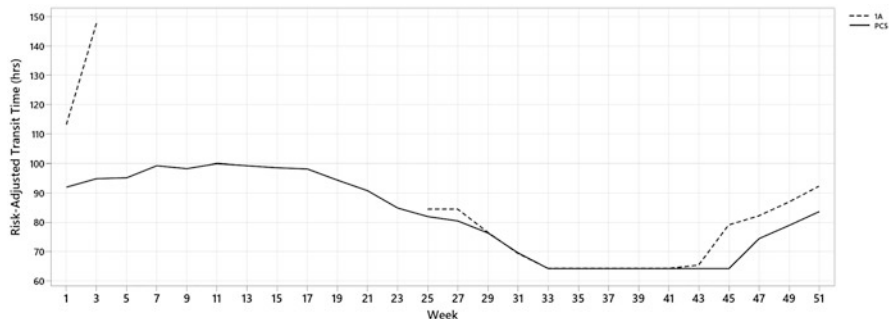


Fig. 12.7 Overview of the fastest route and expected transit time between two locations in the Arctic

### 12.4.2 Incident Response Service Area and POLARIS

Now that we can compute the fastest path between any start and end nodes in the Arctic transportation network, it is possible to compute the IRSA. The IRSA shown in Fig. 12.9 was generated for a Polar Class 1A ship operating in the eastern Arctic during week 29–30 using a 96-hour MRTC. The IRSA can be interpreted as containing all possible start nodes in the graph that can reach the incident location (end node) within the specified MRTC. The MRTC used for the analysis in this section is 96 hours. Figure 12.10 shows how the IRSA size changes throughout the year as the RIO changes due to varying sea ice conditions throughout the year. Other factors

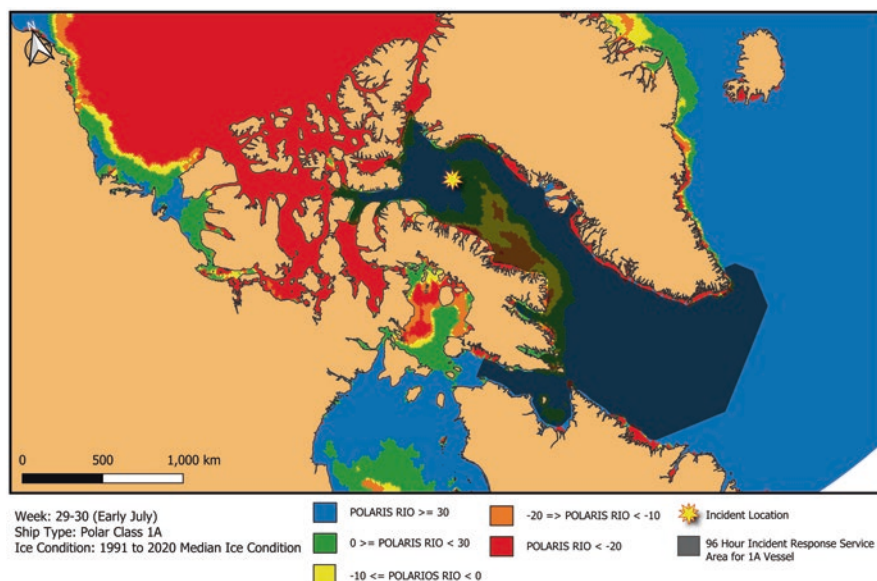




**Fig. 12.8** Comparison of the year-round risk-adjusted transit time for a Polar Class 1A and PC5 ship between a start and end location in the eastern Arctic. Note: When no feasible route exists, the line is not drawn for that particular ship class

**Table 12.3** Summary of year-round risk-adjusted transit time results for Polar Class 1A and PC5

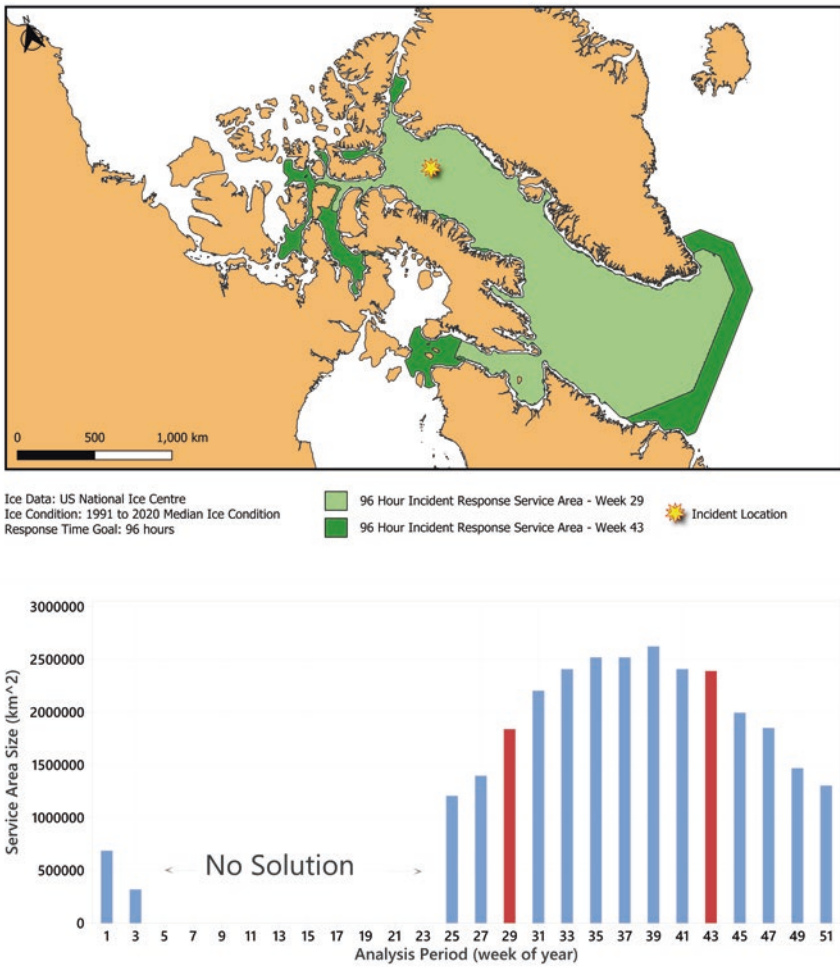
	Polar Class 1A	Polar Class PC5
No feasible route (weeks)	5–25	N/A
Maximum expected transit time (hours)	147.8	100.0
Maximum expected transit time (week(s) of occurrence)	3	11
Minimum expected transit time (hours)	64.3	64.3
Minimum expected transit time (week(s) of occurrence)	33–41	33–45



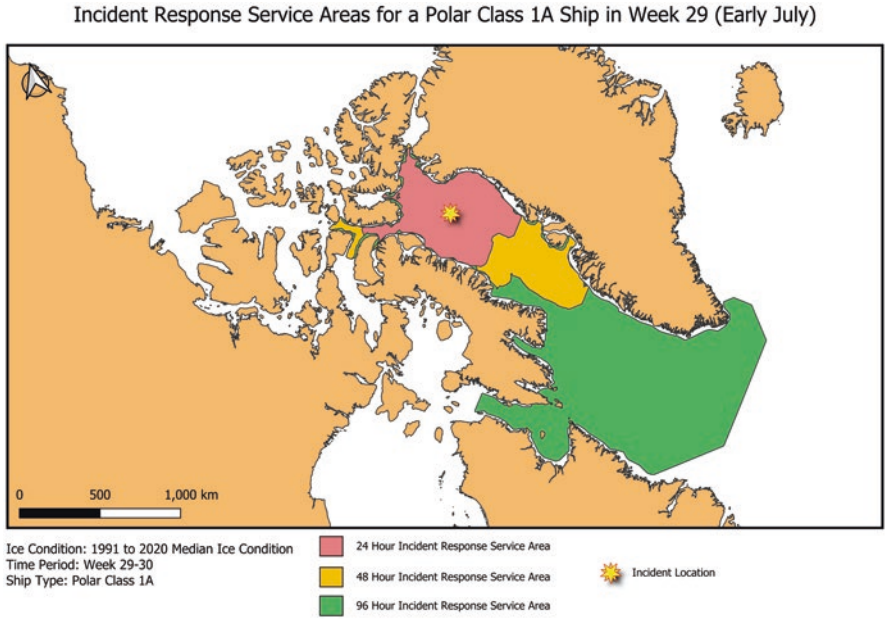
**Fig. 12.9** Computed service area for a Polar Class 1A ship in week 29–30

that influence service area size are the MRTC (see Fig. 12.11) and ship ice class (see Fig. 12.12).

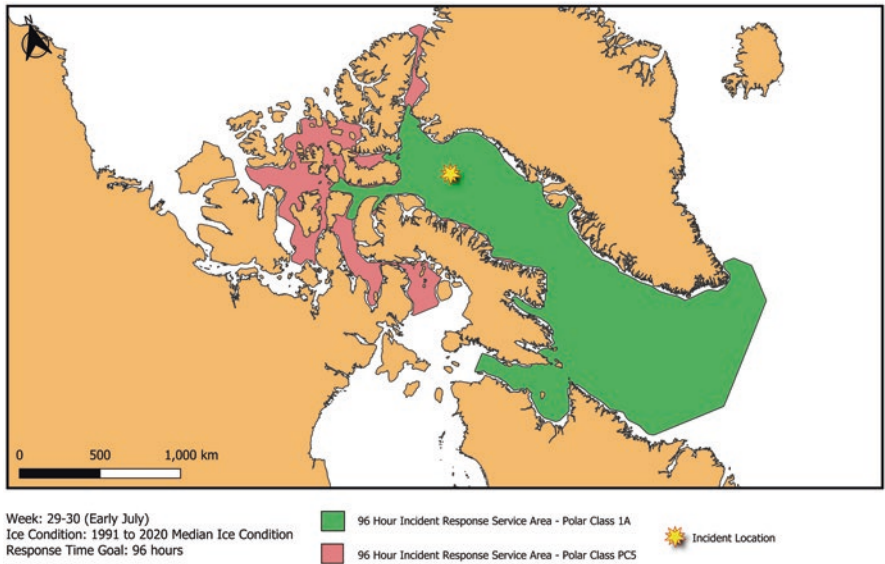
Sometimes it might be more convenient to visualize the MRTC isoline, which is referred to in this study as the IRI. This is the isoline formed around the maximum extent of the service area. The travel time from any arbitrary point on the isochrone to the incident location is equal to the MRTC. Figure 12.13 compares the 96-hour incident response isochrone for a Polar Class 1A and PC5 ship in week 29–30.



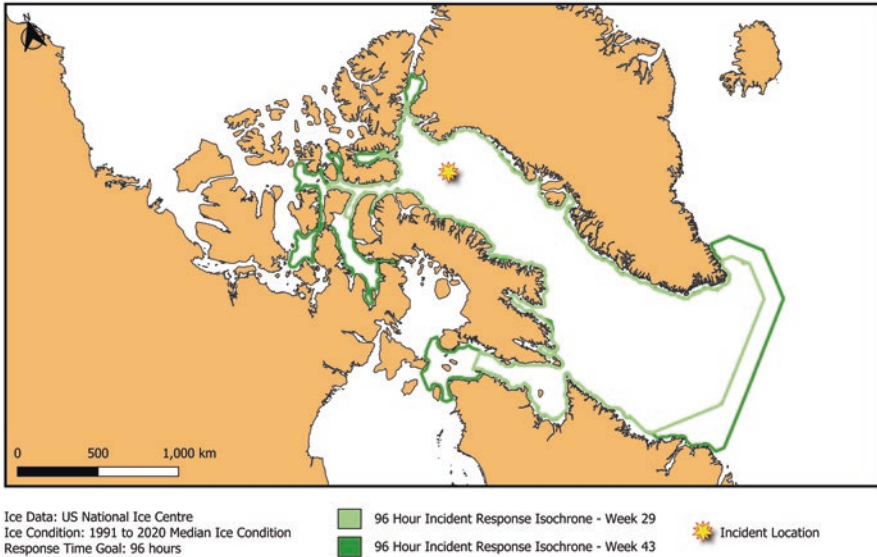
**Fig. 12.10** Comparison of geographic size of the IRSA for a Polar Class 1A vessel throughout the year for a given SAAS



**Fig. 12.11** Comparison of the IRSA size for a Polar Class 1A ship in week 29–30 for 24-hour, 48-hour, and 96-hour MRTC



**Fig. 12.12** Comparison of the IRSA for a Polar Class 1A and PC5 ship in week 29–30



**Fig. 12.13** Comparison of 96-hour IRI for a Polar Class 1A in week 29 and week 43

## 12.5 Discussion

The application of traditional network analysis methods to compute optimal routes in polar waters has resulted in several useful analytics and metrics with potential to support quantitative studies related to incident response and ABM in the Canadian Arctic. Our approach integrates sea ice analysis, navigation risk assessment, and network optimization to compute the expected transit time between two points in polar waters. Once computed, the expected transit time provides an objective measure to examine surface ship incident response in polar waters. The results indicate that incident response times are heavily influenced by the geographic location of the incident and responding vessel, time of year, sea ice conditions, and the ship ice class of the vessel responding to the incident.

The complex geography and variable sea ice conditions found in the Canadian Arctic archipelago are significant contributors to the spatiotemporal variability of emergency response time and overall maritime mobility. The remoteness of the Canadian Arctic and lack of infrastructure affect the timeliness of SAR response, especially maritime-based SAR response. Ships must be prepared to wait days before maritime-based SAR resources arrive at the incident location. Currently, and as mentioned above, the Polar Code requires that all vessels operating in polar waters be prepared to wait at least 5 days for SAR resources to arrive on scene (Polar Code, 2014/15). The National Research Council of Canada has previously evaluated the expected time until recovery for several geographic locations in the Arctic (Kennedy et al., 2013). The NRC study examined emergency response at eight locations dispersed throughout northern Canada but was limited to two

hypothetical emergency scenarios, namely, (1) mild August environmental conditions and (2) severe August environmental conditions.

Figure 12.14 shows the location of the NRC maximum exposure evaluation sites overlaid on the SISAR incident data discussed above. The geographical locations selected by NRC were based on a number of considerations. The first was to ensure that locations were selected throughout the Canadian Arctic in order to provide results that cover the vastness of the region. The second consideration involved the frequency of travel based on current shipping routes and maritime traffic and expected future shipping activity. The third consideration was to ensure the selected locations were positioned at varying distances from existing infrastructure, such as airports, communities, and ports. A future examination of maximum exposure time could also consider using the location of historical SISAR incidents in the site selection process.

The use of IRSA and IRI to quantify and visualize the expected transit time for marine-based assets would be another possible extension to the NRC study of maximum exposure time in the Arctic. This additional analysis would allow for a greater consideration of the spatiotemporal variability of expected response time for marine-based SAR assets throughout the year. The use of IRSA and IRI computed on a bi-weekly basis would allow for a more complete analysis of expected transit time for marine-based response assets throughout the year and its impact on expected exposure time. Figure 12.15 shows the week 33 (mid-August) 12-hour, 24-hour, and 48-hour IRSA for a selected NRC maximum exposure evaluation site.

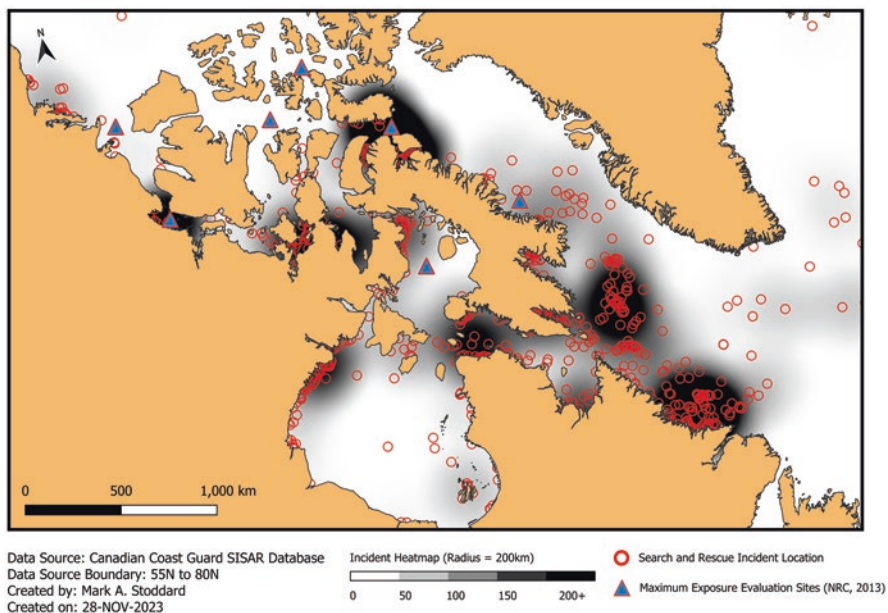
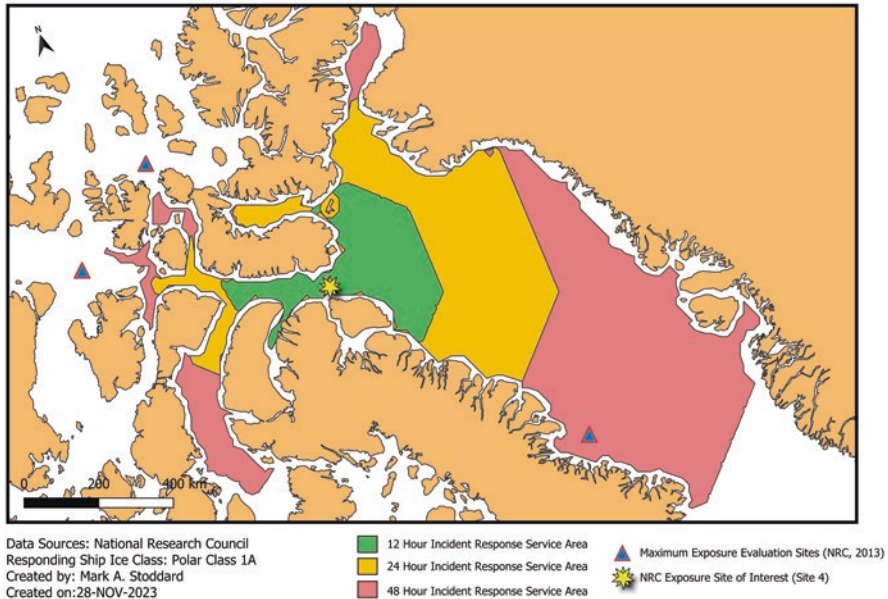


Fig. 12.14 SISAR incident data from 2001 to 2020 with an overlay of the NRC maximum exposure time evaluation sites

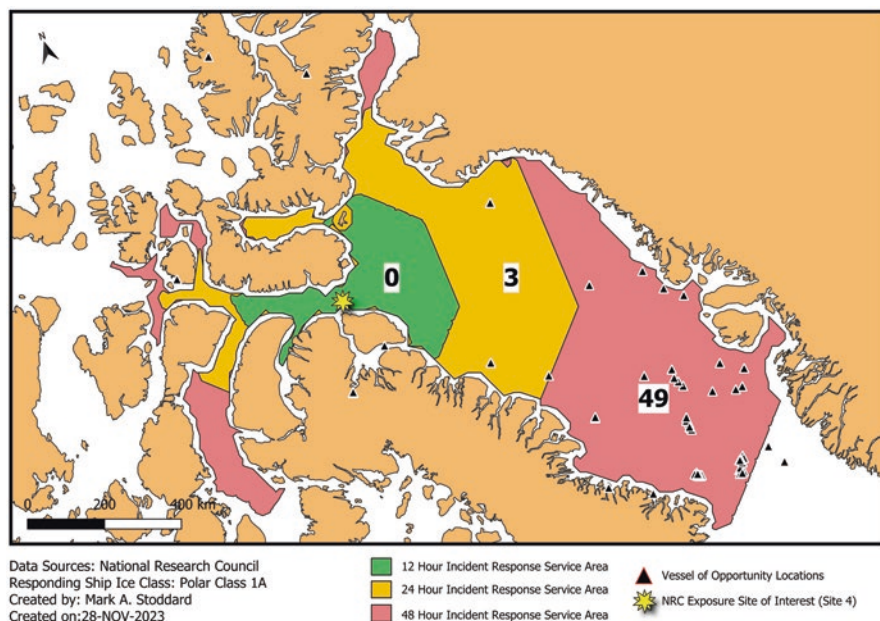




**Fig. 12.15** 12-hour, 24-hour, and 48-hour IRSA for a Polar Class 1A vessel operating in week 33 assuming 1990–2021 median RIO value for week 33–34

The results provide a convenient method to visualize the expected transit time for a Polar Class 1A vessel to reach the NRC evaluation site. A vessel located anywhere in a given IRSA polygon would be able to reach the location of interest within the associated time cut-off.

More specifically, the IRSA and IRI concepts could be used to extend the study results for marine-based SAR response to more formally consider the contribution of VOO in their analysis. This additional analysis would not require a significant change in the study methodology. This could be achieved by combining the analysis of historical shipping activity data (polar class ship type, time, and location) and IRSA results to determine the probability of a VOO being available and able to respond to an incident within the specified time cut-offs. This approach could also support a wide variety of ABM tools that aim to incorporate historical shipping activity into the overall assessment of marine-based SAR response for pre-selected evaluation sites in the Canadian Arctic. Figure 12.16 provides an example of how observations of shipping activity can be combined with IRSA to begin to quantify the expected contribution of VOO to incident response and maximum exposure time. In this case, we see that no VOO can reach the evaluation site within 12 hours, three VOO can reach the site within 12–24 hours, and 49 VOO can reach the site within 24–48 hours. The location and number of VOO shown in Fig. 12.16 are representative of a single instant in time. By analysing shipping traffic data over multiple years, it would be possible to statistically characterize VOO availability to support this form of analysis.



**Fig. 12.16** 12-hour, 24-hour, and 48-hour IRSA for a Polar Class 1A vessel operating in week 33, with an example overlay of vessel of opportunity locations and total vessel counts in each IRSA

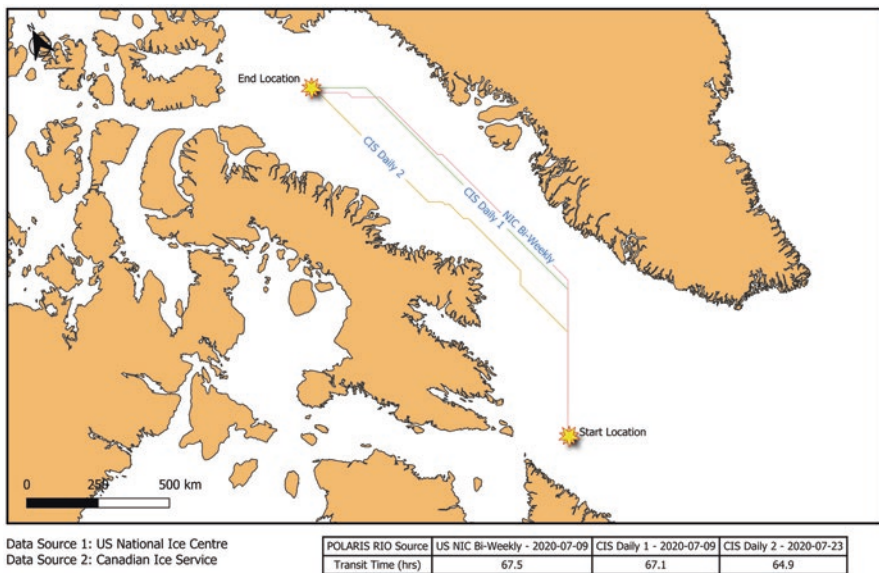
Two major limitations of our approach to analysing incident response using IRSA and IRI are (1) the temporal resolution of sea ice analysis and (2) the use of bi-weekly median RIO values over the 1991–2020 climatological period for route generation and transit time estimation. Our method relies on the use of bi-weekly sea ice analysis from the USNIC to assess navigational risk. The consequence of relying on bi-weekly sea ice analysis is that all subsequent analysis products derived from this sea ice analysis must also be produced on a bi-weekly basis to avoid over-resolving the data. It also means that our network optimization model assumes that sea ice conditions do not change over a 2-week period. For short voyages this should not create much concern, but when examining trans-Arctic routes that could exceed 10+ days, it may seem unreasonable to assume sea ice condition will remain static during voyage execution. Special consideration should also be given to voyages planned during the periods of seasonal break-up and freeze-up, when ice conditions can change dramatically over even a few weeks. This issue is less of a concern when conducting strategic planning but is of greater concern at the tactical ship operations level. Secondly, the use of the climatological median RIO value in our analysis will limit the usefulness of our results for tactical applications.



### 12.5.1 Temporal Resolution of Sea Ice Analysis

Currently, the USNIC is the only authoritative source of detailed characterizations of sea ice that provide circumpolar coverage of the Arctic and Antarctic regions. The USNIC takes imagery and ancillary data from a variety of space-based and terrestrial sensor systems, such as synthetic aperture radar and passive microwave, to produce detailed characterizations of ice concentration, ice type, and general ice thickness. Once the ice analysis is complete, numerous products are created and provided open access to a very broad user community. USNIC sea ice analysis products are grouped by region and produced for different time periods, depending on the nature of analysis contained in the product. The USNIC product relied on for this study is the Arctic Sea Ice GIS shapefile, which is produced bi-weekly. This product has the desired coverage area and sea ice analysis attribute data to compute POLARIS RIO values throughout the Arctic.

While suitable for strategic navigation assessment, it may be more desirable to assess navigational risk using a daily product for tactical navigation assessment. The use of daily sea ice analysis products in our network analysis would make the fastest path optimization and transit time estimation results more applicable at the tactical level. Figure 12.17 compares the fastest path and transit time results using USNIC bi-weekly sea ice analysis and CIS daily sea ice analysis produced at the start and end of the bi-weekly analysis period. There is good agreement between the



**Fig. 12.17** Comparison of fastest route and transit time using the USNIC bi-weekly ice chart issued on 9 July 2020 and the CIS daily ice chart issued at the start and end of the USNIC bi-weekly analysis period (9 and 23 July 2020)

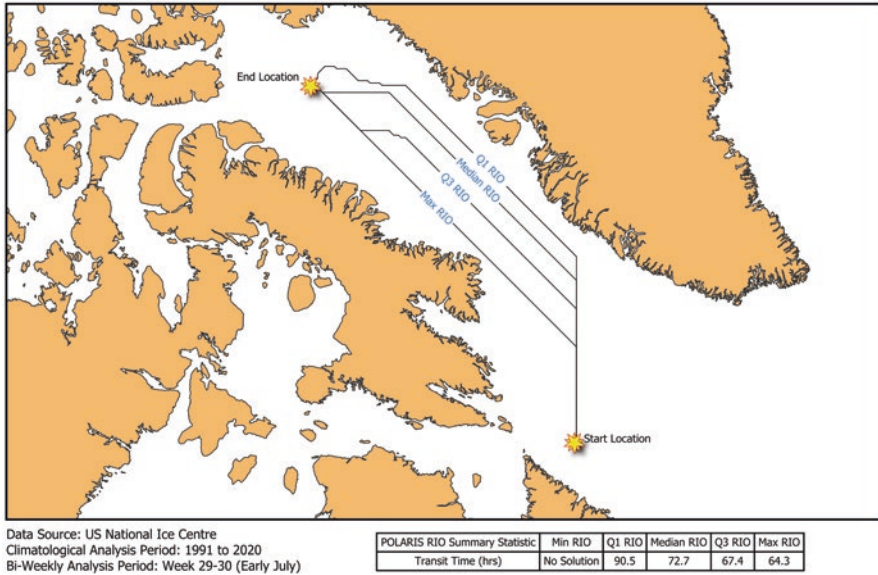
fastest route and transit time produced from the USNIC and CIS sea ice analysis products at the beginning of the bi-weekly analysis period. When we compare the results using the same USNIC bi-weekly chart and a CIS daily product issued towards the end of the USNIC bi-weekly period, we start to observe significant differences between the fastest route and transit time. It should be noted that ice conditions are known to change rapidly in the June/July timeframe, so we would expect the greatest differences between the use of bi-weekly and daily products to be observed during the yearly sea ice break-up and freeze-up periods.

### *12.5.2 Use of Climatological Period Summary Statistics*

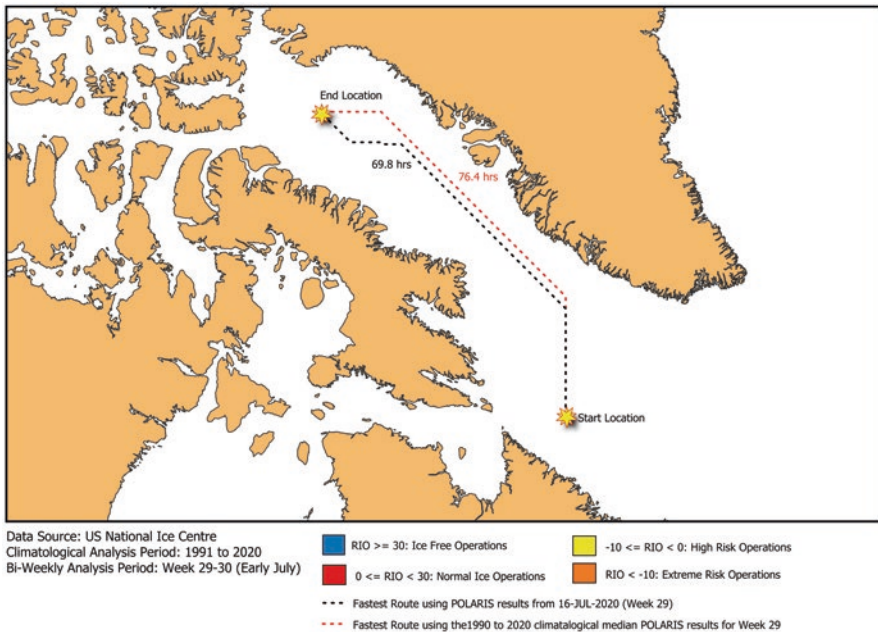
For strategic planning, it is often necessary to plan voyages based on the ice conditions expected to be encountered during a planned voyage. The selection of the appropriate sea ice analysis to use for strategic planning is a difficult task and often relies on expert judgement and the selection of sea ice analysis from similar years. Our analysis has so far relied on the use of summary statistics of historical POLARIS RIO values over a given climatological period to support strategic planning. There are two commonly used 30-year climatology periods used for strategic sea ice analysis, namely, 1981–2010 and 1991–2020. The USNIC moved to a baseline period of 1981–2010 starting 1 July 2013 (NSIDC, 2013). The CIS have adopted a different approach, updating their 30-year ice climate normal every 10 years, with the current period being 1991–2020.

In this study we have chosen to use the 1991–2020 climatological period when examining historical sea ice conditions and their expected impact on polar ship operations. The results focus on the 1991–2020 median RIO value when assessing sea ice risk and its impact on ship routing, transit time, and incident response service areas. The other statistical aggregations that have been computed for our study area include (1) minimum RIO value, (2) first quartile RIO value, (3) mean RIO value, (4) third quartile RIO value, and (5) maximum RIO value. Future studies could compare ship routing and transit time results using different statistical aggregations of POLARIS RIO values to better understand the impact this has on route generation and transit time.

The selection of RIO value affects both the fastest route optimization and expected transit time. When selecting the maximum RIO value (most positive), the resulting optimal route is expected to be the most direct route possible between the start and end location, achieving the minimum expected transit time. One would also expect this voyage to also have the highest average ship speed. Figure 12.18 shows the fastest route and transit time computed using different statistical aggregations of historical RIO values observed over the climatological period from 1991 to 2020. Figure 12.18 shows the spatial variability in the fastest route and transit time based on the selected RIO value statistic. The maximum RIO corresponds to the highest RIO value observed during the climatological period, representing the most favourable operating conditions observed.



**Fig. 12.18** Comparison of fastest route and transit time using different statistical aggregations of historical RIO values observed over the climatological period from 1991 to 2020



**Fig. 12.19** Comparison of risk-adjusted transit time between two points in the eastern Arctic using the 1991–2020 climatological median POLARIS RIO and the POLARIS RIO from a single USNIC sea ice chart for the same bi-weekly period

Figure 12.19 compares the fastest route between the same two points using (1) a single USNIC sea ice chart produced on 16 July 2020 and (2) the 1991–2020 median RIO value. In this case, we see that the fastest route and transit time using the sea ice chart from 16 July 2020 are faster, arriving at the end location 6.4 hours earlier. This would indicate that the RIO values derived from the sea ice chart from 16 July 2020 are more favourable than the 1991–2020 median RIO.

## 12.6 Conclusion

In this chapter, we have demonstrated how network analysis techniques can be used to determine the fastest route between two locations in the Arctic and to compute IRSA and IRI. The results provide several valuable insights into the spatiotemporal variability of marine-based transit time and ship routing in polar waters. The use of IRSA and IRI to determine the expected response time for marine-based SAR assets was discussed as a possible extension to a 2013 study of maximum exposure time in the Canadian Arctic completed by the NRC. The use of IRSA and IRI to support ABM tools that aim to formally incorporate historical observations of shipping activity into quantitative assessments was also discussed. Incorporating IRSA and IRI results into area-based management tools would provide decision-makers with a useful tool to possibly help plan and coordinate incident response in polar waters and support ABM of commercial vessel operation and SAR provision.

Future technical work should concentrate on examining the use of different sources of sea ice analysis to better understand how change to the source data can impact the fastest route and expected transit time results. The use of modelled sea ice data from ice forecasting and GCM systems also offers a particularly interesting opportunity to compare expected RIO values derived from the statistical analysis of historical observations and from the model results. Computing IRSA and IRI using the RIO values derived from forecasted and/or modelled sea ice conditions may give decision-makers a better understanding of the future navigability of the Canadian Arctic and its impact on ship routing and expected transit times. These insights could be used to update policies, industry practices, and regulations that aim to improve shipping safety and SAR response or even assist the rationalization of SAR service delivery and also indicate where infrastructure development would be most beneficial.

The presented methodology and results in this chapter are not intended to provide a ready solution to the challenge of marine-based SAR response in polar waters. It is, however, hoped that the results, especially the data analysis and visualizations throughout this chapter, will stimulate new discussions and insights on the quantitative performance aspects of maritime SAR and Arctic navigation more generally. It is also hoped that these discussions can assist in improving ABM of shipping risks in the Canadian Arctic and beyond.

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