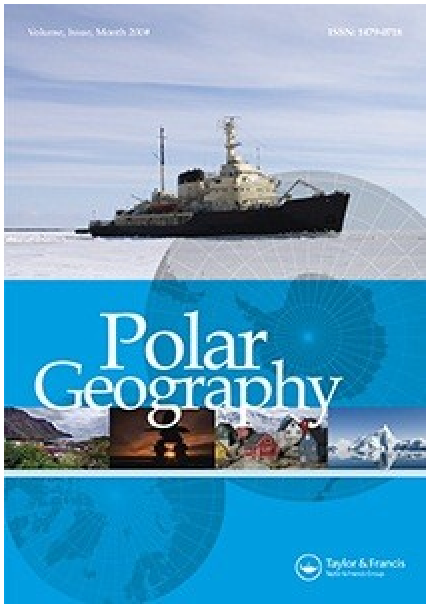
Polar Geography



Sea-ice Information and Forecast Needs for Industry Maritime Stakeholders

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Profound changes in Arctic sea-ice, a growing desire to utilize the Arctic's abundant natural resources, and the potential competitiveness of Arctic shipping routes, all provide for increased industry marine activity throughout the Arctic Ocean. This is anticipated to result in further challenges for maritime safety. Those operating in ice-infested waters require various types of information for sea-ice and iceberg hazards. Ice information requirements depend on regional needs and whether the stakeholder wants to avoid ice all together, operate near or in the Marginal Ice Zone, or areas within the ice pack. An insight to user needs demonstrates how multiple spatial and temporal resolutions for sea-ice information and forecasts are necessary to provide information to the marine operating community for safety, planning, and situational awareness. Though ship-operators depend on sea-ice information for tactical navigation, stakeholders working in route and capacity planning can benefit from climatological and long-range forecast information at lower spatial and temporal resolutions where the interest is focused on open-water season. The advent of the Polar Code has brought with it additional information requirements, and exposed gaps in capacity and knowledge. Thus, future satellite data sources should be at resolutions that support both tactical and planning activities.

Introduction: Environmental and socio-economic changes in the Polar Regions

The Polar regions are undergoing dramatic changes, evidenced in trends in Arctic and Antarctic sea-ice advance and retreat. Arctic sea-ice winter maximum and summer minimum extents have decreased steadily since the 1980's, yet the minimum anomaly has become particularly large, leading to a lengthening of the ice-free season (Stroeve & Notz, 2018) with the 12th lowest summer minima all occurring within the last 12 years (Fetterer et al., 2017; Meier et al., 2018). Also noteworthy was the large opening in winter (February) 2018 of the perennial pack ice in the north of Greenland, caused by offshore winds (Moore et al., 2018), and a new record lowest maximum extent during spring 2018 in the Bering Sea, due to warmer ocean temperatures. These Winter occurrences anticipate similar trends in the future with continued warming water temperatures (McFarland, 2018), and both present good examples on how unstable and vulnerable the Arctic ice pack is becoming, and are more typical of Summer conditions. As thinner ice cover replaces thicker, and creates a more dynamic, less stable ice cover, it is more susceptible to oceanic and atmospheric forcings, particularly during the Summer ice retreat. As observed, the increased rate of pack ice fracturing is now also occurring in winter, with corresponding trends in the rates of deformation and thermodynamic melt (Hwang et al., 2017; Itkin et al., 2017; Stroeve et al., 2014).

In the Antarctic, sea-ice was found to be slightly expanding overall, yet with large regional variations (Comiso et al., 2017; Parkinson & Cavalieri, 2012). In 2012 through 2014, Antarctic sea-ice extent set consecutive record highs for the annual maximum, but in 2016 the extent plunged to unprecedented low levels and has since remained below average (Turner et al., 2017). Some of this decrease appears to be caused by a shift in regional modalities, and has resulted in a reemergence of the

Weddell (Maud Rise) Polynya last observed in the 1970's (Doddridge & Marshall, 2017; Swart et al., 2018; Carsey, 1980). Nevertheless, there is still a substantial variation between the Summer minimum and Winter maximum extents in both hemispheres with large areas of seasonal ice cover. Outside of the Polar Regions, seasonal sea-ice is also found in a number of sub-polar seas including the Baltic and Caspian Seas, and the Great Lakes, often with regional lower salinity characteristics than that of sea-ice in high latitudes (Granskog et al. 2006; Kosarev, 2005). The Labrador Sea is unusual due to the preponderance of icebergs. Around the Antarctic, icebergs have been recorded at sub-polar latitudes in the South Atlantic sector, particularly along the Argentinian coast, and in the South Pacific sector towards New Zealand (Burrows, 1976; Morgan & Budd 1978).

Sea-ice changes have affected socio-economic activity at both ends of the globe, driving types and level of activity that involve established and new stakeholders. Use of trans-Arctic shipping routes and areas of interest for tourism are expected to increase with more accessibility with declining sea-ice and an open-water season that has increased by 1 to 3 months since the late 1970's (Melia et al., 2016; Smith & Stephenson 2013). With the finalization of the International Maritime Organization (IMO) Polar Code (PC) (IMO, 2014) and the construction of new ice class ships, we can expect further significant increases in activities for all economic sectors, including in seaborne trade, shipping, destination voyages and polar tourism (OECD, 2018, Deggim, 2018; Jensen, 2016). Additionally, the PC now mandates that "ships shall have the ability to receive up-to-date information including ice information for safe navigation" and requires a risk assessment methodology, called POLARIS, to determine the limitations for operating in ice (IMO 2014). Increasing activity will require more detailed sea-ice and weather information, which consequently has encouraged numerous new ice information providers (Melia et al. 2016; Lamers et al. 2016; Knol et al. 2018). Navigating ice-covered areas requires both broad and precise knowledge of ice conditions depending on the region and type of activity. Tactical navigation will require information at a high spatial (meter-scale) and temporal (hourly or daily) resolution in near-real time (NRT), to enable those traveling in and around ice to make the best decision and avoid hazardous conditions. Voyage planning, logistics, and infrastructure development requires information at longer time scales (monthly, seasonal, annual and decadal) to be able to prepare for future ice conditions. This group can benefit from the use of current, previous (climatological) and future (forecast) information.

Previous studies identified various platforms and suites of services for providing sea-ice information and forecasts to support ice navigation and planning (Knol et al. 2018; Hamilton & Stroeve et al. 2015; Lovecraft et al. 2012). However, the rate of growth of users and sea-ice information providers is potentially exceeding the understanding that is needed from both groups to work together effectively. Some challenges facing information providers with the uptake and usability of their products are that these are either hosted on platforms that are new and not well-known; are potentially technically inaccessible for some users; information is not in a user-friendly format; it is not clear how to interpret the information, particularly its uncertainty; or possibly the products are not developed with the user in mind, and therefore may not be applicable.

We discuss a brief summary of sea-ice information and potential forecast needs and challenges for Polar Regions stakeholders, including operational, geopolitical and local requirements, and the need for varying levels of spatial (meter to kilometers) and temporal (hourly to annual) resolutions. This paper summarizes user feedback (i.e. surveys from JotForm; workshops; EU projects) and input from representative industries, through personal communication, from those with ice information needs (Lamers et al., 2018; EU-PolarNet, 2018; ACCESS, 2012). The aim is to provide a framework which ice information providers and developers can use to prepare for future user and stakeholder needs and contribute to safe navigation.

Increasing Activity In Ice Covered Regions

State-of-the-art climate models forecast declining sea-ice cover in response to a warming climate caused by increases in greenhouse gases (Massonnet et al., 2012; Stroeve et al., 2012; Hamilton & Stroeve, 2016). While predicted rates of Arctic ice loss differ, navigation will likely become easier as the sea-ice cover shrinks and continues to thin (Melia et al. 2016; Smith & Stephenson, 2013; Stephenson et al., 2011). The thinning and loss of perennial ice, first recorded in the 1990's, is continuing, and could be introducing areas of instability what was previously expected to be consolidated ice (Kwok, 2018). Additionally, ice retreat and advance begin earlier and end later respectively, suggesting that first-year ice (FYI) has less time to thicken throughout the winter and making it more susceptible to summer melting (Stroeve et al., 2014; Stroeve et al., 2018). This trend will allow the Arctic seaways to have longer transit seasons in the future, particularly during summer months. It is unclear whether the recent decrease in the Antarctic ice-cover, following the slight increase observed throughout most of the satellite record, is permanent or part of Southern Hemisphere climatic cyclicity (Turner et al. 2017; Marshall et al. 2004).

The present use of Arctic routes remains a commercial risk for shipping companies as there is uncertainty regarding the risk of encountering ice, leading to potential damage for low/non-ice class ships and delays (Humpert & Raspotnik, 2012). Certain types of vessel (i.e. container) must operate within a specific schedule and are often unwilling to risk delays. Insurance costs are also likely to increase when using

Arctic routes. In addition the development of shipping routes remain tied directly to Arctic natural resources, and in the case of the Northern Sea Route (NSR), the future economic security of the Russian Federation. Consequently, there is an ongoing assessment as to whether or not it is more cost-effective to use these Arctic routes due to the needs for more infrastructure including icebreaker capacity, higher risk for complicated search and rescue (SaR) and disaster preparedness, and improved bathymetric and sea-ice information (Askenov et al. 2017; Barents Observer, 5 December 2018). At present Arctic commercial shipping is primarily destinational for community resupply or resource extraction using bulk carriers, tankers and LNG carriers, and not container traffic. Experts generally agree that it will remain this way for the foreseeable future (Arctic Council, 2009).

A further increase in Arctic and Antarctic polar expedition tourism is anticipated with the changing sea-ice facilitating access to unique locations featuring exotic wildlife and interesting historical connections. In the Arctic, the season ranges from April-September and in the Antarctic approximately from October until the beginning of March. Operations are expected to extend further west through the Northwest Passage (NWP), eastward towards Novaya Zemlya, and to the North Pole. Cruises seek out concentrations of wildlife near and in the Marginal Ice Zone (MIZ), and the coastlines that encircle the Arctic feature a multitude of sites of historical interest that connect the visitor to the age of exploration and tales of extreme endurance under earlier harsh conditions. In the Antarctic, large cruise ships are expected to travel further south along the Bellingshausen Sea coast of the Antarctic Peninsula and into the Ross Sea. Many new locations are associated with coastlines that provide a dramatic backdrop to activities, including narrow causeways and fjords which can be quickly covered in sea-ice or include the presence of hazardous iceberg fragments.

The MIZ and the ice edge is also important for fisheries in both hemispheres, with accurate mapping of sea-ice and forecasting its movements being critical, yet difficult. In the Arctic, the Barents and Bering Seas see high activity all year round with frequent incidents involving vessel casualties. Recent examples include a shrimp trawler, Northguider, that grounded in the Hinlopen Strait, Svalbard during December 2018 (Barents Observer, 31 December 2018), and numerous fishing boats in the Bering Sea lost due to vessel icing (NIOSH, 2017) where the crab fishery has a high activity with a limited entry system for quota shareholders who hold harvesting rights. Authorized users pursue a variety of crab species from October and continue to harvest until their quota share is filled. In 2016 the value of crab harvests in Alaska totaled approximately $250 million with almost $216 million produced by vessels operating in the Bering Sea and Aleutian Islands region (McDowell, 2017). In the Antarctic the krill and Patagonian Toothfish fisheries are important, with most activity during summer months using ice-strengthened vessels that can cope with light ice conditions, but can get caught in heavier than expected ice, for example the Antarctic Chieftain incident in February 2015 (Telegraph, 2015).

Overview of Routes of Operations and Seasonal Ice Conditions

The main Arctic transportation routes include the NSR, Canadian Archipelago (CA) Waters including the NWP, and Svalbard and Greenland coasts. The Arctic Bridge (AB) links the European Arctic (EA) to Canada, and the NSR to the Pacific. A Transpolar Sea Route (TSR) across the North Pole is expected to become a suitable route during future ice-free summers (Dawson et al., 2018; Farre et al., 2014; Rodrigue, J-P. 2017). Areas of resource extraction include the Barents and Beaufort Seas, and Russian Pechora and Kara Seas. The Nordic (Barents, Norwegian, Greenland and Icelandic) Seas and Bering Sea are key fisheries and routes for passenger vessels. Typically operations in these regions are in areas of seasonal ice cover and begin as the ice retreats in summer. Studies from the last 7 years show an increase predominantly in the NSR, and closer to the North Pole. A rise is expected on the eastern NWP as leisure and passenger vessels seek new areas of interest (NASA Earth Observatory, 2018; gCaptain, 2018; AECO, personal communication April, 10, 2017) (Figure 1a). How much northern routes will be affected by drifting multi-year ice in the future remains uncertain.

Operations and sea-ice conditions in sub-polar seas differ to those in the Arctic. The Baltic is critical for seaborne trade, with varied cargoes being transported through sea-ice to Finland during an average winter (HELCOM AIS). Cargo and passenger vessels follow a main trajectory through the Baltic, stopping at main ports along the way, whereas fishing and service vessels are distributed throughout. The ice season varies between mild to severe, depending on the prevalence of below freezing temperatures, with the start of the ice season occurring between October and January. The season ends starting with melt from the south, and by May ice remains in the northern Bay of Bothnia, which disappears by June. Other areas, such as the Labrador coast and large inland bodies of water (i.e. Great Lakes and Caspian Sea), feature some settlements and resource extraction that are otherwise isolated except by seaborne transport, thus operations continues throughout seasonal sea-ice cover.

The Canadian Archipelago (CA) includes numerous straits, sounds, bays and inlets, is a highly heterogeneous region for summer ice conditions. Some regions present a significant interannual variability, both in the actual occurrence and duration of an open water season, and is often observed in the central part which covers a large part of the NWP. In seasonally ice-free areas, freeze-up begins in late September and the ice cover expands during October. Persistence of first-year and multi-year ice typically leads to an early and more rapid freeze-up. The entire CA is then fully ice-covered for about 8 months throughout the winter. As temperatures increase, sea-ice begins to melt in June and break-up occurs in July and August. During the summer months, the remaining sea-ice in the CA becomes highly mobile as a result of winds and currents, causing ice concentrations to vary in a non-linear manner. The NWP does not open every year, although the frequency of opening and duration of the open water season have seen an increasing trend since the mid-2000's (Figure 1a and Figure 2).

There is an interannual variation to sea-ice coverage in the NSR. In the past, a number of regions of perennial ice cover, referred to as ice "massifs" (Marchenko, 2012), were maintained throughout the summer, whereas, recently, some areas show low-ice or ice-free passages for parts of the year. The Kara and Chukchi Seas clear first, followed by the Laptev and East Siberian Seas (ESS) (Figure 1a and Figure 2). Ice clears first from the offshore areas, with inshore ice replenished by discharge from river estuaries and blockages from massifs persisting later (Gascard et al. 2017). Most areas of the Kara, Laptev and Chukchi Seas are clear by July, with the ice edge remaining well to the north. Residual ice is most likely to remain in the ESS where a tongue of perennial ice is often observed extending south from the main ice pack. Icebergs remain an issue in the western part of the NSR, around Severnaya Zemlya and east of Novaya Zemyla (Nakanowatari et al., 2018).

The Antarctic sea-ice area experiences larger seasonal changes than the Arctic, reaching its largest extent in September when an average ~18 million km2 circumpolar ring of sea-ice encloses the entire continent, and reducing to a minimum of ~3 million km2 in February. Only the western coastline of the Antarctic peninsula remains ice-free most years (Parkinson & Cavalieri, 2012; Wadhams, 2000). The ice cover is not homogeneous, with annually recurring polynyas all around the Antarctic continent. The progression of the sea-ice melt differs regionally and in regions with large polynyas, sea-ice retreats not only southwards from the outer sea-ice edge, but also northwards from the shelf-line (Wadhams, 2000). In contrast to the Arctic, there are few locations such as the Weddell Sea where sea-ice survives the melt season and transforms into multi-year ice . The Antarctic Treaty prohibits resource extraction, and activities are limited to expedition cruise ship and extreme recreational tourism, logistical supply to research bases, and fisheries. The primary areas of activity for passenger vessels stretch from southern Chile and Argentina to the western Bellingshausen Sea, along the Antarctic Peninsula. Activity is concentrated on the western side of the peninsula between December and April, as the lightest sea-ice conditions can be found there, however, ships can encounter ice in the small channels and fjords (Figure 1b). Additionally, all Antarctic waters carry a high risk of icebergs all year round. There is also an increasing number of ships going into Antarctic Sound and the Weddell Sea (Bender et al., 2016). Other sources of Antarctic ship traffic are logistics and re-supply for research stations and research vessels, mainly during the Austral Summer.

Types of Stakeholders and End-Users

Sea-ice information provision should be aimed at providing guidance and accurate information for safety and environmental protection at all spatial and temporal resolutions. Stakeholders that use sea-ice and iceberg information to support operations cover a wide range of different applications, but can be broadly distributed into three main groups.

First, there are those who want to avoid all ice, or need dates of ice retreat and return for a region in order to manage their activities. These users have activities that are affected by the presence of sea-ice or icebergs, typically due to vessel or equipment limitation and the associated safety factor needed for safe operation. These include those engaged in resource extraction, and development of infrastructure, particularly where equipment has not been designed for ice-covered regions and non-ice reinforced recreational craft that need to be able to stay clear of ice. The current state of satellite coverage for the Polar Regions allows for long-term outlooks, operational ice charts and other regional satellite-derived daily sea-ice coverage maps that provide an indication of areas where ice is likely to be encountered. These assist when planning transits on a daily frequency and for the upcoming season but details such as leads and pressure ridges are not normally included.

The next type of user can require specialized ice information, as their focus is in areas near or within the MIZ, and require more detailed information to maximise their margin of safety. Of particular interest is accurate mapping of the sea-ice edge, areas of ice separated from the main pack, and iceberg infested waters. This group includes fisheries, for which the MIZ is a biologically active area, expedition cruise ships, and researchers interested in collecting sea-ice data, exploring ocean and atmosphere exchanges and interactions, and hydrographic or seismic surveying ships which often need 100% ice-free areas where even very small patches of ice (<100 m) can disturb planned surveys.

The third type of user is highly specialised, and wants to operate in, on, or under continuous sea-ice cover. These require more detailed sea-ice information, particularly rheology, thickness, ice type, ice age, snow depth and ice motion to maintain a level of safety. This includes specialized commercial trade, transport of logistics in fjords and along coastlines, particularly in Svalbard and by indigenous peoples in Greenland and the Canadian Archipelago, icebreakers maintaining navigation on the NSR and NWP, Canadian and Alaskan Arctic Waters, or McMurdo Sound in Antarctica, explorers crossing the ice, ice runways for air logistics, SaR, and long-duration ice camps for research.

Another type of stakeholder does not use sea-ice information themselves directly for operations, but as an input for other products that are then utilised by the groups described above. These intermediate users include producers of weather and climate forecast models, and require a broad synoptic and daily overview with low spatial resolution (>1km). However, requirements vary with either global or regional application and are likely to be more demanding in future.

Ice information for different stages of activity and planning

Remote sensing signatures of sea-ice vary seasonally, regionally and with different types of satellite sensors. Different frequencies provide the ability to interpret surface characteristics, which can be significantly influenced by snow loading, and freezing and melting phases (Webster et al., 2018; Sandven et al., 2006). When providing sea-ice information for users, it is important to consider the types of ice expected to be present during the early, middle and late parts of the season in order to resolve ambiguities in remote sensing data.

Users sea-ice information are determined by the different stages of activity and planning. Most activity occurs during the Summer and is affected by the timing of Spring melt or Autumn freeze-up conditions. The predictability of the ice advance and retreat are important for planning and can vary regionally. Where activity takes place in regions that perennial ice is likely to be present in, the probability of multi-year ice and ridge intrusions is useful. Ice information needs during the early phase of voyage planning requires good knowledge of the duration of season, its start and end dates, and a measure of the uncertainty through historical information for probability, iceberg density information (if applicable) and preferably ice type, concentration and average ice conditions for a specific area (EU-Polarnet, 2018). While there has been some attempts at seasonal prediction these are still experimental (Onarheim et al. 2015; Melia et al. 2017).

Early Phase: During the early phase of planning, a decision needs to be made whether ice is potentially a factor, determining the Polar Class of vessel used, or if activity can wait until ice-free summer conditions. Historical conditions are useful to ascertain the probability of the start and end dates of the ice-free season, and hence its duration. This takes the form of low resolution synoptic overviews, either from ice charts, or more likely, derived from passive microwave (PMW) derived sea-ice concentration (SIC) data (Stroeve et al., 2016; Lavergne et al., 2019). Information on ice type, such as the presence of multi-year ice, is also useful. If the area is known for icebergs, the availability of climatology data should be determined.

The length of the open water season varies interannually according to the severity of the season, and depending on the geographical area. Because of the influence of ocean currents, some areas can be ice-free almost year round, while others have near continuous ice cover and are only ice-free in more benign years. In the EA for example, warm water from the Norwegian Current ensures that the western Barents Sea, and west coast of Svalbard, are nearly always ice-free. However part of the Transpolar Drift, when directed east of Spitsbergen, and in its main continuation of the East Greenland Current, ensure that the east coasts of Svalbard and Greenland see a longer ice cover than elsewhere (Renner et al., 2014). To these oceanographic factors, the general atmospheric circulation must be included and prolonged winds from a particular direction will cause earlier or later open water conditions. This can occur in the Fram Strait, when southerly winds aid ice-free navigation north of Svalbard and Greenland by blocking the Transpolar Drift. Alternatively, northerly winds can result in a rapid closing of open water areas, particularly flaw leads along the Greenland coast, and the Whalers

Bay polynya north of Svalbard. Extended periods of cold in Svalbard and Greenland also aid the formation of sea-ice in fjords and shallow coastal waters affecting the start of the season. In the Pacific sector, the open water season is dominated by a retreat of sea-ice in the summer away from the coastlines towards the shelf break. Advection of ice in the Beaufort Gyre can result in an interrupted season with ice approaching the Alaska coast, although this is becoming rarer in recent years. Ice massifs can also linger in sectors of the NSR, typically where ridges have grounded anchoring it in place and preventing its dispersion (Marchenko, 2012).

Late Phase: Towards the late planning stage, and into the period of the activity, greater detail and more frequent information and updates are needed. This is mainly available through use of high resolution satellite sensors, particularly all-weather synthetic aperture radar (SAR), or alternatively through NRT observational information which are fed into a data cloud. During icebreaker operations NRT SAR images are used to identify open leads in the ice cover. In Summer, due to ambiguities in the surface caused by melt, cloud-free optical satellite imagery can also play a role but is not always reliable due to low pressure systems and prevalent Arctic Stratus Cloud cover. In particular, it is necessary for users to know the age of ice (World Meteorological Organization (WMO) stage of development) and locations of multi-year ice, deformation in the form of ridging and rubble fields, and floe sizes. These, coupled with frequent temporal updates to observe ice dynamics, are essential for determining safe passage. Other properties, including sea-ice and snow cover thickness, and ice strength, would also be useful but are more difficult to derive with any level of accuracy from satellite data. Thickness can be derived from satellite radar and laser altimetry, but only if assumptions are made as to the snow cover thickness since this can only be estimated approximately and at coarse resolution through PMW radiometers (Comiso et al., 2003). Ice strength is more difficult, as this cannot be observed directly and has to be deduced through a time series of observations of sea-ice drift and calculation in theoretical models (Ungermann et al., 2017).

Parameters can be estimated through forecast modeling that includes a degree of data assimilation, for example PIOMAS, but are still very much experimental (Schweiger et al., 2011). Research-level information products require further, and preferably continuous, validation by in situ observation networks (i.e. WMO Global Cryosphere Watch (GCW) program (WMO, 2015)). Forecasts can be divided into long (climate), medium (sub-seasonal 5-10 days) to seasonal (3 months) and short (daily to weekly) range lead times. For stakeholders, these equate to long-term planning and business perspectives (climate prediction, 1–10 years), also referred to as strategic, immediate planning (sub-seasonal) referred to as operational, and basic security of people and operations (weather forecast horizon) known as tactical. Particularly in the early or planning phase, various forecasts are essential, although there must be a certain level of confidence in the forecasts for them to be used to make decisions.

Insight into Stakeholder and User Needs

There is great interest in identifying and providing support for stakeholder needs. However requirements vary depending on the type of stakeholder, season, ice conditions and capabilities of the ship or platform to receive and understand the information. Whether it is vessel construction, planning requiring months or year lead times, voyage planning, or NRT tactical activities, users want and need to make decisions on whether or not to proceed. This is especially critical for platform and ship requirements for being able to withstand expected sea-ice conditions. For those working near ice-infested waters, relevant sea-ice information needs to be accessible; its usefulness well understood; suitable spatial and temporal resolutions available; low bandwidth, and should have the ability to be visualized on user platforms to efficiently aid users making informed decisions.

How users make decisions

In the shipping industry, decisions are influenced not only by the season, and presence of ice along a shipping route, but also by economical and geopolitical considerations. Various factors can lead to the decision of whether vessels can navigate predetermined routes within the open water season, or if there is a need to extend the shipping season beyond the open water period (e.g. community resupply vessels). Commodity market prices, annual tonnage targets and resource life-cycle continue to govern decision-making for Arctic transits (EU-Polarnet, 2018, Lamers et al., 2018). In terms of long-term strategic planning, historical data is typically used to assess the feasibility of a navigation route by determining the duration of the shipping season based on vessel ice class. Ice atlases and ice charts are used to provide a broad picture of ice conditions, namely the average timing of ice retreat and advance. Satellite imagery and local ice charts can be used to assess specific ice-related challenges such as deformation features in the ice cover (rubble and ridges), recurrence of dynamic processes (pressure and shearing) and inclusions of glacial or old ice within the pack (Fequest, 2002). This information helps to define possible areas for travel and the average length of the shipping season, leading to the creation of a commercial model that will be crucial in deciding if the project is financially viable. Once this early planning stage is completed, decisions can be made for defining shipping schedules.

Decisions are also made on the tactical scale by navigators and those in activities that support daily operations. Currently, ice information products are essential for planning and adjusting routes on a daily basis. These products should include user-friendly routine ice information, NRT satellite imagery (if applicable), as well as short-range Oceanographic and Meteorological data (i.e. wind and air temperatures) and ice forecasts. Ice forecasts are ideal for navigators to understand forecasted ice drift and pressure to allow for continuous routing adjustment and search for openings or areas of minimal ice cover. For example, in commercial shipping, the objective is to complete a voyage safely while avoiding delays, reducing fuel consumption and eliminating the risk of encountering ice that could lead to besetment or damage to the vessel.

Following International Polar Year (IPY) there has been an increased recognition of the sea-ice information needs of local communities in the Arctic. Activities including subsistence hunting and transportation between settlement sites has relied on a stable fast ice cover that is changing through climate change (Laider et al. 2009). To provide updated information products and allow local communities to collect their own in situ observations, a number of initiatives have been developed including SmartICE in the Canadian Archipelago, which allows people travelling by dog sled to record sea-ice thickness through electromagnetic induction sensors (Bell et al, 2014). Design, construction, and maintenance of instrumentation systems are performed by the communities themselves and ensure the local communities have access to up-to-date and accurate information, plus have a stake in its continuity.

User requirements for sea-ice information and forecasts

Sea-ice information is primarily provided from remotely-sensed data because satellites are able to cover large areas, and observe environmental conditions at multiple temporal and spatial resolutions. However, the relationship between the two acts as a trade-off where the ability to monitor at higher spatial resolutions yields smaller footprints, thus lower spatial coverage and vice versa (Meier & Stroeve, 2008). Expanding volumes of satellite data allow information providers to generate a copious amount of sea-ice derived products for potential stakeholders. This introduces challenges in the communication between data information providers and stakeholders. To begin with, the customer will use products they are already familiar with and have used in the past. Previous experience allows them to have confidence in the information available and its limitations, and allow them to quickly access the information when needed. With new products, it's not always clear to users which products are available, how to distinguish the difference between individual products, and how to use the data and format. For example, in the Barents Sea there has been interest in the ice edge due to proximity of energy company exploration activities, with the different parties drawing on ice edge products and using them to illustrate their argument (Rommetveit, 2017; Steinberg & Kristoffersen 2017). This has introduced a certain amount of confusion between products used for climatological studies, and those intended for tactical purposes, when both are valid for planning purposes. In order to identify what is useful for different stakeholders, it is important to recognize the scales required for varying operations, locations and seasonal ice conditions (Figure 3).

A principal obstacle for the use of forecasts for navigation and planning is a misunderstanding between providers and stakeholders on what they think is needed from a forecast. Feedback from users express the desire to have uncertainties included in forecasts, which is not always easy to provide due to the difficulty of accurately assessing critical initial conditions for the weather, sea-ice and oceanographic parameters (Katz & Lazo, 2012 and EU-Polarnet, 2018). This results in forecasts that have not always been developed with the needs of the user community in mind, potentially limiting their usefulness. Along with the technical challenges there is also a knowledge aggregation problem with many stakeholders not knowing how they would use seasonal-scale forecasts. While sub-seasonal forecasts remain an important informational component of maritime operations there is little understanding of what contributions long-term forecasts can make, due to the lack of familiarity. In the case of the Bering Sea crab fishery, sub-seasonal forecasts are used for navigation and planning purposes during the harvest season (October-February). SIC and drift are particularly important because they help vessel captains identify locations to set-up, and identify when gear may be at risk of damage. Bering Sea crabbers as users are familiar with the informational content of sub-seasonal forecasts but have little understanding of how seasonal scale forecasts might be used for planning and operations. This deficiency belies the endogenous nature of the product development process: forecasts have not always been developed with the needs of the user community in mind, but how can you develop a forecast which meets stakeholder needs when stakeholders themselves do not necessarily know what those needs are?

Availability of Sea Ice Information from Service Providers

Low spatial (~3-25 km) and high temporal resolution PMW satellites provide synoptic coverage of both hemispheres and can yield sea-ice information, such as SIC, ice age, ice motion, and timing of ice retreat and advance (Shokr & Sinha 2015). The data does not accurately resolve the ice edge location due to the coarse spatial resolution, and also underestimates the true ice fraction once melt begins. For these reasons, the dataset is good for planning and providing an overview for many users, but for navigation and tactical purposes, this scale does not effectively capture the MIZ, ice edge, and coastal zones where many users travel (Askenov et al., 2017). However, for vessels with an ice class of PC1 or PC2, meaning they can travel through medium FYI and old ice, this type of lower resolution information can be adequate because this type of user is prepared for all ice types and can safely navigate through pack ice.

High spatial resolution (<1km) data, such as SAR and optical (visible and infrared), provide good information on sea-ice features including sea-ice ridges, leads and deformed ice. However, these sensors do not have comprehensive coverage unless compiled, mosaicked, or interpolated through model data assimilation but can support tactical navigation needs and planning purposes, depending on whether or not users require knowledge of ice floes such as dimensions, ice classification and features. However, given the highly variable nature of these features, long-term planning is limited. The provision of more detailed information can aid the passage of vessels with lower ice classes in ice encumbered areas, but at greater risk. The user should be aware of inherent ice dynamics and the risk of becoming beset, and prepared to navigate to safe areas.

Iceberg tracking with the sole use of satellites is more challenging, particularly for smaller icebergs ranging in size from growlers and bergy bits (<1m - >5m) to larger icebergs (~<200m), with the minimum size that is detectable being dependent on the spatial resolution of the satellite sensor, and the sea state. Most high resolution satellites are unable to accurately identify smaller icebergs from ships and other surface features (Hughes et al. 2014; Akbari & Brekke, 2017; Mazur et al., 2017). Effective tracking then requires good intercomparison with in situ observations, satellite (or airborne) detections, and iceberg forecast models. Depending on the cloud cover, optical satellite data may not be available. Open water detection of icebergs is seen as routine, but can be limited by high sea states (Power et al., 2001). Detection within pack ice is difficult, due to the surrounding radar returns from ice edges and ridges. More recently, the capability of some SAR sensors to provide fully polarimetric data has allowed improved classification of icebergs within sea-ice, and the reliability of this would be enhanced by a multi-frequency approach, particularly with the addition of lower frequency, L-band, SAR information (Singh et al. 2018; Johanssen et al., 2017). This differs from the standard single polarisation, Constant False Alarm Rate (CFAR) approach where a pixel comparison is made with the characteristics of the surrounding background (Buus-Hinkler, et al., 2014). Where observations are combined with an iceberg drift and deterioration model (Kubat et al. 2005; Kubat et al. 2007), tracking and improved filtering of false targets becomes theoretically possible and is the subject of further research. This new approach could also allow for improvements to confidence mapping of icebergs where information can be tailored for specific users who are only interested in potential icebergs in their trajectory, or relevant to their operational area.

Gaps in Knowledge for Sea Ice Information Needs and Forecasts

Sea ice data information gaps

There are significant gaps in the ability to provide accurate information for sea-ice covered areas that in turn affects the provision of forecasts. Though PMW has been routinely used, it is only in the past 15 years that large volumes of NRT SAR imaging has become widely available. A key information gap is the provision of detailed and accurate snow depth and sea-ice thickness information, particularly during the Spring and Summer seasons. Snow depth is a critical parameter for accurately measuring sea-ice thickness from satellites (Liston, et al., 2018). It is also increasingly important, even for high ice class vessels (PC1 and PC2), due to the observation of "Antarctification" in the Arctic with a seasonal sea-ice covered by a heavier snow layer (Granskog et al., 2017) where the snow layer acts as a cushion reducing the efficiency of ice-breaking vessels (Mironov et al., 2012). Also not observable using current satellite technologies, is the distribution of ridge sizes and keel depths. These affect the ability of vessels to operate in ice, and forecasting ability due to ridges being a feature of sea-ice roughness and altering the drag coefficient (Tsamados et al., 2014). While SIC is now routinely assimilated into forecast models (Lindsay & Zhang, 2006; Wang et al., 2013), parameters including sea-ice pressure, stress and strength are also not readily observable leading to a key data assimilation gap for models. For ice of land origin and icebergs, many areas lack reliable climatologies from observations. Although there is a large volume of SAR satellite images, there has been no overarching attempt to process this consistently for iceberg detection because it requires a more robust validation through the use of observation data and drift forecasts to filter out false detections.

Forecast Information Gaps

With these critical information gaps, the lack of decent routine quality observations introduces corresponding challenges in the ability to provide accurate forecasts, or to validate them to provide meaningful measures of confidence or uncertainty. Additionally, it is difficult to formulate proper model evaluations specific for different users because sea-ice and weather forecasting models will require the improved snow depth and sea-ice thickness in order to generate forecasts that better capture temperature, weather and ice variables (Prasad et al., 2018, Caya et al., 2010). Only recently have there been some attempts to devise other metrics for comparing model forecast data with observations, that could also be applied to automated products derived from satellite data, such as the integrated ice-edge error (IIEE) (Zampari et al., 2018 and Goessling et al., 2016). This is surprising, given the widespread use of observation data for forecast initialisation and, more recently, forcing through data assimilation. Data assimilation into numerical models is achieved through a number of schemes that can be broadly categorised into so-called 3D-Var, for initialisation of a 3D-matrix of parameters at single point in time, and 4D-Var, where the parameters are further "nudged" towards the observed values through time. A typical 3D-Var technique involves optimal interpolation (Gandin, 1963; Wang et al., 2013), and when expanded to include the temporal aspect in 4D-Var, Kalman filtering (Sakov et al., 2012). The more complex techniques of 4D-Var incur a much greater computational cost, thus limiting their widespread deployment until recently. In nearly all cases, analysis includes minimisation of a cost function (Hestenes & Stiefel, 1952; Saad & Schultz, 1986). However, the increase in availability of computational resources has also allowed forecasts to develop from purely deterministic, where one scenario is forecast using the hopefully most accurate set of initialisation data, to probabilistic. For probabilistic forecasts, a range of different input values are used covering the distribution of possible scenarios. This results in a number of end results, which can be used to produce a probability of an occurrence, for example the position of the ice edge. However ensemble predictions, because of their greater computation cost, although widely used in weather and climate forecasting are rarely used in operational sea-ice predictions. Thus, there is an unfamiliarity for most stakeholders in using and understanding the information that they portray, that limits the ability to assess their utility.

Discussion and Future Needs

Changes in the pack ice and dynamic conditions expected in the MIZ will result in a need for new approaches to sea-ice information provision and forecasts (Eicken, 2013). This will include integrating requirements for improved data on sea-ice rheology and small-scale features, winds and ocean currents (Askenov et al., 2017). In addition, better coordination with support services in preparation for a changing Arctic will need the incorporation of information about optimal shipping routes and voyage planning based on probability forecasts and model projections, improved knowledge of accessibility of ships transit for specific areas, improvements in technology and infrastructure, and higher bandwidth communication with information providers and stakeholders (Stephenson et al., 2011; Farre et al., 2014).

Another challenge is determining how to optimally process large volumes of data, especially the vast quantities of Earth Observation (EO) data. There is increasingly a role for smaller, specialised entities, including private companies, to provide additional bespoke information products either as a public service or for commercial gain. However increased information, temporal availability and improved spatial detail results in greater data volumes, and the question then arises of how can this be transmitted to users in remote areas? If data can be transmitted it is important to know if users are in a position to receive it and make use of it. Though improved satellite communications coverage is expected to be available for the high latitudes of the Arctic and Antarctic (Barents Observer, 27 March 2018), it is still unclear when it will be ready or what costs to the user are involved. In preparation for ship operators, planners and other new operators to be able to receive and benefit from new developments in technology when traveling through ice-encumbered areas, the assessment of on-board systems should also be considered. An Electronic Navigational Chart (ENC) provides the data component of an Electronic Chart Display Information System (ECDIS), which is under review as an approved aid to navigation, as a platform for ice information in standard formats, and supported by The International Hydrographic Organization (IHO) (Falkingham, 2014). An ideal ice information system on board a ship could include, but not limited to, all of the above mentioned products on demand with the following criteria in Table 1.

Improved dialogue between service providers and stakeholders

It is essential to acknowledge that information product development for users requires dialogue between service providers and stakeholders. It includes being able to understand the same terminology (Eicken, 2013), standard format and integrating stakeholders during the development process (EU-Polarnet, 2018). These are issues that have been highly under-represented, but is now the subject of several European projects including SALIENSEAS (http://salienseas.com/) and the EU KEPLER project (https://kepler-polar.eu/) that will help identify how to make the best use of the information and communication currently available, and recommend further infrastructure improvements. SIPN2 is implementing an iterative knowledge development process to introduce and subsequently identify user preferences to address challenges with users understanding of seasonal forecasts, including a survey currently underway for organization members to begin identifying areas of operation where seasonal forecasts can contribute. Along with collating background information about vessels, experience, and harvest practices, respondents are also being asked how long-term forecasts can be used to support an array of planning and operations related activities. Information from the survey will then be used to inform the design of a best-worst scaling (BWS) exercise. This is a method which allows for the systematic collection of preference data that is commonly used in social science related research. In this instance the Bering Sea crabbers will identify activities where seasonal forecasts are most and least likely to make a positive contribution. Through this process it will be possible to develop a ranked list of planning and operations activities that can be used by SIPN2 team members as they develop the content and presentation of the forecast product. In addition, the iterative approach also identifies those areas where seasonal scale is not needed which enhances efficiency and allows the research team to focus resources on high value areas of need.

Presence of new satellite sensors

Major advances have been made with the widespread, and freely available, NRT SAR imaging from the European Sentinel-1 constellation that has improved products for end-users with navigation, planning and forecasts. This provides nearly daily, and sometimes twice daily, coverage of key areas in the Arctic. Yet critical gaps remain at lower latitudes including southern Greenland, and for the Antarctic and areas of the Arctic outside of the European sector, where coverage is more sporadic. Pan-Arctic coverage is expected to be a possibility with the launch of the Canadian Radarsat Constellation Mission (RCM) in February 2019, although issues remain to be resolved which are discussed further in the following section. Data volumes are vast, so research efforts are underway to make more use of automated processing (Koubaris et al., 2019). However, challenges with ambiguities in classification remain from fundamental limitations with the sole use of microwave sensors to monitor sea-ice and it is therefore necessary to combine SAR with other sources of data. PMW can augment areas not covered by SAR; however, it operates at similar frequencies and has much lower resolution. This can be valuable for planning and forecasts, but unsuitable to provide information on sea-ice features smaller than ~3 km necessary for tactical purposes. Optical and infrared are preferable, as these are at a resolution similar to SAR but a key drawback is that they cannot see through clouds which are prevalent around the MIZ areas in summer. To get around these issues, an integrated approach incorporating all relevant satellite (and in situ) information and forecast modelling can be useful. The data assimilation techniques available now allow for different types of input information, with sporadic temporal and spatial coverage (Houtekamer & Mitchell, 2001), and a forecast model, along with satellite derived sea-ice drift information, can also provide a tracking capability where ice is followed from one satellite image to the next (Thomas et al. 2008). This allows for reducing uncertainty by building up a detailed picture of the sea-ice properties from multiple satellite sensors, and its development from one ice type to another monitored.

Next steps and new technologies for derived products

These issues demonstrate some fundamental aspects forecast and sea ice provision services need to consider when developing information products specific for stakeholders and end-users. Though processing large data volumes can be overwhelming, the challenge lies with providing the best information on the scales necessary for all users at any given time. To overcome some of these challenges, Machine Learning, and Artificial Intelligence, can play a role in the automatic analysis but this is dependent on good quality satellite information and ground truth information for training the systems and to maintain validation. Real intelligence is also needed to incorporate these factors into an overall system. Automatic classification of sea-ice is improved by access to fully-polarimetric, multi-frequency SAR (Singha et al., 2018). Currently the majority of SAR sensors, and all those used for routine operational monitoring, are in C-band (frequency 4-8 GHz). The "C" is also sometimes referred to as "compromise" because it represents a compromise between the size of the antenna aperture, which decreases with frequency and attenuation of the radar signal through rain and clouds which increases with frequency (Doerry, 2004). Unfortunately, as snow cover is present on sea-ice, a lower frequency is required for greater penetration depth and detection of deformation features. The use of L-band (frequency 1-2 GHz) when combined with C-Band, has shown promise with improving monitoring sea ice features deemed critical for tactical and navigation operations (Dierking & Busche, 2006; Dierking & Dall, 2007, Casey et al., 2016; Howell, et al. 2018; Johansson et al., 2018), though an antenna length of ~10 metres makes for a more difficult satellite post-launch deployment. *In situ* observations (i.e. ship-based, buoy and drones) are needed to provide the ground truth for certain parameters and aid in confidence mapping, provision of NRT information, and improved initialization of forecasts. Sea ice forecast models are reaching a complexity whereby they are able to parametrize or recreate sea-ice dynamics and characteristics (Rae, J-L. et al., 2015; Vancoppenolle, M. et al. 2012; Rampal, P. et al., 2016). In particular, the ability to extend forecasts into the seasonal timescale requires use of improved sea-ice thickness measurements that could be provided by altimetry (i.e. CryoSat-2 (Blockely & Peterson, 2018), Sentinel-3, ICESat-2 (Schweiger et al., 2011), PMW interferometry (SMOS) (Mu et al., 2017) and thermal infra-red optical imaging. Short-range forecasts require accurate weather forecasting with, ideally, a fully-coupled ocean-ice-atmosphere model to cover the 24 hours to 7 days period as this time-frame is generally preferred for sub-seasonal planning that allows users to reduce their immediate risks. Here more in situ observations and a better understanding of ocean-ice-atmosphere fluxes and boundary layer physics is necessary [ref]. Whilst there has been research into inverse modelling of raw values (Lee et al., 2017; Remund & Long, 2003) to provide model outputs directly comparable with the satellite observations, the additional parametrizations to calculate these still require detailed understanding of the processes involved. Drift measurements, both in situ from buoys and derived from satellites (Löptien & Axell, 2014; Schweiger et al., 2015) especially high resolution SAR (Korosov & Rampal, 2017; Karvonen, 2012) and optical, are another underutilised resource that could improve drift forecasts. Finally, more transparent assessment using readily understandable metrics of forecast skill will generate trust with stakeholders (Zampieri et al. 2018).

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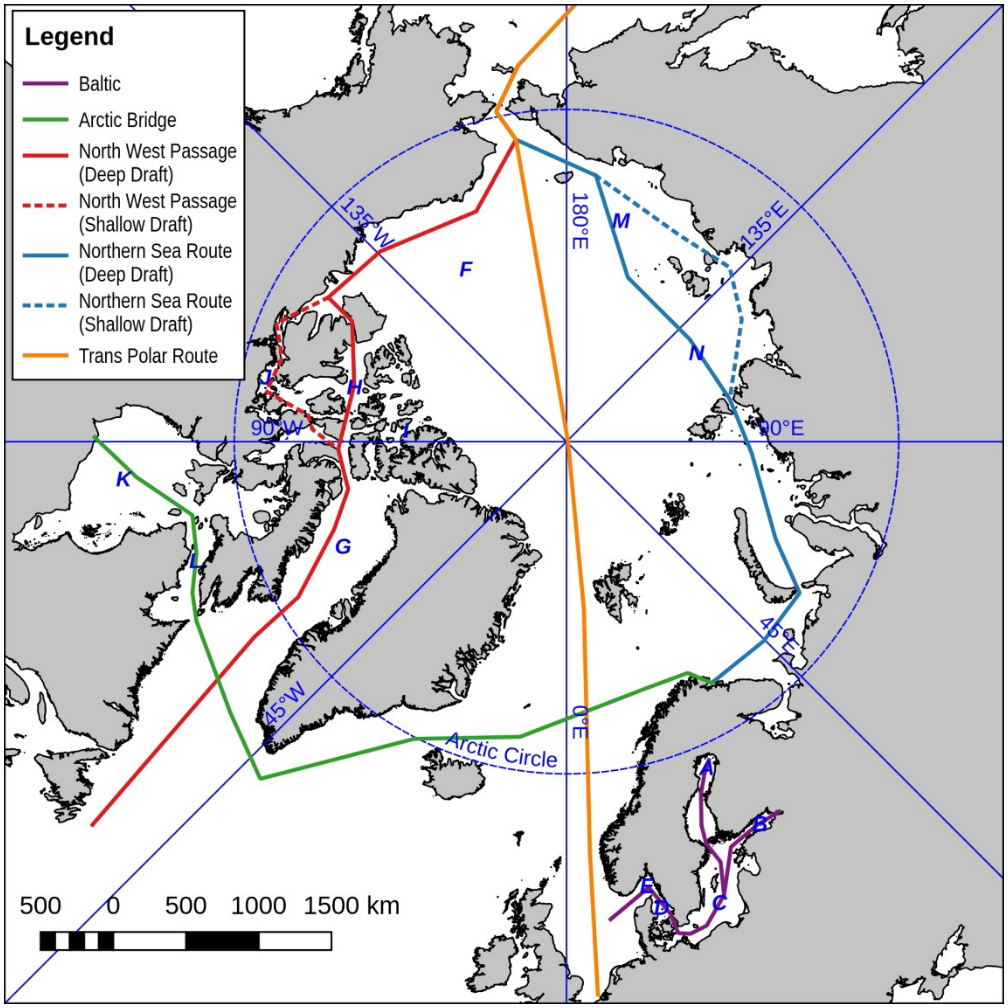

Figure 1a. Main Arctic routes for the Sub-Polar Seas, Canadian Arctic(CA), and the Northern Sea Route (NSR). In the sub-polar seas, ice formation typically starts in the Bay of Bothnia (A) and develops toward the Gulf of Finland (B), but in mild winters both areas see only partial ice cover. In severe winters, sea-ice reaches the central Baltic Sea (C) and the Kattegat (D) and Skaggerak (E) between Denmark, Norway and Sweden. The season ends starting with melt from the south, and by early May there is normally only ice remaining ice remains in the northern Bay of Bothnia, which disappears by June.

In the Canadian Arctic, the main route for deep draft vessels links the Beaufort Sea (F) to Baffin Bay (G) through the Parry Channel (H). The western part of this is affected by persistence of ice in summer, and instrusions through the Queen Elizabeth Islands (I). Routes for shallow draft vessels through sounds connecting to Queen Maud Gulf (J) normally open up in summer, and the Hudson Bay (K) and Strait (L) are also only seasonally affected. The Northern Sea Route typically only sees residual sea ice in summer, "massifs", in the East Siberian (M) and Laptev (N) Seas.

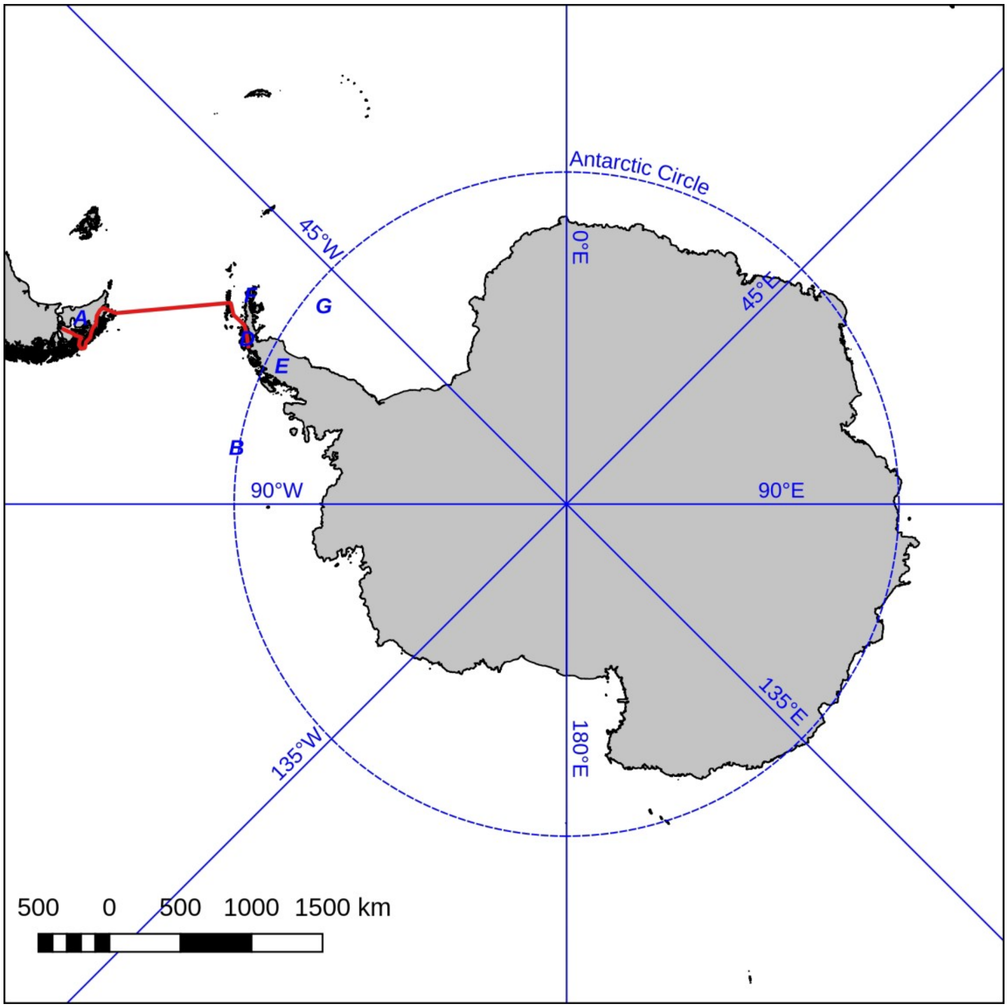

Figure 1b. Main Antarctic routes from southern Chile and Argentina (A) to the western Bellingshausen Sea (B). Ice formation during the high travel season is predominantly encountered in small channels and fjords in the Bransfield Strait (C) and Gerlache (D) Strait along the Antarctic Peninsula (E), in the Antarctic Sound (F), and Weddell Sea (G).

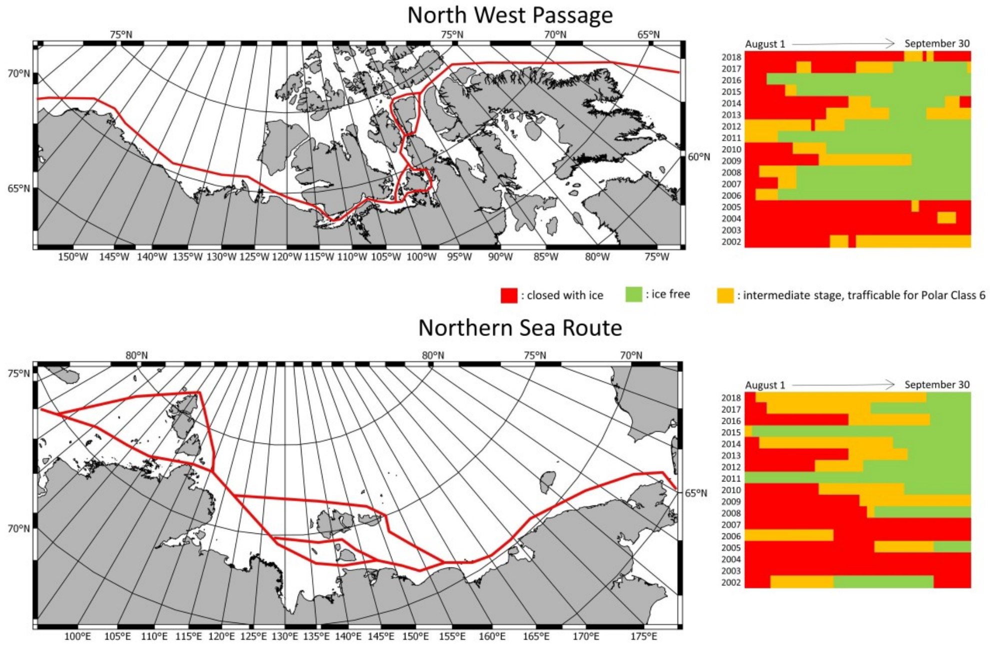

Figure 2. Interannual comparison (2002 - 2018) of the trafficability of the NWP and NSR for the two months period August 1 to September 30. The examined routes are marked as a red line. Trafficability was examined for any of the possible route options. Defined trafficability stages are: "Closed with ice" means that even a Polar Class 6 vessel could not traverse the passage. "Ice free" means that retrospectively even a ship with no ice class could have made the traverse. "Intermediate stage" would have required a Polar Class 6 ship for the traverse. Judgement of the trafficability stage was done on the basis of AMSR-2 sea-ice concentration data and MODIS optical images.

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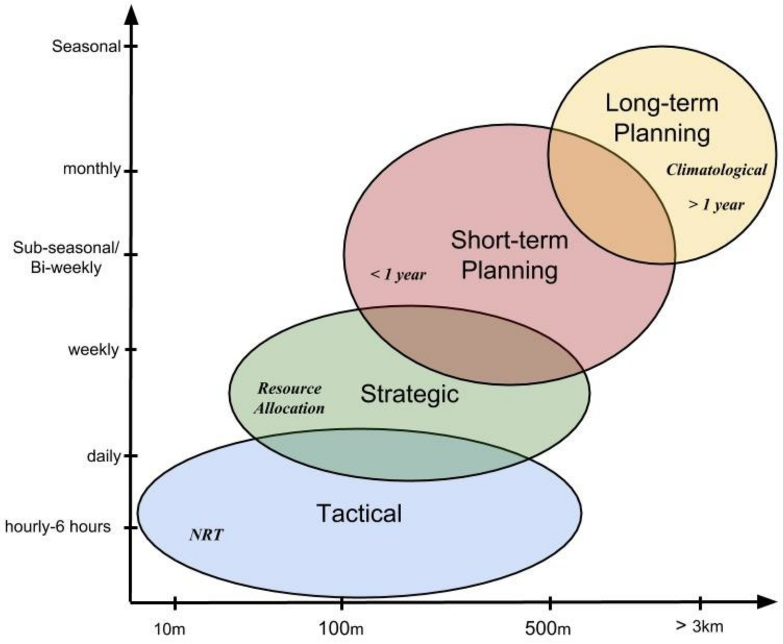

Figure 3. Schematic illustrating an example of the range of typical spatial and temporal scales of information required by users.

338x254mm (72 x 72 DPI)

Product Types	**Providers**	**Description**
Current ice conditions	Ice Services Third-parties and commercial Copernicus services	• An automated or semi-automated data provision system for NRT • Provision of relevant information sources available at all spatial and temporal scales (planning to tactical) • Capability of large data analytics and multi-mission satellite observations
Automated Frontend	Third-parties and commercial	Ease of reception and display of ice information on demand without any preparations and/or manual data management by the user
Prognostic of sea-ice conditions	ENC developers	The development of route trafficability can be assessed by the navigator when information from a synoptical forecast model are merged into the display
Navigational	ENC developers	Navigation software for route and voyage planning
Informative	Ice services Third-parties and commercial	Ability to be visualized and easily interprepreted for users
Low bandwidth compatible	Ice services Third-parties and commercial	Can function in a minimal mode even with an Iridium connection
Training	Ice services Copernicus services	• Transparency and materials readily available on how to use different ice information products and forecasts • Easily accessible information on IMO Polar Code requirements • Contact information for data and support services