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Table of contents

Glossary

This report uses terminology used within the sea ice forecasting community, which may differ from other uses.

Automated products - The process of generating products automatically typically using little to no manual input or quality control.

End-users – A person or group that uses a product or service for decision making or research, and may use these to generate a product or service for a next end-user (KEPLER, 2019, 2020)

Forecast – short-term (up to two week) projections of sea ice conditions

High resolution - Sub-kilometer (meter scale) for spatial resolution

Ice edge – The boundary that separates the edge of the sea ice and open water in the sea, rivers or lakes. The region over which sea ice concentration is at least 15 percent per pixel (25km), based on the Norwegian Polar Council estimates for September 1st sea ice over the period 1985-2014, as defined by the Norwegian Ministry of Climate and Environment Barents Sea Management Plan. The operational definition used by sea ice services refers to the WMO No.259, Sea Ice Nomenclature where "The demarcation between the open sea and sea ice of any kind, whether fast (fast ice edge) or drifting. The drift ice edge may be termed compacted or diffuse." The difference between the two interpretations is significant because it can mean differences in ice edge locations from a few to hundreds of kilometers. This affects how the location of ice edges in a product is disseminated and affects how decisions are made for the types of activities that will be permitted in the area in question.

IMO – International Maritime Organization

Model – a numerical representation of sea ice evolution, using either statistical methods based on past sea ice extent, or using physical measures based on physical parameters of sea ice (rheology, albedo, thickness, etc)

MIZ – marginal ice zone. "The region of an ice cover which is affected by waves and swell penetrating into the ice from the open ocean" (WMO No. 259).

Operational - The term 'operational' under the mandate of the IMO and WMO sets standards for sea ice products for dissemination to end-users. To be operational, a product needs to be: Relevant (user AOI, needed suite of parameters, WMO standards); Accurate (resolution, parameters mapped properly); Reliable (agreed provisions received, strengths/limitations known, continuity); Actual (near real time or on a routine basis); and Accessible (band width, format, availability, production scheme).

Operation - A practical application or activity being planned or executed in a particular environment.

Product - a presentation of data in the form of maps, visual imagery, tables, or other format that is intended for use by operators and planners. E.g. sea ice forecast product.

Derived product - Products or information created through use of other sources, of data. For example, sea ice concentration products are derived from raw satellite data information.

Services - Assistance provided to users in the form of consultation, products and product support.

Skill - the level of ability, here used for the performance of climate and forecast models to reproduce observed events

WMO – World Meteorological Organization

Summary

Two virtual conferences brought together participants from forecasting, operations, climate and sea ice forecasting, economics, and planning. The aim was to better understand user needs in Arctic operations and planning, and more specifically to explore whether the development of sea ice forecasts can be useful for future maritime operations and planning, particularly along the ice edge and marginal ice zone (MIZ). Given the challenges of maritime users often working on multiple temporal and spatial scales at any given time, it is essential that the information providers (researchers, forecasters) understand the difference between the use of products that are appropriate for projections of sea ice extent for future investment and policy, and those that are more suitable for planning and supporting operations (Wagner et al, 2020). The workshops were supported by the Svalbard Strategic Grant SSG, (The Research Council of Norway), with the aim of fostering international cooperation, open sharing of data, coordination of logistics, the use of new technologies, and to reduce the environmental impact of fieldwork.

This report recommends:

1. Translating operational model outputs and where appropriate, research model results, into decision-relevant products that are easily understood and accessible for all users.
2. Forecast products should be integrated into maritime navigator training curriculum: Forecasts could be beneficial for end-users if there is more effort on capacity building and training programs. This will allow users to have a better understanding of forecast capabilities.
3. Building user capacity to accommodate uncertainty in existing forecasting products and in climate projections as they plan over shorter operational time scales, and over longer investment and policy timescales.
4. Indicating and relating a mariners' level of experience in ice relative to the ice class of the ship they are operating. Navigator experience should be commensurate with the ice class of the vessel, but ice dynamics introduce risks with consequence for safety and preparedness also for open water vessels, particularly in areas along the ice edge, coastal zones, MIZ and outer ice pack where polar lows can rapidly change ice conditions.

From the workshop, this report recommends that researchers and product developers

1. Establish formal cooperation opportunities to develop a longer-term strategy that allows researchers, forecasters, and user groups to jointly develop and validate prototype products. An open dialogue with users will enable researchers to tailor products that better suit user needs and ensure awareness and capacity building for the use of tools that are available today.
2. Create initiatives that allow product developers to integrate end-user needs during the development process to strengthen the relevance of methods and findings.
3. Facilitate the communication of limitations and possibilities presented by forecasts for Arctic marine operations, planning, and investments over different time scales
4. Identify and address hindrances that prevent users have from accessing to and making use of sea ice information

Introduction

This white paper reports on two virtual workshops held with representatives of the Norwegian Coastal Administration, the Reference Fleet, sea ice research communities in Norway and the United States, and the Norwegian Ice Service. The workshops were planned as sessions at the High North Dialogue in Bodø in March 2020, with funding from the Svalbard Strategic Grant. The High North Dialogue was cancelled due to the Covid-19 pandemic, and could not be rescheduled for the following meeting. The organizers opted instead to host two virtual meetings. This format permitted a different set of participants to the intended academic audience. This produced more applied discussions of sea ice forecasting needs and product development with the Norwegian Ice Service, the Norwegian Coastal Administration, the Norwegian Reference Fleet, and researchers.

The pair of workshops were inspired by the growing need for improved skills among mariners, forecasters, and modelers to reduce the risks of operating in ice-encumbered areas. The Arctic is home to approximately 4 million people, and the number of residents and visitors is expected to increase from the growth of industry, shipping, and polar tourism. For leisure visitors to the Arctic, multiple vessels, ranging from large overseas and expedition cruises to small personal yachts, and of varying ice classes, will continue to sail in the region. This will also be the case for an expected increasing number of fishing vessels, and cargo, container, and oil tanker vessels. This increase will also bring new and less experienced mariners into Arctic waters. Understanding knowledge needs among current and future mariners, as well as the capabilities of models and technology is key to reducing the risks from increasing Arctic marine traffic.

This report first outlines the workshops' contributions to the strategic objectives of the Svalbard Strategic Grant. It then presents the state of the art in sea ice forecasting, and highlights key knowledge needs. The report outlines the workshop findings in the following sections. User perspectives on knowledge needs, state of the art, and perspectives on the future of the Arctic are presented in the form of quotes and insights shared by participants. In the discussion, the report reflects on these findings and recommends action points and priorities for further research.

Meeting Svalbard Strategic Grant’s strategic objectives

Svalbard Science Forum’s (SSF) strategic objectives of cooperation, coordination, sharing of data and reduced environmental impact were at the core of this project’s purpose, scientific contribution, and organization. Meeting the SSF strategy for open sharing of data and information, the workshops included discussion of user needs and the limitations and possibilities for research. Topics included possible challenges in sharing different forms of sea ice information, issues concerning intellectual property rights, the timing and extent of information sharing, forecasting, access to sea ice maps and information, and other issues relevant to debates over open information sharing for Arctic operations and research.

The proposal to hold the workshops built on recommendations from previously funded SSF research, including the “1st Science-Industry platform on expedition cruise tourism in Svalbard (Oslo, 2012), and the SSF-funded workshop on “Barents Sea Ice sheet - insights into the climatic sensitivity of marine based ice sheets” (Anne Hormes, 2012). Workshop participants brought insights from the ERC-funded project “Mixed-phase clouds and climate (MC2)” (Storelvmo, UiO 2018), the EU-funded LC-SPACE-02-EO-2018 “KEPLER (Key Environmental monitoring for Polar Latitudes and European Readiness)” (MET Norway, under the “Copernicus evolution – Mission exploitation concepts for the Polar Regions” (2018-2021)), and the United States NSF-funded project “Modeling Risk From Black Carbon In A Coupled Natural-Human System At The Arctic Ice Edge” (Brown Univ. 2018-2021).

SSF-funded workshops are required to contribute to a reduced environmental impact. The project team achieved this in two key ways. First, on the project level, the workshop was organized using the online meeting platform, Zoom, where approximately ~25 end-users from the Norwegian Coastal Administration, the Reference Fleet (Referanseflåten), and researchers from Norway and the United States participated in a roundtable discussion. Second, on the policy level, there is a need for improved understanding of user needs as a wider global community of shipping operators make decisions to navigate in Arctic waters as sea ice regimes respond to anthropogenic climate change. Decision-makers need improved tools to plan for futures in which Arctic shipping increases markedly. The two workshops allowed exploratory conversation to synergize research that will improve products for operations and planning at all scales of sea ice forecasts.

State of the art and knowledge needs

The rapid retreat and altered dynamics of Arctic sea ice has long been a symbol of global climate change. As summer sea ice transitions from largely Multi-Year Ice (MYI) to mostly First-Year Ice (FYI) with longer open water seasons, new routes are expected to become more accessible and transit seasons are expected to begin earlier and end later. While there is wide agreement on the long-term trend in sea ice retreat, there are many uncertainties in medium term projections of sea ice extent and dynamics, as well as in short term forecasts for navigation. The rates and variability of retreat, particularly on seasonal time scales (Boeke and Taylor 2016) are subject to much disagreement among climate models. Furthermore, the Svalbard and Barents Sea sector of the Arctic shows a large variability in seasonal sea ice extent (Figure 1), therefore places greater demand on conveying a more accurate representation in sea ice models and forecasts. Moreover, about 80% of all Arctic shipping crosses Norwegian waters (St. Meld. 31 2015-2016).

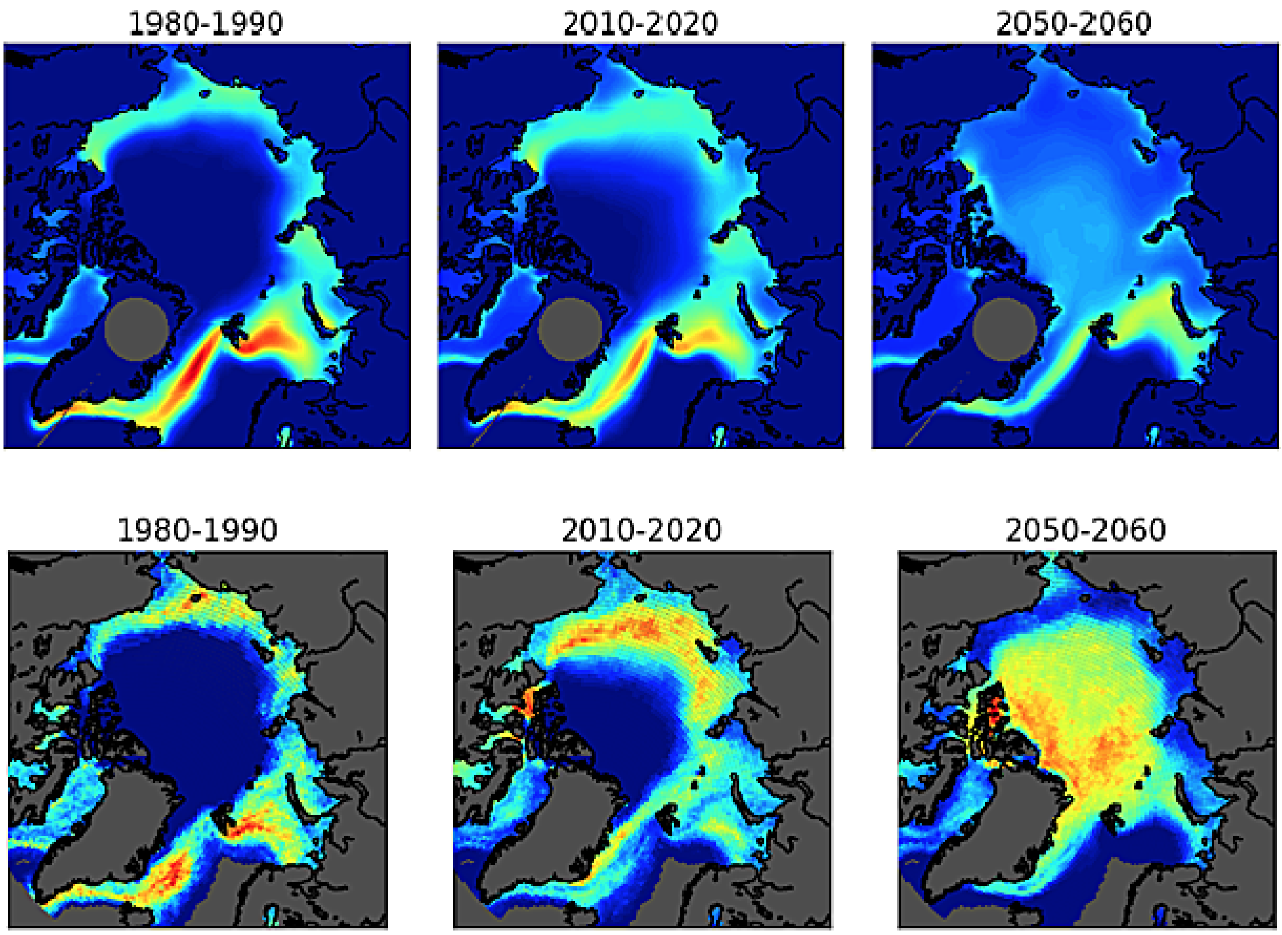

Figure 1: Top row: Standard deviation of number of ice-free days for selected decades of a 40-member ensemble of the NCAR CESM (Kay et al., 2015). Values range to 100 days (red). Low row: Total number of breakpoints detected by Rodionov (2004) routine for ensemble members. Maximum values reach 60 instances (red).

Current operational short-range (lead times 1-10 days) sea-ice forecasting systems have a km-scale resolution and mostly assimilate satellite data with a resolution of O(20km). In order to make those sea-ice forecast products useful, the forecast accuracy and resolution needs to be further improved by advancing on sea-ice reologies, physics, and data assimilation of high-resolution (greater than 1km spatial resolution) satellite data. In addition, there needs to be a stronger emphasis on the development and choice of the verification methods (Melsom et al. 2019). Sea ice forecast systems for long-term (e.g. investment) planning can provide an overview on sea ice conditions and progress towards skillful seasonal forecast of for example the sea-ice edge (Palerme et al. 2019) the length of open water season in a given area (Dirkson et al. 2019). These uncertainties, variabilities, and limitations present challenges to managing risks from increasing marine operations, and for the good governance of expanding Arctic industries (Veland and Lynch 2017).

At the same time, investors and nations alike are planning for potential futures where receding sea ice, lower fuel prices, and industry consolidation might make the transpolar shipping route competitive with the Suez Canal alternative (see Bennett et al. 2020, Stephenson and Smith 2015). Humbert and Raspotnik (2012) find that Arctic routes are presently a commercial risk for shipping companies, citing potential ship damage and delays caused by ice risk. Based on differences in estimated costs and risks, Lasserre (2014) and Meng et al. (2016) find there is divergence in perspectives on the viability of Arctic sea routes. To-date, traffic has been modest. After a peak in traffic along the Northern Sea Route (NSR) in 2013, when 71 ships transited, transits remain below 40 per year (Figure 2 , Li et al. 2021). Nevertheless, cautious optimism among nations and shipping operators has driven some early investment in vessels and infrastructure. In particular, future raw material shipments from the Arctic region to Asia drives this interest, although policy barriers between nations remain a limitation (Lee and Kim 2016). For the time being, the majority of Arctic marine traffic is limited to shorter transits within the Atlantic, Russian, and Pacific sectors. Fishing vessels make up the majority of this traffic, followed by other industrial vessels (Table 1). Passenger vessels such as cruise ships, ferries, and other smaller vessels together make up only ca. 8 percent of the traffic.

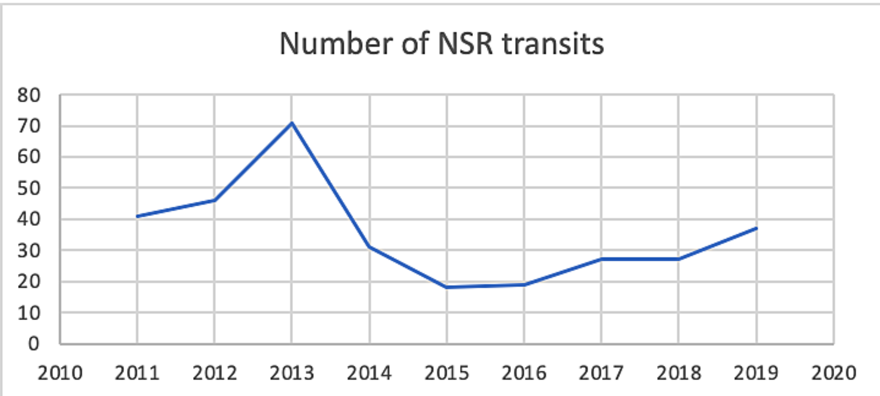

Figure 2: Number of transits on the NSR per year 2011-2019 (data source: CHNL 2020, arctic-lio.com)

Ship class	Geographic Arctic		IMO Arctic	
	Number of ships	Percent of fleet	Number of ships	Percent of fleet
Fishing vessel	1903	18.8	755	36.2
General cargo	2035	20.2	243	11.6
Service vessel	618	6.1	198	9.5
Bulk carrier	1287	12.7	181	8.7
Tug boats	501	5.0	138	6.6
Chemical tanker	874	8.7	109	5.2
Oil tanker	691	6.8	94	4.5
Refrigerated bulk	213	2.1	90	4.3
Offshore	521	5.1	64	3.0
Cruise	154	1.5	63	3.0
Container	292	2.9	43	2.1
Ferry-to-pax	387	3.8	37	1.8
Ferry-pax only	192	1.9	21	1.0
Ro-ro	119	1.2	20	1.0
Yacht	76	0.8	13	0.6
Vehicle	51	0.5	11	0.5
Liquefied gas tanker	172	1.7	4	0.2
Other	4	0.0	1	0.0
Non propelled	7	0.1	1	0.0
Other liquid tankers	3	0.0	-	-
Total	10,099	100	2,086	100

Table 1: Number of vessels in the geographic Arctic and the IMO Arctic for 2015 (modified from Comer et al. 2019). The IMO definition of the Arctic excludes high-traffic areas of the Atlantic Arctic region.

Due to the increased risk of health and safety, the International Maritime Organization (IMO) International Code for Vessels Operating in Polar Waters (Polar Code) was implemented in 2017 and is mandatory for ship operators travelling in the polar regions to follow under both the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL) (IMO Doc. MSC.385(94)). The Polar Code provides guidance for navigators on required training, relevant environmental information (i.e. weather, ice, oceanographic, etc.) and types of ice regimes in which specified ice class vessels may operate (Table 2).

Table 2: Polar Classes (from IMO 2019)

Polar Class	Ice Description (based on WMO Sea Ice Nomenclature)
PC1	Year-round operation in all Polar waters
PC2	Year-round operation in moderate multi-year ice conditions
PC3	Year-round operation in second-year ice which may include multi-year ice inclusions
PC4	Year-round operation in thick first-year ice which may include old ice inclusions
PC5	Year-round operation in medium first-year ice which may include old ice inclusions
PC6	Summer/autumn operation in medium first-year ice which may include old ice inclusions
PC7	Summer/autumn operation in thin first-year ice which may include old ice inclusions

Mariners' Levels of Experience

Today, mariners operating these vessels are overall well experienced, and the use of ice pilots is currently required and will continue to be under the Polar Code for specific ships over a certain tonnage. The Polar Code will also require all navigators to have a basic training certification for those planning on travelling in ice-encumbered areas. However, the level of expertise for navigators travelling in this area varies (Lovecraft et al. 2013, Hamilton & Stroeve 2016, Knol et al. 2018), and the diversification and increase in economic activity following industry growth is expected to intensify this variation (Wagner et al. 2020). All navigators will want to comply with the Polar Code regulations but some of the guidelines can be vague with regards to specific ice conditions or requirements for sources of information. Future challenges include finding the balance between the shifting ice regimes in high-traffic areas in the Arctic and assuring that navigators with less experience know where to access the correct data to support their activities and how to interpret the information.

Given such factors, Wagner et al. (2020) argue marine operators should not be treated as a homogenous group where it is assumed everyone will have the same knowledge or are able to interpret large suites of data products, for all areas during all seasons. For instance, the KEPLER (2019) and IICWG (2019) reports show highly experienced navigators may prefer different ice information than those who are less experienced, who may travel near ice or completely avoid any ice. Distinguishing a mariners' level of experience can also be considered and related to the ice class of the ship they are operating. For example, ships that are built with higher ice classes will require a more advanced level of certification because it is assumed that the navigators will be travelling through different types of ice regimes within the pack ice or outer pack ice. However, the concern is that a navigator with little experience with sea ice, is operating a ship (that also has a lower ice class) in areas where open water and MYI or glacier ice can be advected from the main ice pack and very quickly drift into an unexpected area. So the linkages between absolutely no ice, low ice area, and a need for more experience for the navigator are weak. It is important to consider these scenarios to determine the best way to support navigators so they can make the best decisions (Polar Code 12.3 – Regulation). Furthermore, Blair et al. (2020) find that planners and navigators frequently face contradictory solutions as they manage uncertainties across different spatial and temporal scales. They therefore recommend knowledge co-production processes for forecast product development (Blair et al. 2020). To understand the differences between mariners, the International Ice Charting Working Group (IICWG) found that there is a need to account for ship capabilities, vessel sizes, level of experience, seasonality, ice regime, and certification and training (Table 3).

Table 3: Factors relevant to the differences in skill among mariners in Arctic waters (KEPLER International Ice charting Working Group 2019)

Ships capabilities	Multiple ice classes from no ice class to Polar class (yachts, cruise, tanker, bulk carriers, coast guard, container and others) and these may travel through various ice regimes (i.e. ice edge, marginal ice zone, outer pack ice, etc)
Vessel Size	Small vessels to cruise ships
Ship Operator/Navigator	Ranges from background with limited experience to high level expertise
Seasonality	Calm and ice free to extremely harsh with no visibility and blocked by ice
Ice regime	Ice free to MYI/SYI and FYI ice mixed with icebergs
Mariner training	Many training facilities specialize in polar regions training and are appropriate for operations in ice, but Polar Code certificates are also issued by Bahamas, India, Philippines.

Sea ice regimes and user information needs

Sea ice conditions vary considerably across the Arctic. In addition to sea ice variability (Figure 1), there are differences in sea ice age, thickness, floe size, and movement, among many others. In the Northern and Eastern part of Greenland and within the pack ice above Svalbard and the Barents Sea, year-round ice cover in some areas and partly very rough ice conditions including ice pressures and heavy multi-year floes. Sea ice mapping in the Arctic is highly dependent on meter-scale remote sensing for operations as the primary source of information, due to numerous safety and environmental risks of in-situ mapping.

As investment continues to grow in the Arctic, marine operations will call for a substantial need to improve information provision through Earth Observation (EO) services and products, to ensure that safe and efficient operations can be adequately supported throughout the year. In particular, ensuring better support for relevant sea ice data products through the Global Data-processing and Forecasting System (GDPFS) will be critical for operationalization efforts. Based on the EU-funded project SALIENSEAS Jeuring et al. (2020, p. 139) identify three key issues in user–producer interfaces of the Norwegian Meteorological Institute(1) the importance of knowing how information is used, (2) the increasing automation of meteorological practices and the growing need for user observations, and (3) the need for bridging research-to-operations gaps.

For Arctic marine operations, proximity to the ice edge determines typical requirements of sea ice products (Table 4). For instance, a captain several days away from the ice edge may be satisfied with an ice product (see glossary) that is several km off, provided it offers a relevant picture of the ice situation. The Norwegian Ice Service defines the sea ice edge as 1/10 of ice or more, but hazardous small scale ice is often also present outside the ice edge, pointing to a need for the resolution to describe ice edge properly and the small scale ice outside. The IICWG Mariner Training Survey (2019) found that there is a need to define quantitatively the qualitative scale "far from ice." This term is used today but raises considerable challenges in terms of accuracy.

Highly experienced navigators prefer to have access to all available information. They will recognize what may require background information to understand the limitations, and interpret difficult areas along coastal zones and the outer pack ice, as well as during the melt and Summer seasons. For these mariners, it is important that information supplementing any other ice information is received onboard and that they are equipped to understand the history of ice in critical areas for navigation. Maps at the kilometer scale and greater are not suitable for tactical navigation in critical areas such as along the ice edge, in the fjords and coastal areas, outer pack ice and marginal ice zone, especially during the sea ice and glacial melt and Summer seasons. In these areas, ships operate and require sub-kilometer regional/local products to serve any vessel all the way from the open ocean to shore and harbor in ice-covered waters. User needs for ice information in the Arctic vary between ice services due to the conditions in which they are required

Table 4: Mariner needs relative to their distance from the ice edge (IICWG 2019, KEPLER 2019)

Ships far from any ice	High spatial resolution ice products are probably not necessary: Typical need: iceberg limit, iceberg clusters, sea ice edge, sea ice distribution compared with average conditions at the scale of 10-100km
Ships near shore and near the ice edge	High resolution and short term ice products (10 m scale, iceberg positions, fast updates, hourly forecasts, observed changes since last observation, daily outlook produced ice analysts, high resolution satellite images in certain regions)
Ships in the pack ice (far from the ice edge)	High resolution ice products (ice thickness, pressure, ridges, drift, strength, leads) nowcasting and 24 h forecast. Scalable files to onboard systems. satellite images, scale 20-50m

to navigate, dissimilar regulation requirements and differences in infrastructure where some may support more frequent in situ observation sites and stations.

Ice service products, requirements, and capabilities

National ice services are the regulatory authority on sea ice information provision of routine information to mariners to support life and safety (Table 5). They follow an international structure to provide standard products and reduce the effort for any one nation to support their national interests for ice navigation and safety in the Polar regions (WMO-No. 574). Norway's area of operational monitoring is considered the European Arctic, the area between Eastern Greenland and Russia. The Norwegian Ice Service and weather forecasting division in Tromsø, Norway, is designated by the International Maritime Organization (IMO), the International Hydrographic Organization (IHO) to provide standardized sea ice and weather information, forecasts and warnings to ensure the safety of life and property at sea. The same mandate applies to national weather forecasters.

Today, the Norwegian Meteorological Institute (MET) Norwegian Ice Service and the Danish Meteorological Institute (DMI) Greenland Ice Service have a common core of end users across their two different areas of monitoring responsibility: MET in the Atlantic section from the east coast of Greenland to Cape Chelyuskin, and DMI in Greenland Exclusive Economic Zone (EEZ). While they have many shared users, the two also serve different needs, and have different expectations of what the other provides. DMI provides regional analysis and broad overview of sea ice including stage of development and icebergs, with a detailed focus on South Greenland inshore and critical areas. MET Norway focuses on the MIZ for Greenland, Norwegian and Barents Seas, and the ice concentration up to the North Pole.

The European Arctic has the highest density of marine traffic in the region due to high population density at high latitudes and increasing socio-economic activity in this sector. Dynamic sea ice conditions in this area provide a seasonality that facilitates easier travel during the Spring and Summer, unlike other areas of the Arctic. Arctic waters are unregulated in terms of shipping lanes. This is in contrast with the Baltic waters, in which there is an international cooperation to keep waters open for traffic by breaking channels where other ships follow.

Operational sea ice mapping and routine products mainly use satellite data but areas where sea ice operations are highly regulated or include communities (i.e. Greenland, Russia and Canada) may include the use of more reconnaissance and in situ observations.

Table 5: National ice service providers in the Arctic (Source: WMO 2019)

United States	US National Ice Center, North American Ice Service (NAIS)
Canada	Canadian Ice Service, North American Ice Service (NAIS)
Russia	Centre for Ice Hydrometeorological Information at the Arctic and Antarctic Research Institute
Norway	Norwegian Ice Center, Meteorological Institute (MET)
Denmark	The Admiral Danish Fleet
Finland	Finnish Institute of Marine Research (FIMR)
Iceland	The Icelandic Meteorological Office
Greenland, Denmark	The Danish Meteorological Institute
Baltic	Baltic Sea Ice Services (BSIS)

The use of satellites has allowed for ice analysts to combine their expert knowledge of ice conditions of a given area, and create valuable services and products for mariners. Ice analysts continue to produce routine ice charts manually because the geophysical caveats caused by melting snow on sea ice during the Spring and Summer, limits the satellites ability to accurately distinguish areas of ice and open water and thicker ice from thin ice types. Currently, most ice services use SAR (synthetic aperture radar) data at approximately 50m resolution or less, yet augment areas of sparse coverage with optical imagery and visible infrared (when available) or passive microwave data (not ideal due to low spatial resolution). The current state of satellites in the European Arctic will continue to have almost full SAR coverage over the monitoring area between Greenland and Russia, however, future satellites may make it possible to provide more semi-automated or fully automated products that can be effectively validated to overcome seasonal limitations. Yet, current satellite capabilities have demonstrated that long-term and seasonal sea ice forecasts can be a reliable source for navigators, but require modifications to make them more easily accessible and understandable for all marine navigators. It is also necessary to note how precision of sea ice feature tracking differs from what is required for routine products from end-users. For example, operational ice services use SAR data for routine ice charting products and for filtering target/iceberg products. In the case of iceberg products, that information can be used in production of an iceberg limit (limit between ice free and bergy waters) in the Northwest Atlantic, monitored by the Greenland Ice Service and U.S. International Ice Patrol (Rudnickas et al, 2018). The iceberg limit is updated 2-3 times weekly and the accuracy is in kilometers; however, it requires approximately meter-scale resolution from SAR in order to be produced.

The EU project KEPLER aims to determine how current information and products developed from the Copernicus satellite observational programme succeed at meeting the needs expressed with user feedback, as well as determine how the term “operational” may be defined differently by an information provider, product developer, researcher and end-users (IICWG 2019, KEPLER 2020). Feedback from surveys, workshops, and personal communication with the maritime community concur that the purpose of ice information is to ensure their activities are conducted in a safe, more efficient manner and to avoid the potential of an environmental impact. In general, KEPLER finds that end users involved in maritime activities request higher spatial resolution data than is currently available from operational satellites, as well as additional parameters such as deformation, leads, ice type, stage of development that are currently not available in routine products fit for marine navigation (IICWG 2019, KEPLER 2019, 2020). Short and mid-term sea ice forecasts (multiple days to up to two weeks) that can represent areas along the coastal zones, MIZ and indicate when leads will open and close, are consistently requested (KEPLER 2019). The “Safe maritime operations under extreme conditions: the Arctic case (SEDNA)” project, concluded that the Arctic activity sector does not often use current sea ice forecasting products for ship navigation because they are not suitable for using on board vessels, have not been adequately verified, validated or enhanced for operational use or strategic ice management (SEDNA 2019).

Maritime operators may use historical data for strategic planning and design, and forecasts for tactical and route planning. Forecasts can be obtained from ice services (if available) and data centers. Yet often they will rely on their own personal knowledge of the area and previous experiences to interpret how this information can be used to support their decision. In the context of a non-stationary climate, these approaches have the potential to yield maladaptations. However, new mariners obtaining Polar Code certification may not have adequate training to operate in ice-encumbered areas, depending on where the training center is located, and certificates can also be procured online. This introduces numerous inconsistencies with mariner experience operating in the polar regions and their level of understanding on how to interpret data, if clear information on product quality is not readily available.

As sea ice forecast products are made available to users, there is a need for understandable and clear metadata included in the data. The IICWG (2019) recommends data quality and uncertainty information in routine products and forecasts, and need to be included in order to be part of an operational product for navigational safety. Furthermore, inaccessible data platforms and barriers to communication continue to be a challenge in the uptake of information products.

This is particularly the case with products that are developed as part of a research funded project and not necessarily developed with the end-user in mind. Most users can obtain information with the use of satellite and iridium connections at high latitudes yet, these do not allow easy integration with large (approx. >1MB) or complicated file formats, especially those that are not scalable. This also can be applied to areas where topography limits clear data transmission (i.e. vessels next to areas in fjords and mountains).

Overall, there are some key areas that present specific challenges for improved operational monitoring that can be supported with the use of improved sea-ice forecasting systems which utilize data assimilation approach with input data on meter-to-kilometer scales and thus relevant for operators and navigators, particularly for areas in the Northern Sea Route (NSR), Svalbard and Greenland waters including the Fram Strait. Climate modeling and research requirements are mainly focused on retrieving long reference datasets over periods of years that use coarser spatial resolution, compared to what SAR or altimetry information can provide today. The key is finding how all information products can support maritime users whether it is short or long-term planning needs. It is well known that there is great variability in region-scale or Pan-Arctic sea ice information products as a result of different retrieval algorithms (Ivanova et al., 2014), that has an influence on how consistent ocean-sea ice analyses tend to be that assimilate those products (Chevallier et al., 2016; Uotila et al., 2018), and the skill of seasonal predictions initialized from those reanalyses (e.g., Bunzel et al., 2016). From an operational information provision service, the key is to find the balance between information that is relevant for end-users and those useful for research-only activities, but that have the potential to lead to value-added products to support navigation.

Workshop findings – Future of the Arctic from a user perspective

The following sections report on the contents of the two workshops by remaining as true as possible to the original way in which statements were made. As such, they focus purely on the contents of what was said, and do not correct or refer to published literature. After this presentation of results, the report continues with a discussion of these findings within the context of the literature and future work.

Expectation for significant increases in Arctic activity:
In the last few years, the Norwegian Coastal Administration has observed that new traffic patterns are being recognized and driven by raw material trade. Despite year-to-year traffic fluctuations, ships continue to utilize the Northern Sea Route to transport resources along the west and eastern regions of the Russian Arctic, with 17 of 28 million total tons being transported through the Norwegian waters and close to the coast. It is projected that 51 million tons of liquefied natural gas (LNG) and condensate minerals will be transported along the Northern Sea Route in 2024, not including traffic from Murmansk and Arkhangelsk. New trends are emerging where Canada exports iron ore to China and Taiwan. These routes trend very close to 79 degrees north before entering the NSR. Today, this area (March 2020) has very heavy pack ice, maybe 1 – 1 ½ meter thick, so this is not possible at present. These routes are often inaccessible in October at present due to heavy ice conditions, but may open for longer periods in the coming years. Additionally, there has been an approximate 40% increase in fishing activity in the Barents Sea since 2013. For future scenarios, this traffic is expected to increase since some fish species move northward. Thus, forecasts are very important for operators to understand, specifically annual and regional anomalies and where unpredictable conditions can be expected due to climate variations.

Recent observed changes in ice regimes:
Despite the sea ice retreat in the Arctic, the region is characterized by seasonal and interannual sea ice variability. For instance, comparing the amount of ice around Svalbard in April 2020 to the ice conditions during the same time in 2019 and 2018, there have already been enormous changes from the perspective of mariners who frequently use this area and are familiar with seasonal ice regimes (Figure 3). These changes - which include all aspects of the sea ice state as well as the underlying ocean structure - combine a response to anthropogenic climate change with large interannual variability, making them challenging to interpret.

Preparedness in Svalbard and in the NSR will benefit from any long-term forecast which can reveal, if possible, anything about how changing sea ice regimes will affect the shipping routes in that area. If there is a situation 5 - 10 years from now where there is less ice and more unpredictability, this will have an effect on preparedness efforts for the NSR. It is unclear whether the situation in the 2019-2020 season, where there was more ice around Svalbard and sea ice extended further south than previous years, was predicted, but participants from research indicated there were some signals to that effect. The fishing industry representative stated, “we’ve seen evidence in the last 3-4-5 years that the water temperature in the Barents Sea has been going down.”

The forecasters said the Bergen group (Bjerknes Center for Climate Research) published predictions on expected cooling in the Barents over the next years because of a cold anomaly of water masses moving northward. The forecast is tentative, however: it is unclear how strong the anomaly is and which regions it may impact. For this reason, it is difficult to say something specific about local areas, for example, the Hinlopen strait, though a rudimentary indication can be provided a few years before in some circumstances. The climate modelers contributed that regional variances can be seen when assessing a global climate model projection. Though the overall

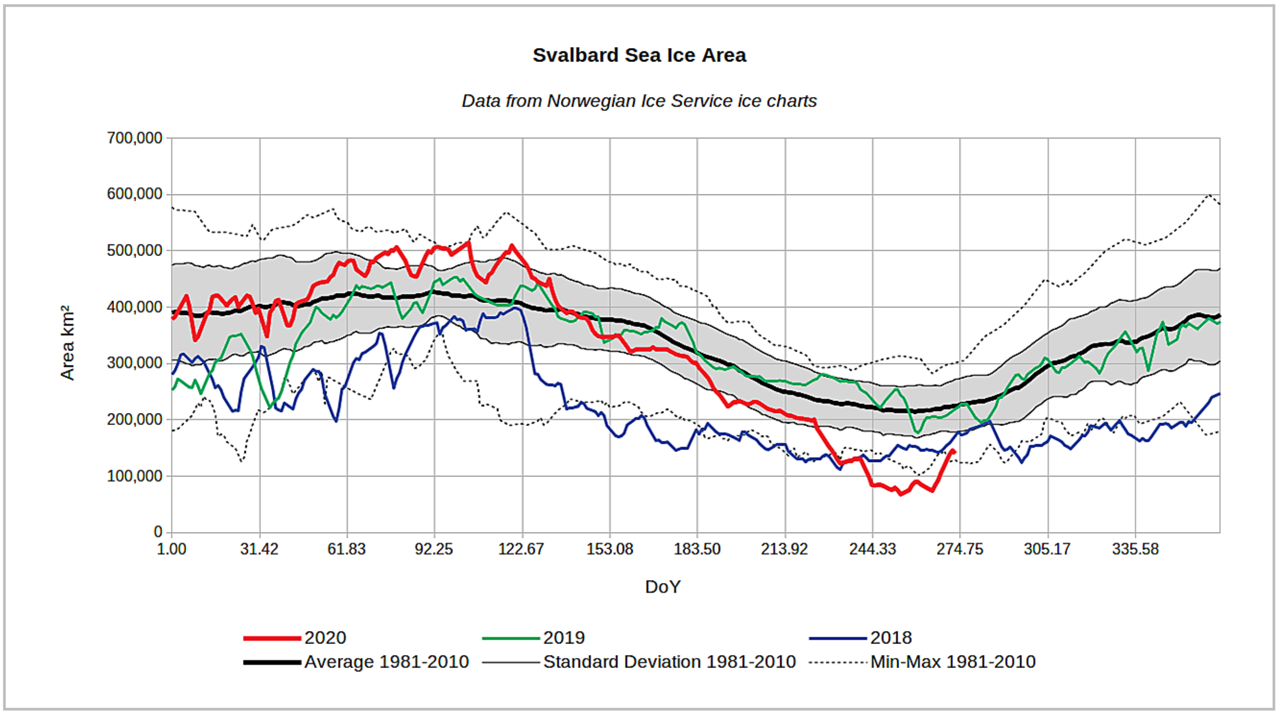

Figure 3: Svalbard sea ice area extent 2018-2020. Data: Norwegian Ice Service (MET)

globe will undergo warming, regional cooling signals can be observed. For many years the Global Climate Models (GCMs) have shown that there are these signatures of North Atlantic cooling spots. Climate modellers are trying to understand some of these features in their models. Improved models of such features will provide more accurate predictions of use to end-users.

From the mariner perspective, the challenge is determining how far south the sea ice will extend. It is a key concern because should some areas experience increased sea ice concentration it will certainly affect both fishing vessels and shipping (i.e. LNG concerns) and almost all vessels, in different ways, travelling in the Arctic waters. Currently (at the time of the workshop), there is a lot of ice south of Storfjord-area and further towards Novaya Zemlya and also Franz Josephs Land, in contrast to the East Barents Sea, where there is significantly less. The extent of the ice edge in these areas influences whether or not there will be more or less ice present rather than open water, for the duration of the summer season.

Maritime Industry User Needs in the Polar Regions

The following discussion provided insights into how users understand products and forecasts. The Arctic and Antarctic Research Institute (AARI), the U.S. National Ice Center (U.S. NIC) and the Finnish Meteorological Institute (FMI) ice service were used as examples of how sea ice forecasts provided from operational providers are used from a user perspective. These institutes deliver many types of forecasts such as long-range, short-range, and compression, in addition to their ice forecasting services, that support their specific maritime community operators. Feedback from participants stated the forecasts from these institutes, as well as the National Snow and Ice Data Center (NSIDC) can be quite accurate, sometimes up to 1-2 weeks, using freezing degree days and other climate parameters.

Additionally, commercial sea ice forecasts are routinely developed using both publicly available and commercial-in-confidence data and models. These are used by gas companies when setting up operations and for long-term planning to understand when they should install platforms and other equipment in ice-covered areas. This is important when considering when and where to charter support vessels. The vessels and equipment should be available to support the operation once ice conditions become favorable. Oil and gas companies may require 5 or more years before a seismic finding requires ice exploration analytics. Once environmental assessments begin, specific personnel will be tasked to investigate ice, weather and climate information and undertake a risk assessment, which may require soliciting commercial support from third-party or national services to perform long-term climatological analysis. However, to reach the goal of enhanced maritime safety, all relevant sea ice information and products must be publicly available and linked to other main authorized data information centers that provide information to support navigation (i.e. web pages, national ice service web pages, Arctic Council and others).

Users apply experience-based knowledge with both ice analysis and sea-ice forecasts

For the most part users understand that ice analysis and ice forecasts are two completely different products. They use forecasts to understand how the ice will move, the type of ice and its age, when it will freeze and melt, and areas of pressure ridges and how or when they may open. Good long term ice forecasts are available today; however, there is a need to include the correct climatological inputs in the models, including seawater temperature, as an important parameter, in order to improve accuracy. Currently, there is not a reliable short or long-term forecast available that provides the detail required for navigation. Instead, navigators use routine ice analysis and imagery to plan operations. For this purpose, navigators need imagery that provides a broad-scale overview of an area larger than their immediate surroundings, as well as point information of the area of operations. For instance, if a ship is traveling 10 knots, it will be moving near 240 miles in 24 hours. Thus, the navigator needs to be able to get an overview of the ice and weather conditions to understand how they will influence one another.

Another example can be illustrated using a fishing vessel operating in an area that contains a lot of ice, for example around the south cape of Svalbard (as it was a case in Spring 2020), where dynamic ice conditions can be expected from the main pack ice or calving glaciers can quickly advect into areas of open water. If the tides around South Cape are approximately 2 knots, and there is a strong north-east wind, the ice can arrive quickly and create a dangerous situation where the vessel can be in a compromising position. This becomes a safety and environmental hazard situation that may require multiple levels of emergency services and corrective action. Subsequently, if when fishing, a long tether is employed over a long period, there needs to be some assurance that the vessel can safely navigate over that duration without having to cease operations. Thus, the fishing boat operator will need to be able to predict where the sea ice will be to make the best decision.

The role of experience and intuition in sea ice navigation

To forecast ice conditions, mariners make use of synoptic maps, local/regional maps, ice charts and imagery to predict where the ice will be the next day. They compare the sea ice observations with the current and forecasted weather conditions and plan the route accordingly. This forecasting requires considerable analytic skills and experience and the navigator needs to rely on their own intrinsic understanding of the whole environmental system and not only the small area around the vessel. They need to understand what is currently present and what should be anticipated based on sea ice conditions, concentration, weather and wind and ocean currents.

While improved sea ice forecasting products are key to securing future Arctic operations, the role of experience and intuition were highlighted at the workshop. The need to develop skills to gain an intuitive sense of how the ice moves in this highly dynamic environment also plays a key role, a participant noted. “You can’t just be in the environment for a few days and then know how to operate,” they warned. Better forecasting tools and products may never completely fill the gap to allow inexperienced Arctic mariners to operate safely. The panel agreed, however, if a sea ice forecast were available this would present a second opinion. Yet, there is and will likely remain a considerable component of navigation in ice covered waters that relies on skill and some degree of intuition. Over time, trust in new services and products should develop after demonstrating the capability to support particular operations. There is therefore a need for continued engagement between operators, forecasters, and researchers.

In the example of fishing operators, a short and long-term forecast (approximately up to 1 week) would be preferred. Currently, the Norwegian Ice Service only offers observations that the mariners then use to make their own predictions of how ice will move in the next 24 hours. From a user perspective, in the absence of forecasts it is preferred to have a good overview of the whole system. This means the Ice Service providing a combination of area and regional observations and images will be a useful compliment to support maritime users with decision making.

Information needs and requirements

The participants shared several key areas in which there are needs for better information and data sharing infrastructure. The participants called for information that:

1. Provides more detail about the location of the ice edge, with higher frequency and in a simplified version of current ice information. The Information should not be too complicated and must be easy for mariners to read and interpret. On today's observations they have to zoom in on imagery, and sometimes it can be hard to determine the exact position of the ice edge just from the pictures. Interannual variability and the dynamics are a considerable source of uncertainty in planning operations, particularly during the melt and summer seasons where satellites underestimate areas of ice due to masked signatures of water. The seasonal variations make it difficult to monitor sea ice in a routine way if we want to include all features that are of interest to mariners with a high level of accuracy.
2. Dissemination of accurate past and future state of the sea ice for navigational safety. Today, the current state of the sea ice is available on the Ice Service web pages and includes a high level of precision on the ice edge and high spatial resolution concentration of sea ice, mainly based on SAR data. Critical information for mariners is knowing when the ice will break up or refreeze, how the location of the ice edge will change over a longer time period, and whether the sea ice is multi-year or first-year medium ice type. These parameters are very important because such forecasting is critical for maritime operations, shipping and tactical and strategic planning. For example, if the ice edge is pushed approximately 3 nautical miles to the north and undergoes forcing from northerly winds, the mariner will need to determine whether this will cause damage to the vessel, equipment, or how this will affect the operation. As an example, a 5 -10 day forecast and short term forecast for sea ice would be good in combination with the long term forecast. Services and products that can present this type of information on these scales should be included in the Ice Service, as a recognized authority of ice information.
3. Has an accessible and user-friendly data format. Forecasts will need to be accessible, have a high compression and must be scalable. Current information with routine products is easy for users to access while at sea, where bandwidth continues to be limited and information is needed quickly. Ice Services and other information centers that want mariners to adopt their products should offer two different web interface options for telephones and easy ingestion for (1) high bandwidth and (2) low bandwidth options. A simple way to implement a forecast would be to offer an image showing ice in a 6-hour time step on expected conditions. The high bandwidth option could be an animation presenting the ice forecast that is ingested directly into the electronic chart system.
4. Provide as a long-term service estimates of the beginning or end of the navigable season. Such a service would provide information on a specific date or week in which to plan for specific sea ice conditions and operations and when the season begins and ends. The historical data would give comparability to understand what the next season might bring.
5. Operational ice information for navigational safety Is provided more frequently. The main request from mariners is that they need to have daily ice charts or ice information that supports navigational safety. Satellite images are available, of course, but the coverage of the satellite image does not always represent ice information in specific positions that may be required. This is where the development of an accurate short term forecast would be extremely helpful.
6. Develop products to support situational awareness to indicate where dangerous ice phenomena can occur. For example, some areas can have high tides and wind travelling in the same direction. This introduces a high velocity in the ice regime and causes potentially dangerous ice conditions to quickly develop in the area. Ice warnings and alerts should be included similar to weather warnings for storms on the coast.
7. Is compatible with the Electronic Navigational Chart (ENCs) on board vessels such that the

information can be displayed there. The German Ice Service (BHS) in Hamburg already do their analysis of the Norwegian ice chart. This format is much easier to ingest on the ship because you can assess the information in relation to the whole marine operation and vessels.

8. Translates climate model outputs into products that provide decision support. For instance, long term business planners may need information about the expected variability in season length. Understanding the influence of and resilience to uncertainties in these medium range outlooks is critical. There is also interest among modelers to ensure their research outputs are made relevant to mariners. In addition, projections from multiple models are needed to provide a sufficient envelope of sea ice variability and change reflecting a range of possible futures.

Limitations with communications and data size requirements

The participants report they need the information sent by email from the Ice Service. These emails should not exceed more than 5 Mb. Even at that file size it sometimes takes 2-4 hours to download the emails. While communications are improving, it is a slow process. Marine operations require attention to many things simultaneously, but "to download heavy maps is not always possible when you are on the edge of the world," the member of the fishing fleet said. During specific operations, persons at the Ice Service respond to e-mail requests for smaller (lower resolution) images that include comments and a forecast for a couple of days. Such communication is helpful because the satellite images themselves are still today very often too big to download.

Obtaining smaller file formats remains a challenge, and mariners therefore need to find ways of downloading and processing data with low bandwidth. The VSAT communication has offered some improvement, but precipitation, snow, freezing snow, the icing on the antenna and other issues can limit bandwidth even within coverage of VSAT communication. North of 78-79N, meanwhile, VSAT is not available, such that North of New Ålesund there is no connection, apart from some small spots in Hinlopen, for instance. Furthermore, Iridium will be operational soon, and the HEO satellite is coming up soon, giving broadband communication in the north. For custom support, Ice Services can upload maps and imagery and it allows the mariner to access the FTP client to download data for easy connectivity in the very high Arctic and pole expeditions.

File sizes are a limiting factor at 'the edge of the world' where a 5 MB might be a limit, as well as at other places and times where reception is spotty and speed of information is important. While some suggestions were to increase the radio coverage or bandwidth, another suggestion was to have maps that cover a much smaller area that is more tailored to the general location of the ship and the direction of sea ice and the ship's track. Since they cover less area, these files could still contain notable detail but would likely be smaller and thus easier and faster to both transmit and receive, especially in bad weather or locations with spotty or intermittent reception.

Future of the Arctic from a user perspective

Changes to the dynamics of Arctic sea ice presents challenges to careful planning of Arctic marine operations. The Arctic draws increasing attention from a variety of actors seeking to take advantage of expectedly increased access to Arctic waters. The varying level of skills and experience of these new shipping actors presents a need to prepare for a near-future influx of inexperienced mariners in an increasingly dynamic system. This concerns all ship and polar classes, from larger to smaller overseas and expedition cruises, yachts, fishing vessels, and cargo, container, and oil tanker vessels. With this motivation in mind, the results from the two-part workshop contribute to ongoing consultations with end-users in order to better understand knowledge needs, as well as to highlight some key capabilities and limitations of models and technology in the ability to deliver on those needs in the immediate and longer term.

Findings from previous workshops suggest additional ice certified pilots is only part of the solution to safe navigation in increasingly dynamic arctic waters (c.f. recent sea ice-related projects SALIENSEAS, SEDNA, KEPLER). There are concerns with internet-based certification courses that are inadequate and may compound problems with safe navigation and skillful interpretation of sea ice products during operations. Indeed, these consultations with end-users have uncovered that misinterpretation of sea ice information across temporal and spatial scales is widespread also among experienced mariners. Two recent high profile events are testament to this issue, such as the salvage operation of the fishing vessel Northguider in the Hinlopen Strait, and the delayed resupply of Polarstern's MOSAiC Expedition.[1] Both these incidents by expert operators in 2019 were affected by unexpected sea ice conditions that caused severe delays. These findings are echoed by the IICWG Mariner Survey, 2019 and TASK TEAM 8: Mariner Training Requirement document, 2019 (IICWG 2019). Overarching recommendations include: 1) develop improved predictive and monitoring capabilities for hazards and key climate indicators in the physical environment in Polar Waters, 2) establish routine procedures that connect product development with needs from the user base, and 3) establish regulations and requirements to fit the changing Arctic. There is a need for these types of information to be accessible, intuitive and understandable, with the intent of supporting and targeting the region-specific user needs in mind with the right products. Feedback also clearly states that it is important to create awareness that products developed for data centers and operational products and services for navigational safety should not be confused or presented in a way that can mislead end-users as to the intended purpose. For instance, the satellite images from NSIDC and Copernicus are not readily produced for all end-users, though experienced mariners may be able to use them. However, they are often pan-arctic and therefore not specific enough for tactical or strategic operations, though may be helpful for long-term planning. Information required for long-term planning may require more precision, where on climate scales may mask much of the variability in sea ice extent. In addition, projections from multiple models are needed to provide a sufficient envelope of sea ice variability and change reflecting a range of possible futures (Stephenson and Smith 2015).

It is important to note that the term "operational" has introduced some confusion in the past with researchers, operations and end-users, but this is an issue that arises more widely (International Ice charting Working Group 2019). Hunke et al. (2020, p. 122) highlight the differences between researchers and operational communities work, saying, "research and operational communities have different goals, requirements, and

1. https://mosaic-expedition.org/

needs." The need for an agreed and known definition of what constitutes an operational sea ice map product is an issue that has also been raised by the EU, UK MET Office, Russian Ice Service, and MET in previous consultations, as well as within the Norwegian Ice Service itself. "Operational" has many colloquial uses, leading many to have an intuitive understanding of the term in sea ice forecasting. For instance, researchers may expect that a novel mapping or forecasting tool of use to mariners should be made available on the Ice Service web pages. The reluctance to include such innovative tools leads to some contestations of the roles and responsibilities of the operations group and the research and development group. This contention can be resolved by clarifying where product development fits in connection with products that are fit for operations for navigational safety.

The issue of access to timely information in an accessible format at the right temporal and spatial resolution was raised by several participants at the workshop. Some of the challenges relate to a lack of coordinated information sharing among different information providers, analysts, forecasters, and users. One potential innovation that can render the information processing and communications flow would be a more structured, closed loop system in which appropriate inputs and feedback in the Norwegian Ice Service work flow are predictable and allocated (Figure 4).

A more structured and predictable network of interactions with MET might also allow for more integrated international information sharing. For instance, MET's section in the Atlantic from the east coast of Greenland to Cape Chelyuskin contains many shared users with DMI in the Greenland Exclusive Economic Zone (EEZ), but the two also serve different needs, and have different expectations of what the other provides. This in turn can present challenges to users moving across the DMI and MET service areas. More structured future work flows within the MET between the two institutes will use the opportunity of collaborating on shared areas of monitoring and aim to improve ice products and services to the shared user community.

Some restrictions on access to improved sea ice products arise due to the short life span of research projects. Some products from the research and development group that may have navigational value for mariners cannot be provided reliably over time and

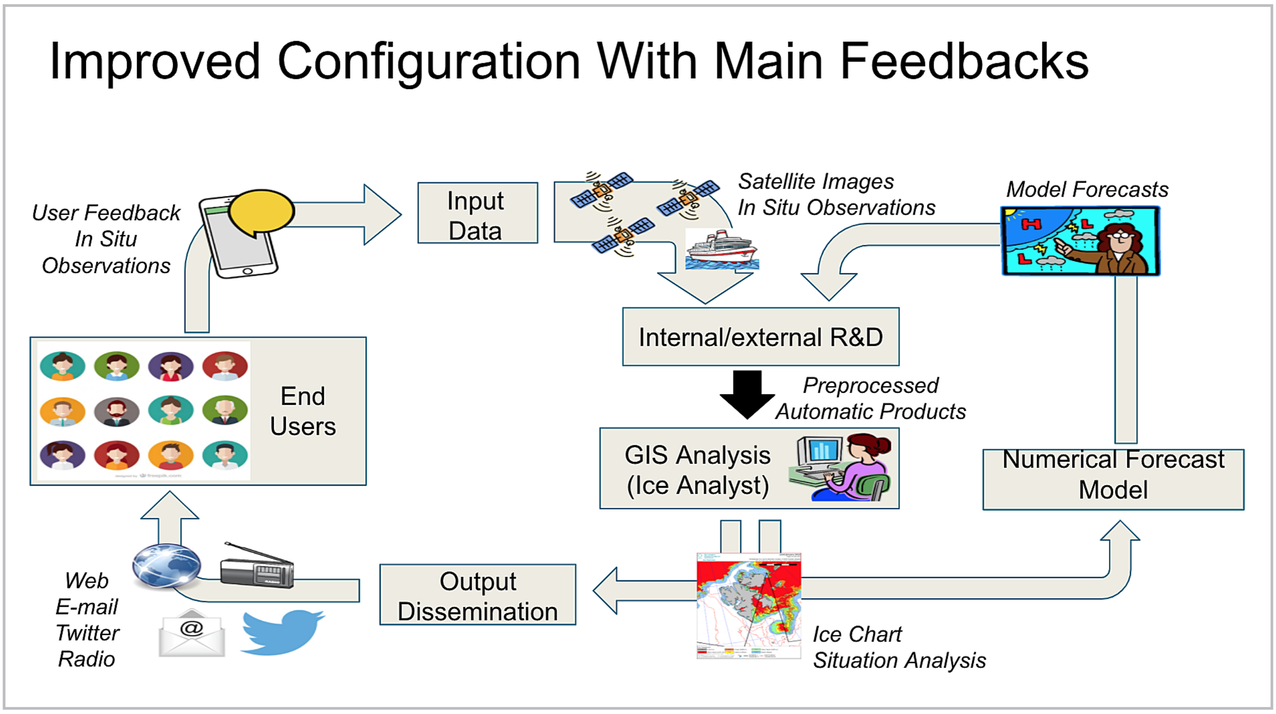

Figure 4: A conceptual diagram showing the linear perception of the Ice Service workflow. Note that the workflow starts from the input data and ends with users and numerical forecast models. The only connection returning information through this supply chain is direct from end-users to the GIS analysts.

as such are not ‘operational’ under WMO and IMO mandates

Key information for mariners is knowing when the ice will open up and close and the current state of satellite capability has not yet demonstrated the ability to accurately represent these features. The Barents-Roms 2.5 km ocean model AMSR2 can detect some of the opening closing areas, and has been evaluated by the Research and Development division in MET and was used to provide additional support for the Northguider operation in Hinlopen Strait, July 2020. Additionally, due to the previously stated limitations during the melt and summer seasons where it is more difficult to accurately detect ice types and concentration in the outer pack ice and at the ice edge, low resolution satellite images over the ocean should be avoided for areas with low concentration sea ice and rough sea state. From ongoing feedback from The EU Horizon2020 project KEPLER and other previous and ongoing collaborations with users including SALIENSEAS, we know that an experienced mariner always follows ice development and history in critical areas, in order to be prepared for the worst and aim for the best/safe route in ice-covered waters. KEPLER (2020) found that the types of concerns the mariner will have is (1) whether or not the vessel can go through a given area, (2) how long to wait or divert, (3) how will conditions change with the tides, and (4) develop contingency plans for unexpected occurrences (IICWG International Ice Charting Working Group report, 2019).

Participants in the workshop expressed a need to set up long-term collaborative projects. An example of this can be seen between the fishing fleet and ice researchers. Such a collaboration has been ongoing, for instance, in the Reference Fleet, the continuation of a project from 1983-1990 on fisheries ecology. Fishing vessels today continue to report catch data in the continuation of that study. In weather forecasting, there is a process connecting ice service, users, and researchers - in the manner that is done today in weather forecasting. Such a collaboration for sea ice mapping and forecasting would be beneficial moving forward into the changing traffic and sea ice dynamics of the Arctic Ocean.

Future work

This pair of workshops was intended as the start of a conversation to explore issues and to open for longer, more in-depth, and targeted discussion of needs, as a step in the continued work to identify and fill knowledge needs for navigation in ice-covered waters. The authors are engaged in several ongoing and proposed projects to understand the interactions between sea ice change and decision-making at various policy levels. Participants at these two SSG workshops expressed a wish for long-term collaborative projects in this effort. For instance, future research with the fishing industry can help ensure they are integrated in the research and product development process of the Norwegian Ice Service. Today their needs are not well represented, while those of the cruise sector have received much attention. Further work also with the Coastal Administration can ensure engagement on multiple scales for strategic and tactical operations.

There appears to be a disconnect between what the models say and what changes in sea ice the users, planners, or investors expect. This disconnect between forecast developers and end-users is largely due to inherent limitations with the use of low spatial resolution input data, unclear communications of forecast uncertainty, difficulties with accessibility from the user and a lack of coordination during the product development phase, that affects the relevance of these products to support operations. For end-users, their willingness and wish to integrate their feedback and requirements through an iterative process will help develop synergies and better understand skills, limitations, and promote tools to communicate user needs and researcher capacities. This can be facilitated by connecting with complementary programs and initiatives. An easier way to engage end-users is to establish formal cooperation opportunities, with continued discourse, to develop a longer-term strategy. This allows both groups to jointly develop and validate prototype products. It has the co-benefit of building capacity among product developers and end users engaged in the process. Sea ice models can be used for more practical applications by users from governance and investment. Projects that develop forecasting products can aim to include relevant information that allow users to make informed decisions for navigational safety, which can then be developed into operational products for consistent access by mariners.

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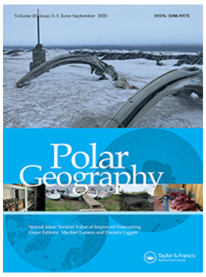

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Sea-ice information and forecast needs for industry maritime stakeholders

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ABSTRACT

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 into 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. Although 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.

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Sea-ice; forecast; stakeholders; operational; navigation; spatial and temporal resolution

Introduction: environmental and socio-economic changes in the Polar regions

The Polar regions are undergoing dramatic changes, with Arctic sea-ice winter maximum and summer minimum extents decreasing steadily since the 1980s, with the 12th lowest summer minima occurring within the last 12 years (Fetterer et al., 2017; Meier et al., 2018), and summer navigation seasons lengthening (Stroeve & Notz, 2018). Localized winter openings of the pack ice (Moore et al., 2018) anticipate similar future trends with increasing water temperatures (McFarland, 2018) and demonstrate how unstable and

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le the Arctic ice pack is becoming. As the ice cover becomes thinner and more , it is more susceptible to oceanic and atmospheric forcings. Pack ice fracturing is to be increasing during winter, contributing to further deformation and thermo- melt (Hwang et al., 2017; Itkin et al., 2017; Stroeve et al., 2014).

Antarctic, sea-ice was slightly expanding overall (Comiso et al., 2017; Parkinson & , 2012) with consecutive record highs for the annual maximum in 2012 through ›wever, in 2016 the extent plunged to unprecedented low levels and has remained ›erage (Turner et al., 2017), apparently caused by a shift in regional modalities lted in the re-emergence of the Weddell Polynya (Carsey, 1980; Doddridge & Mar- l7; Swart et al., 2018). Nevertheless, there is still a substantial variation between the minimum and winter maximum extents in both hemispheres with large areas of sea- cover. This is also found in a number of sub-polar seas including the Baltic and Seas, and the Great Lakes, often with regional lower salinity characteristics (Gran- l., 2006; Kosarev, 2005). The Labrador Sea is unusual due to the preponderance of Around the Antarctic, icebergs have been recorded at sub-polar latitudes in the :lantic and South Pacific sectors (Burrows, 1976; Morgan & Budd, 1978).

e changes have affected socio-economic activity, driving new levels of activity invol- blished and new stakeholders. The use of trans-Arctic shipping routes and areas of 'or tourism is expected to increase with the longer open-water seasons (Melia et al., ıith & Stephenson, 2013). With the finalization of the International Maritime Organ- MO) Polar Code (PC) (IMO, 2014) and construction of new ice class ships, increas- ity in all economic sectors is expected (Deggim, 2018; Jensen, 2016; OECD, 2018). ıally, the PC now mandates that 'ships shall have the ability to receive up-to-date ion including ice information for safe navigation' and requires a risk assessment ›logy, POLARIS, to determine the limitations for ice operations (IMO, 2014). ll require more detailed sea-ice and weather information, encouraging numerous information providers (Knol et al., 2018; Lamers, Duske, et al., 2018; Melia et al., owever, navigating ice-covered areas requires both broad and precise knowledge nditions depending on the region and type of activity.

ler to produce appropriate products for users, it is necessary to define suitable spatial poral scales. In meteorology, short-, medium-, and long-term temporal resolution ›nsidered a few days, a week or ten days, and from a month to seasonal, respectively. resolution of 10 km in numerical weather prediction (NWP) is usually categorized ı resolution. Definition of low, medium, or high resolution in the satellite remote community depends on the data provider or user. For example, satellites using nicrowave (PMW) images are considered low resolution for navigational purposes, resolution for NWP (Montmerle, 2018). Tactical navigation will require high spatial cale) and temporal (hourly or daily) resolution in near-real time (NRT), to enable decisions and avoiding hazardous conditions. Voyage planning, logistics, and infra- development requires longer time scales (monthly, seasonal, annual, and decadal) re for future ice conditions. This group can also benefit from real-time, historical ogical), and forward-looking (forecast) information.

›us studies identified services providing information and forecasts to support ice ›n and planning (Hamilton & Stroeve, 2016; Knol et al., 2018; Lovecraft et al., owever, the rate of growth of users and information providers is potentially exceed- ınderstanding that is needed from both groups to work together effectively. Infor- providers face challenges with the uptake and usability of their products when 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 (EU-PolarNet, 2018). We summarize sea-ice information and potential forecast needs and challenges for Polar Regions stakeholders, including the operational, geopolitical and local requirements, and the need for varying levels of spatial (meters to kilometers) and temporal (hourly to annual) resolutions.

30

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 (Hamilton & Stroeve, 2016; Massonnet et al., 2012; Stroeve et al., 2012). Navigation will likely become easier as the sea-ice cover shrinks and thinning continues (Melia et al., 2016; Smith & Stephenson, 2013; Smith et al., 2011). The thinning and loss of perennial ice continues, and could introduce areas of instability where consolidated ice was previously expected (Kwok, 2018). Ice retreat and advance begin earlier and end later, respectively, so that first-year ice (FYI) has less time to thicken throughout the winter is more susceptible to summer melting (Stroeve et al., 2014, 2018). This trend will allow seaways to have longer transit seasons in the future. It is unclear whether the recent decrease in the Antarctic ice-cover is permanent or part of Southern Hemisphere climatic cyclicity (Marshall et al., 2004; Turner et al., 2017).

The use of Arctic routes is presently a commercial risk for shipping companies as there is uncertainty regarding the ice risk, leading to potential damage for ships and delays (Humbert & Raspotnik, 2012), with certain types of vessel (i.e. container) often unwilling to risk delays to maintain a specific schedule, and greater insurance costs. The development of shipping routes remains tied directly to natural resources, and for the Northern Sea Route (NSR), the future economic security of the Russian Federation. There is an ongoing assessment to evaluate if it is more cost-effective to use these Arctic routes due to requiring more infrastructure including icebreaker capacity, higher risks for search and rescue (SaR) and disaster preparedness, and improved bathymetric and sea-ice information (Aksenov et al., 2017; Barents Observer, 2018, December 5). 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 (Ellis & Brigham, 2009).

An increase in polar expedition tourism is anticipated with reduced sea-ice facilitating access to unique locations featuring exotic wildlife and interesting historical connections. In the Arctic, the season ranges from April to September and operations are expected to extend further west through the Northwest Passage (NWPS), eastward toward Novaya Zemlya, and to the North Pole. Cruises seek out concentrations of wildlife near the Marginal Ice Zone (MIZ), and the Arctic coastlines feature a multitude of sites of historical interest that educate the visitor in understanding the local inhabitants extreme endurance and ability to thrive under difficult conditions. In the Antarctic the season is from October to March, and cruise ships are expected to travel further south along 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 where the sea-ice and iceberg regime can change rapidly to hazardous.

The MIZ and ice edge are also important for fisheries in both hemispheres, with accurate mapping and forecasting being critical. The Barents and Bering Seas have high activity all year round with frequent vessel casualties. Recent examples include a shrimp trawler, *Northguider*, grounding in the Hinlopen Strait, Svalbard during December 2018 (Barents Observer, 2018, December 31), and numerous crab fishery boats in the Bering Sea lost due to vessel icing (NIOSH, 2017). The Bering crab fishery has a high activity with a limited entry system for quota shareholders who then harvest until their quota share is filled. In 2016, the harvested value in Alaska totaled approximately $250 million with the majority (almost $216 million) produced by the Bering Sea and Aleutian Islands (McDowell, 2017). In the Antarctic, the krill and Patagonian Toothfish fisheries have most activity during summer months using ice-strengthened vessels that can cope with light ice conditions, but can get trapped by heavier 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 NWPS, 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 ice-free summers (Dawson et al., 2018; Farré et al., 2014; Rodrigue, 2017) (Figure 1(a)). Resource extraction occurs in 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. Operations in these regions begin as seasonal ice retreats in the summer. Studies from the last 7 years show an increase in the NSR and closer to the North Pole. Leisure and passenger vessels are expected to seek new areas of interest in the eastern NWPS (AECO, personal communication, April, 10, 2017; gCaptain, 2018; NASA Earth Observatory, 2018). How much drifting multiyear ice will affect northern routes 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. 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 continue throughout seasonal sea-ice cover.

The CA that includes numerous straits, sounds, bays, and inlets, is a highly heterogeneous region for summer ice conditions. Some regions present a significant interannual variability, in both the actual occurrence and duration of an open water season, and they are often observed in the central part which covers a large part of the NWPS. 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 nonlinear manner. The NWPS does not open every year although the frequency of opening and duration of the open water season has seen an increasing trend since the mid-2000s (Figures 1(a) and 2).

Alternatively, in the NSR, a number of regions of perennial ice cover, referred to as ice 'massifs' (Marchenko, 2012), are maintained throughout the summer, yet, some areas show low or ice-free passages for parts of the year. The Kara and Chukchi Seas clear first,

32

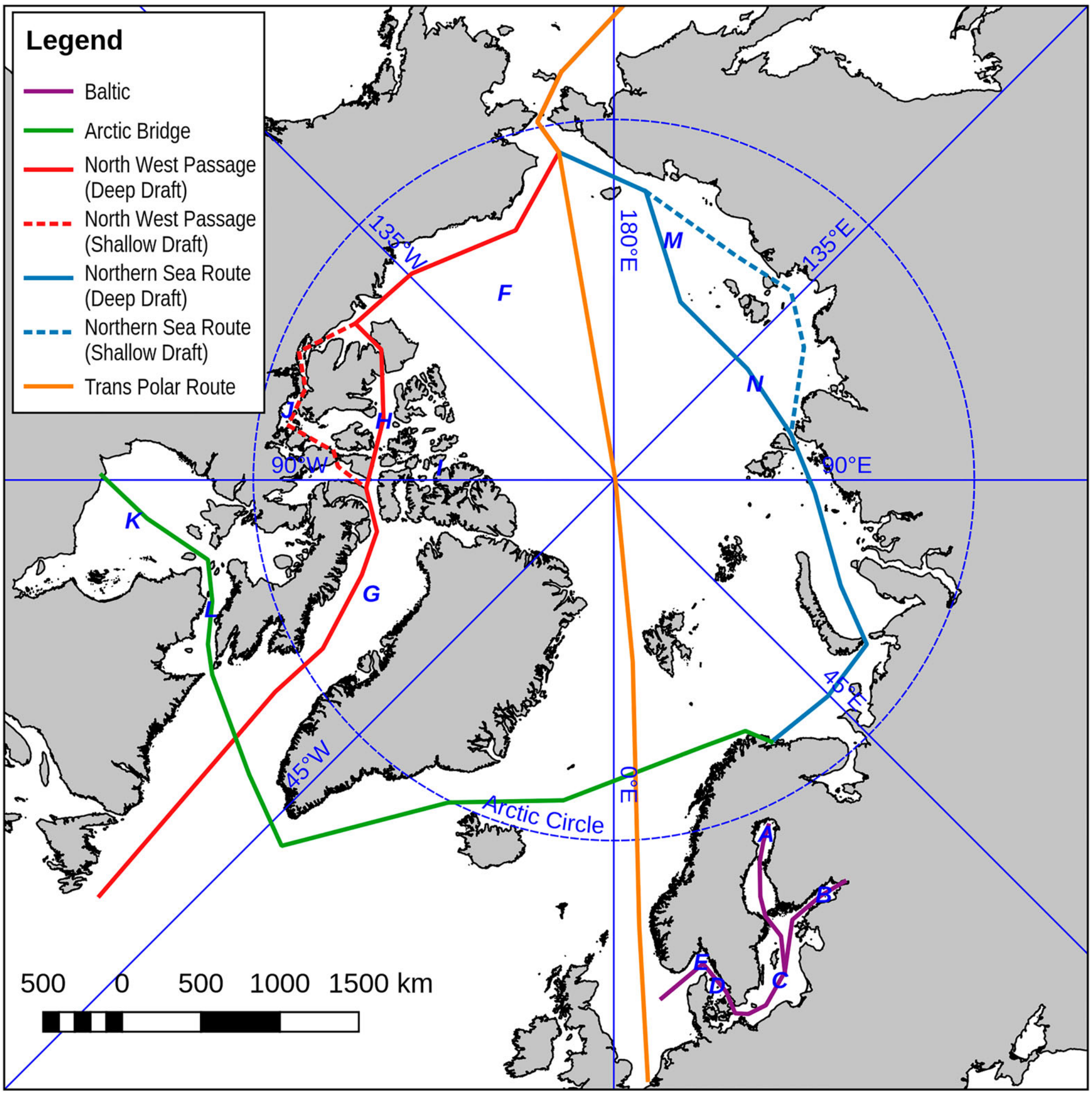

Figure 1. (a) Main Arctic routes for the Sub-Polar Seas, Canadian Arctic (CA), and the Northern Sea Route (NSR). In the sub-polar seas, ice formation typically starts in the Bay of Bothnia (A) and develops toward the Gulf of Finland (B), but in mild winters both areas see only partial ice cover. In severe 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. (b). 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).

followed by the Laptev and East Siberian Seas (ESS) (Figures 1(a) and 2). Ice disappears from 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

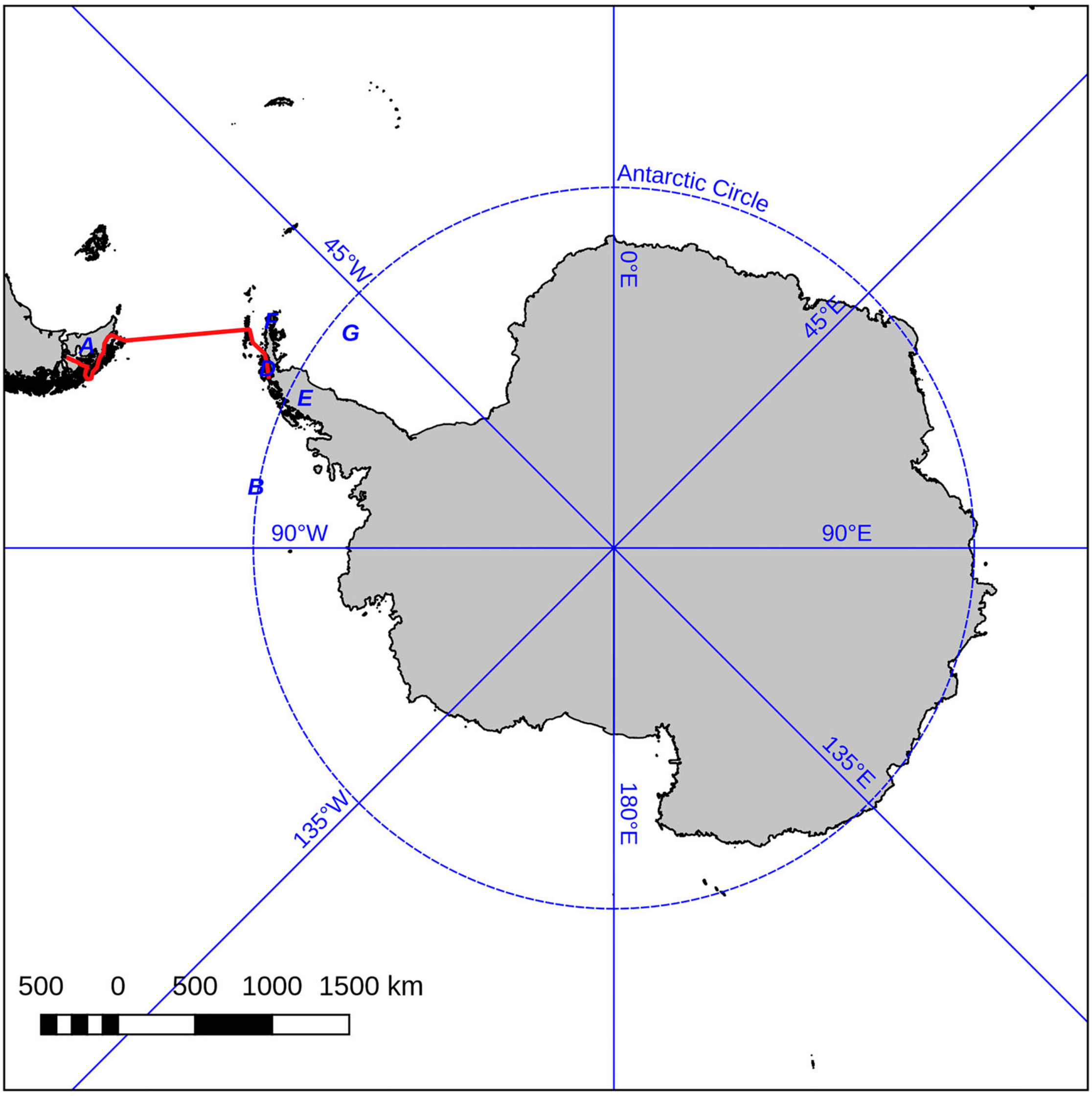

Figure 1. *Continued*

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 Zemlya (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 km^2 circumpolar ring of sea-ice encloses the entire continent and reducing to a minimum of ~3 million km^2 in February. Only the western coastline of the Antarctic peninsula remains ice-free most years (Parkinson & Cavalieri, 2012; Wadhams, 2000). The ice cover is heterogenous, with recurring polynyas all around the Antarctic continent. Sea-ice melt differs regionally where in regions with large polynyas, sea-ice retreats southward from the outer sea-ice edge and northward 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, thus activities are limited to expedition

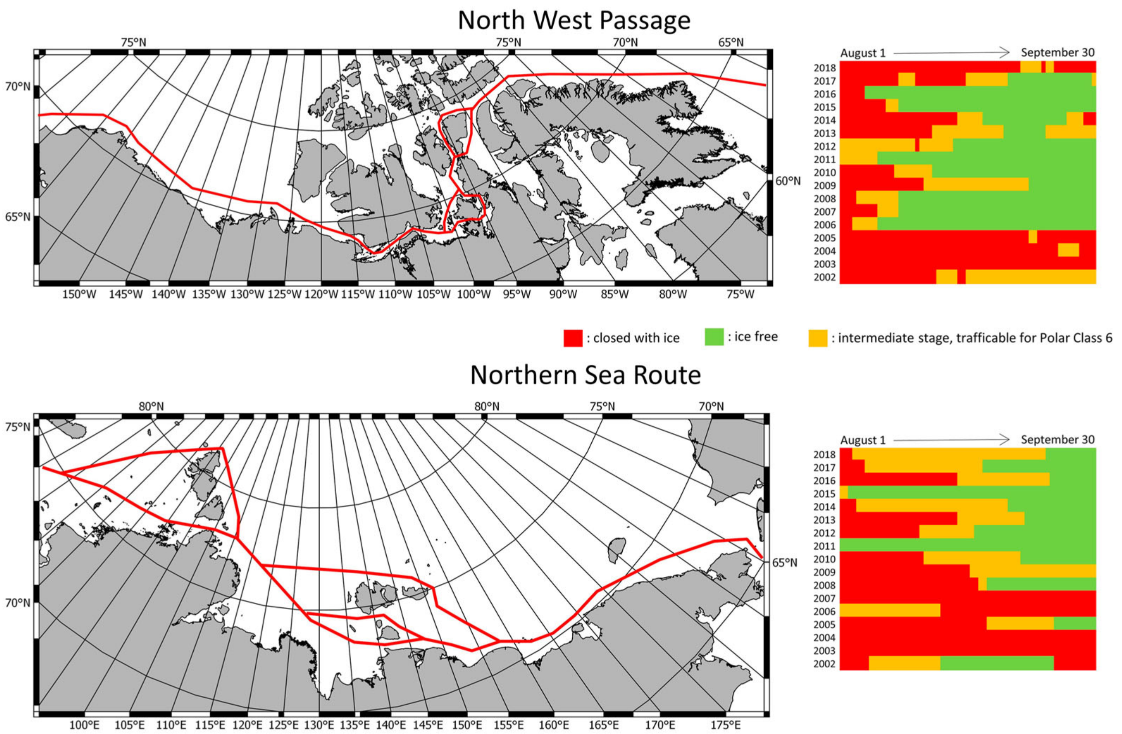

Figure 2. Interannual comparison (2002–2018) of the trafficability of the NWP and NSR for the two months period August 1 to September 30. The examined routes are marked as a red line. Trafficability was examined for any of the possible route options. Defined trafficability stages are 'Closed with ice' 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.

cruise ship and extreme recreational tourism, logistical supply to research bases and fisheries. 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 small channels and fjords (Figure 1(b)). Additionally, all Antarctic waters carry a high risk of icebergs all year round. There are also an increasing number of ships going into Antarctic Sound and the Weddell Sea (Bender et al., 2016).

Methods

This paper collates combined experiences and knowledge of the authors on stakeholder and end-user feedback over the past decade. Conclusions from previous reports, funded by the European Commission (EC) and the European Space Agency (ESA) assessing user-needs assessments and stakeholder needs, are compared with recent documented feedback user surveys and workshops organized and conducted by the national ice mapping and research agencies. These show consistent agreement in the monitoring requirements for maritime safety in ice-covered water and these are reviewed here. The number of studies addressing sea-ice information provision demonstrates this is an important issue for the information and forecast provider community. However, challenges remain as to which user requirements should be addressed, and how these should be fulfilled. Sources for user feedback have been assembled by various funding agencies, research and operational institutes both independently and in collaboration. Efforts to determine user requirements have been primarily driven in the sphere of European scientific development, beginning with the joint EC and ESA programme Global Monitoring for Environment and Security (GMES) that evolved into the present Copernicus global monitoring programme. The authors were engaged in preparing a number of these reports (ACCESS, 2012; Goodwin et al., 2004; McDowell Group, 2017; Polarview Earth Observation Limited, 2016a, 2016b; Seina et al., 2013; SIDARUS, 2011) and these are listed in Table 1.

In addition, there have been a number of unpublished surveys, originating from national ice charting agencies and recent project workshops, including SALIENSEAS and KEPLER (EU-PolarNet, 2018; Lamers, Knol, et al., 2018). Inputs from personal communications with representative industries have also been included. A list of these workshop reports and unpublished surveys are shown here as Table 2.

The aim of combining previous and current user and stakeholder feedback is to present a framework that ice information providers and developers can use to prepare for future needs and contribute to safe navigation.

Types of stakeholders and end-users

Sea-ice information, ocean, and meteorological 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 needed for tactical or navigational information, such as leads and pressure ridges, are not normally included in derived operational products.

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 maximize 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 specialized 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,

36

Table 1. Participating partners in European Space Agency (ESA), European Commission (EC), and consultancy reports specifying end-user needs for information provision to support maritime activities.

Title	Funding Agency	Participating Partners	Pub	# of Respondents	Industries
ACCESS (2012)	EC	A	Yes	24	Shipping Oil, Gas and Energy, Fishing, Air Logistics, Navigation and Operations, Climate and monitoring research
SIDARUS (2011)	EC	A	Yes	18	Shipping, Marine Safety, Marine and Coastal Environment, Fishing, Climate and monitoring, research, Navigation and Operations, Marine Offshore
ICEMON, Goodwin et al. (2004)	ESA	a,j	Yes	N/A, representation from industries	Ice Navigation and Transport, Ship design and offshore construction, Port and maritime authorities, Environmental Monitoring, Weather and Ice Services, Climate and monitoring research
POLARIS: Executive Summary, Polarview, (2016b) POLARIS: D2.1: Gaps and Impact Analysis Report, Polarview (2016a)	ESA	j	Yes	50	Environmental Impact Assessment, Engineering design, Navigation and Operations, Risk Management Emergency Response, Weather and ice Services and Forecasting, Climate and Monitoring Research
ISABELIA, Seina et al. (2013)	ESA	Finnish Ice Service	No	5	International Organizations, Icebreaker and Maritime Authority, Marine Safety, Shipping, National Maritime Authorities
The Economic Value of Alaska's Seafood Industry, McDowell (2017)	McDowell Group and personal communication	g,h,i	No	N/A	Fishing

particularly in Svalbard and by indigenous peoples in Greenland and the Canadian Archipelago, icebreakers maintaining navigation on the NSR and NWPS, 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.

37

Table 2. Participating partners in workshop reports and unpublished surveys.

Title	Funding Agency	Participating Partners	Pub	# of Respondents	Industries
Arctic Frontiers 2018 – Arctic Sea Ice Prediction Stakeholders Workshop	Clic, SIPN2, NIS	a,c, d,e,f,g,i	Yes	55	Tourism, Oil, Gas, and Energy, Shipping, Climate and Monitoring Research, National Maritime Authorities, Fishing, Information Providers, Arctic Logistics and Planning
Arctic Frontiers 2018 – SALIENSEAS Stakeholder Advisory Group Workshop	SALIENSEAS	a	Yes	20	Tourism, Navigation and Operations, Weather and Ice Services, Icebreakers, Information providers, Marine Safety
Polar Tourism	MET Norway	a	No	16	Tourism
KEPLER Arctic Shipping Forum	EU	a,b,j	No	13	Shipping
IICWG	IICWG/Nautical Institute	Pers. comm., Greenland Ice Service	No	95	Shipping, Navigation and Operations, Weather and Ice Services

Another type of stakeholder does not use sea-ice information themselves directly for operations, but as an input for other products that are then utilized 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 (>1 km). However, requirements vary with either global or regional application and are likely to be more demanding in future with higher resolution regional models featuring resolutions <1 km or Finite Element Method (FEM) variable triangular gridding (Rampal et al., 2016).

Insight into stakeholder and user needs

There is great interest in identifying and providing support for stakeholder needs. Yet, 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 need to make decisions on how to proceed. This is especially critical for infrastructures ability to withstand expected sea-ice conditions. For those working near ice-infested waters, sea-ice information needs to be accessible; its relevance well understood; suitable spatial and temporal resolutions available; low bandwidth, and should have the ability to be visualized to efficiently aid users making informed decisions.

User requirements for sea-ice information and forecasts

Information is primarily provided from remotely sensed data because satellites are able to observe at multiple temporal and spatial resolutions over large areas. However, the relationship between the two is 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 copious sea-ice-derived products, yet sending the relevant information can be a critical issue that is overlooked. Users often desire high-resolution data in NRT, but their ability to obtain it is a trade-off where factors include data transmission limitations and cost. Customers will use easy and familiar products in preference to new products until experience allows them to have confidence in the information and its limitations, quick access to the information when needed. It is not always clear to users which new products are available, how to distinguish differences between products, and how to use the data and format. In the Barents Sea, there has been interest in the ice edge due to the proximity of energy company exploration activities, with the different parties drawing ice edge products and using them to illustrate their argument (Rommetveit, 2017; Steinberg & Kristoffersen, 2017). This has introduced confusion between products used for climatological studies and those intended for tactical purposes, though both are valid for planning purposes. In order to identify what is useful for different stakeholders, it is important to acknowledge the scales required for varying operations, locations, and seasonal ice conditions (Figure 3).

Forecasts are used by stakeholders to plan future activities and provide guidance in gaps of sporadic satellite coverage. 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. Feedback from users express the desire to have uncertainties, which is not always easy to include due to the difficulties of accurately assessing critical initial conditions for the weather, sea-ice, and oceanographic parameters (Clements et al., 2011; EU-Polarnet, 2018). This results in forecasts that have not always been developed with the needs of the user community in mind, despite users articulating their needs well, potentially limiting their usefulness for tactical or strategic activities. Along with 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). Drift and SIC are particularly important because they help identify relevant locations, and when equipment damage may occur. Bering Sea crabbers 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. The inability to meet user needs is often attributed to the main fundamental factors; (1) absence of technology (sensors incapable of providing the accuracy to real-life data that users require), and (2) lack of cooperation, harmonization, and standards at the national or international level.

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 (Sandven et al., 2006; Webster et al., 2018). When providing sea-ice information for users, it is important to consider types of ice expected to be present during all parts of the season in order to resolve ambiguities in remote sensing data.

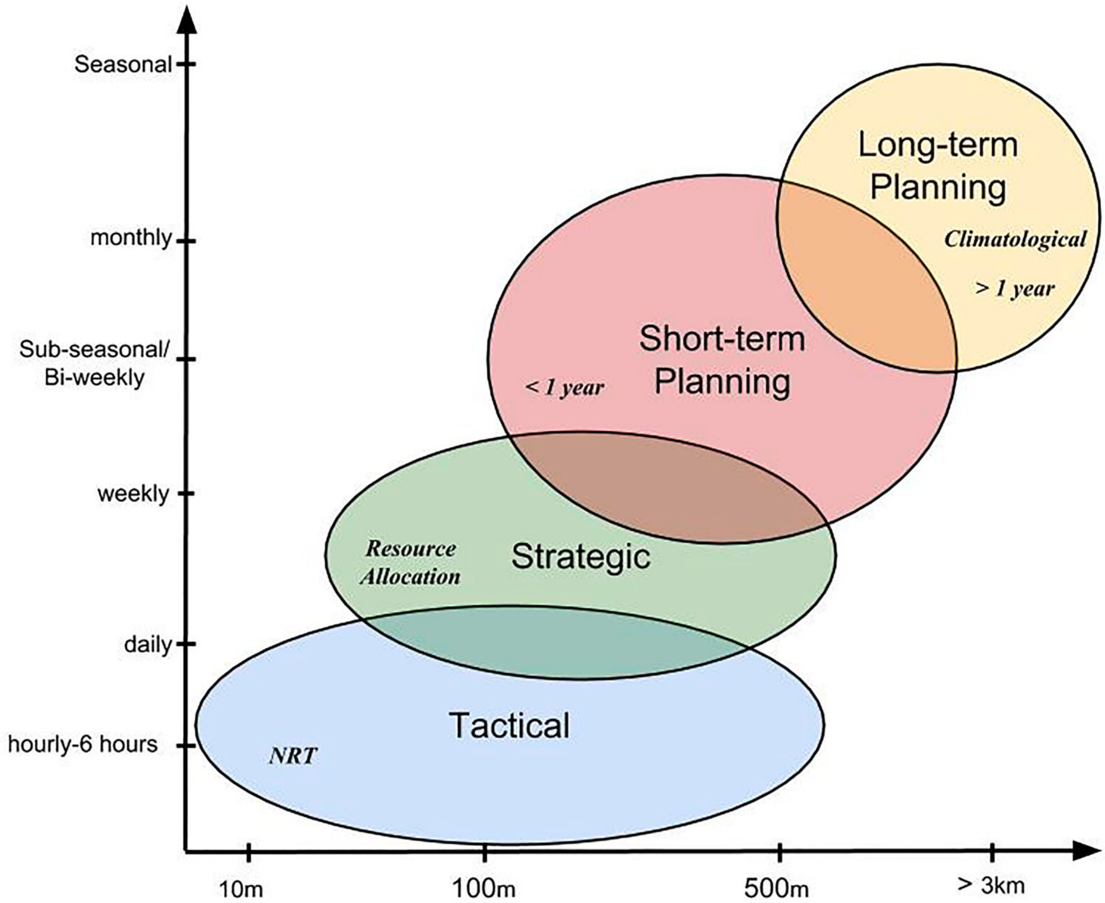

Figure 3. Schematic illustrating an example of the range of typical spatial and temporal scales of information required by users.

Information requirements are determined by different stages of activity and planning. Most activity occurs during the summer and is affected by the timing of the spring melt or autumn freeze-up conditions. The predictability of the ice advance and retreat is 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 multiyear ice and ridge intrusions is useful. Ice information needs during the early phase of voyage planning require 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, and preferably ice type, concentration and average ice conditions for a specific area (EU-Polarnet, 2018). Attempts at seasonal prediction are still experimental (Melia et al., 2017; Onarheim et al., 2015).

Early Phase: A decision needs to be made at this phase whether ice is potentially a factor, determining if ice-class vessels are needed, or if activity should commence in ice-free summer conditions. Historical conditions are useful to ascertain the probability of the start and end dates of the ice-free season and its duration. This takes the form of low-resolution synoptic overviews, either from ice charts, or more likely, derived from PMW sea-ice concentration (SIC) data (Lavergne et al., 2019; Stroeve et al., 2016). Information on ice type, such as multi-year ice or icebergs, is also useful.

The length of the open water season varies interannually according to the severity of the season and depending on the geographical area. Ocean currents can cause some areas to 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). The general atmospheric circulation must also 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
40 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. In the Pacific sector, the open water season is dominated by a retreat of sea-ice in the summer away from the coastlines toward the shelf break. Advection of ice in the Beaufort Gyre can result in an interrupted season with ice approaching the Alaska coast. 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: Toward the late planning stage and into the period of the activity, greater detail and more frequent information updates are needed. This is available through the use of high-resolution satellite sensors, particularly all-weather synthetic aperture radar (SAR), or alternatively through NRT observational information. During icebreaker operations NRT SAR images are used to identify open leads in the ice cover. In the 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 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 multiyear 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 included for them to be useful for decision-making.

How users make decisions

In the shipping industry, decisions are influenced not only by the season, and the 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 (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, Duske, et al., 2018). In terms of long-term strategic planning, historical data are 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 for continuous routing adjustment and searching for openings or areas of minimal ice cover. 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, have relied on a stable fast ice cover that is changing through climate change (Laidler et al., 2009). A number of initiatives have been developed to provide updated information products and allow local communities to collect their own in situ observations, including SmartICE in the Canadian Archipelago, which allows people traveling 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 they ensure the local communities have access to up-to-date and accurate information, plus have a stake in its continuity.

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 (Inoue, 2008; Liu et al., 2019; Shokr & Sinha, 2015; Waseda et al., 2018). The data do not accurately resolve the MIZ, ice edge, and coastal locations due to coarse spatial resolutions and also underestimate 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 main areas where many users travel (Aksenov et al., 2017). 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.

42 High spatial resolution (<1 km) 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. This additional level of detail further adds to the communications bandwidth problem at high latitudes, which is why the compression of sea-ice rheology information through ice-charts is relevant. 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 (<1 m – >5 m) to larger icebergs (~<200 m), 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 (Akbari & Brekke, 2018; Hughes & Wagner, 2015; Mazur et al., 2017). Effective tracking requires good intercomparison with *in situ* observations, shipborne radar, satellite (or airborne such as helicopter or Unmanned Aerial System [UAS]) 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 that 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 (Johansson et al., 2018; Singha et al., 2018). This differs from the standard single polarization, 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, 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. Although PMW has been routinely used, it is only in the past 15 years that large volumes of NRT SAR imaging have become widely available. However, as this increase in the amount of data runs into the satellite communications bandwidth limitations, more advanced techniques are required to convert and reduce it to manageable and understandable information products. 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 (Caya et al., 2010; Prasad et al., 2018). 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) (Goessling et al., 2016; Zampieri et al., 2018). This is surprising, given the widespread use of observation data for forecast initialization and, more recently, forcing through data assimilation. Data assimilation into numerical models is achieved through a number of schemes that can be broadly categorized into so-called 3D-Var, for initialization of a 3D-matrix of parameters at single point in time, and 4D-Var, where the parameters are further 'nudged' toward the observed values through time. A typical 3D-Var technique involves optimal interpolation (Gandin, 1966; Wang et al., 2013), and when expanded to include the temporal aspect in 4D-Var, Kalman filtering as used in the Copernicus TOPAZ4 forecasts (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 minimization of a cost function (Hestenes & Stiefel, 1952; Saad & Schultz, 1986). However, the increase in the 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 initialization 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

Feedback from the last 10 years remains consistent regarding the spatial and temporal scales that marine users require for sea-ice and iceberg information. The challenge for the ice information provision community is to produce relevant data products, which include sea-ice parameters at the high spatial resolution needed for these users, and deliver it over communications links with restricted bandwidth. In addition, different types of information, over a longer forecast range, are required to adapt to climate change and the retreat of Arctic sea-ice cover. This also highlights the need for different types of model, and better climate forecasting to address issues such as coastal erosion and greater risk to small fishing boats due to increasing wave height (Waseda et al., 2018). 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 (Aksenov 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 (Farré et al., 2014; Stephenson et al., 2011).

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, specialized 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 result 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. Although improved satellite communications coverage is expected to be available for the high latitudes of the Arctic and Antarctic (Barents Observer, 2018, March 27), it is still unclear when it will be ready or what costs to the user are involved. Presently high bandwidth solutions, like Iridium NEXT, are prohibitively expensive for most users. This is likely to change as more providers enter the market with further innovations, for example Highly Elliptical Orbiting (HEO) communications systems such as the constellation funded by Norway for launch in 2023. In preparation for ship operators, planners, and

Table 3. Recommendations for ice information systems to be implemented on vessels and potential informationprovision resources.

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 interpreted 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

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 3.

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. Main outcomes from user responses for the research community were challenges in using 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
46 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 (Koubarakis 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 a 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 the summer. To get around these issues, an integrated approach incorporating all relevant satellite (and *in situ*) information and forecast modeling 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. Although 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 (Casey et al., 2016; Dierking & Busche, 2006; Dierking & Dall, 2007; Howell et al., 2018; Johansson et al., 2018), though an antenna length of ∼10 meters 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 parameterize or recreate sea-ice dynamics and characteristics (Rae et al., 2015; Rampal et al., 2016; Vancoppenolle et al., 2012). In particular, the ability to extend forecasts into the seasonal timescale requires the use of improved sea-ice thickness measurements that could be provided by altimetry (i.e. CryoSat-2 (Blockley & Peterson, 2018), Sentinel-3, ICESat-2 (Schweiger et al., 2011), PMW interferometry (SMOS) (Mu et al., 2018)), 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 are necessary (Jung et al., 2016). While there has been research into inverse modeling of raw values (Lee et al., 2017; Remund & Long, 2003) to provide model outputs directly comparable with the satellite observations, the additional parameterizations 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 & Zhang, 2015) especially high-resolution SAR (Karvonen, 2012; Korosov & Rampal, 2017) and optical, are another underutilized resource that could improve drift forecasts. The modeling community relies on PMW and deems it essential for forecast model initialization (Liu et al., 2019). However, its usage may also result in a forecast of the future PMW product. Its replacement by higher resolution products of greater accuracy, particularly for areas of the MIZ, may assist in providing forecasts results with greater accuracy (Caya et al., 2010; Meier et al., 2015; Zampieri et al., 2018). Finally, more transparent assessment using readily understandable metrics of forecast skill will generate trust with stakeholders (Zampieri et al., 2018).

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48

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52

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Copy of application for funding from the SSG

Climate system couplings to shipping policy and investments in Svalbard and the High Arctic

Leaders: Siri Veland (NF), Julia Olsen (NF), Grete Hovelsrud (NF) and Nataly Marchenko (UNIS).

Contribution towards fulfilling the SSF's strategic objectives

The SSF's strategic objectives of cooperation, coordination, sharing of data and reduced environmental impact are at the core of this project's purpose, scientific contribution, and its organization. The project initiates new scientific cooperation, includes a strategy and discussion for open data sharing, and aims to reduce environmental impact on the level of the project itself and on the level of Svalbard and the Arctic's environmental policies. In this endeavor, the project builds on recommendations from previously funded SSF research. These include the "1st Science-Industry platform on expedition cruise tourism in Svalbard (Oslo, 2012)," which aimed to include cruise tourism operators (and other shipowners) in the research agenda, some of which are already involved in ongoing projects with Veland, Olsen, and Hovelsrud, and will be invited to the proposed workshops. The SSF-funded workshop on "Barents Sea Ice sheet - insights into the climatic sensitivity of marine based ice sheets (Anne Hormes, 2012)" indicated the need for an open access database (DATED database) and increase scientific cooperation through co-supervision of Master and PhD students. The proposed workshops aims to foster further data sharing, and to foster collaboration on existing and future supervision of Master and PhD, and postdocs.

Initiation of new scientific cooperation initiative

This pair of conferences brings existing expertise in ongoing projects together with new researchers and research questions in order to better understand the coupled dynamics of aerosol mixing, sea ice extent, environmental policies, and shipping policies. Participants in ongoing research at the Ny-Ålesund Flagship Program on Atmosphere Research, including the "Combined Aerosol Evaluation With Lidar And Comparison To In-Situ Aerosol Observations" (2017-2022, AWI), as well as the "Studies Of Near-Surface Aerosol And Spectral Aerosol Optical Depth (SASAOD)" (AARI 2015-2020), as well as projects on sea ice and shipping at Longyearbyen (UNIS), such as the "Sustainable Arctic Marine and Coastal Technology" (NTNU 2011-2018), will be brought into conversation with the ERC-funded project "Mixed-phase clouds and climate (MC2)" (Storelvmo, UiO 2018), the EU-funded LC-SPACE-02-EO-2018 "KEPLER (Key Environmental monitoring for Polar Latitudes and European Readiness)" (MET Norway, under the "Copernicus evolution – Mission exploitation concepts for the Polar Regions" (2018-2021)), and the United States NSF-funded interdisciplinary project "Modeling Risk From Black Carbon In A Coupled Natural-Human System At The Arctic Ice Edge" (Brown Univ. 2018-2021). To link these research efforts, a Norwegian team led by Nordland Research Institute has submitted a proposal "Modeling Arctic climate dynamics emerging from coupled geophysical and anthropogenic processes (ArcMod)" to the Research Council of Norway under the joint POLARPROG-KLIMAFORSK program. Combined, this international team of researchers will work together to share research questions, find synergies in data gathering and analysis, and develop a collaborative research proposal for the Research Council of Norway.

1.
Strategy for open sharing of data
and logistics coordination

Data sharing is emerging as a key issue as the number of discrete research efforts in Svalbard and in the Arctic increases, and the potential for both synergies and parallellisms increases. Data sharing is also a challenging issue, since datasets are often the outcome of long-term investments by individual researchers and research teams, and form the foundation of academic achievements and careers. Meeting the SSF strategy for open sharing of data, the workshop will present the benefits and methods of use of existing databases, and will include a discussion of possible challenges in sharing different forms of data, issues concerning intellectual property rights, the timing and extent of data sharing, reporting and dissemination, and other issues relevant to debates over open data sharing. Databases to be presented and discussed include the RIS-platform for data sharing on Svalbard https://www.researchinsvalbard.no/, and the NSF Arctic Data Center at the National Center for Ecological Analysis and Synthesis, which is located at UC Santa Barbara.

2.
Reduced environmental impact

The project contributes to a reduced environmental impact in three key ways. First, on the project level, the workshop will be organized in conjunction with the annual Arctic Shipping Forum, to which industrial stakeholders will already be traveling such that the project does not contribute additional emissions for these participants. Second, on the policy level, Norway and the local government in Longyearbyen now pursue visions of green and low-emission energy powering the archipelago as a transport hub (Palm 2016). Decision-makers therefore need improved tools to plan for futures in which shipping increases markedly, and where the Paris Agreement and the Sustainable Development Goals demand emissions reduction. The project aims to synergize research that will improve understanding of the role of aerosols, and BC in particular, in the climate system, and will improve estimates of likely future shipping volumes and pollution levels. Third, in relation to risk management by shipping operators, decision support products currently underestimate the price of variability, and may as such increase risk-lovign behavior in years where shipping operators have underestimated the length of the shipping season. As was seen with the drill rig Kulluk in 2014, the need to recover cost and make returns on investments can result in accidents and potential environmental impacts. The NSF-CNH project will contribute refined pricing estimates of sea ice variability based on the climate models, and in that way reduce the risk of making poor investment decisions.

Scientific justification of the topic:

Uncertainties in projections of Arctic climate change remain a challenge to good governance of expanding Arctic industrial activities, even as rapid Arctic sea ice loss has come to symbolize global climate change. To navigate toward a future where Svalbard may become a major shipping hub for trans-Arctic shipping, there is pressing need to understand the reciprocal relationships between dynamics of the atmosphere, cryosphere, hydrosphere, and anthroposphere. The process whereby the Arctic region experiences warming 2-3 times the global average, Arctic amplification, describes, but does not fully explain, the rapid pace of change. Models have to date disagreed on the attributes and rates of retreat, particularly on seasonal time scales (Boeke and Taylor 2016). A large portion of recent Arctic warming has been attributed to reduced aerosol emissions in Europe in recent decades, but the exact mechanisms remain unclear (Acosta Navarro et al. 2016). Corresponding aerosol-induced cloud changes were invoked, but the magnitude of such indirect effects is extremely sensitive to model assumptions, and the role of BC is particularly uncertain in this respect (Storelvmo et al., 2011). New laboratory studies continue to emerge on the ability of BC particles to act as nuclei in cloud formation under different conditions, dependent on the degree of mixing with other aerosol types (e.g., Ritter et al. 2015, Kanji et al., 2017). Observations that indicate sudden shifts in sea ice cover have already occurred (Goldstein et al. 2018), although sea ice models do not perform well at the time and spatial scale of relevant investment planning, rendering the future uncertain (Veland and Lynch 2017). Well-known

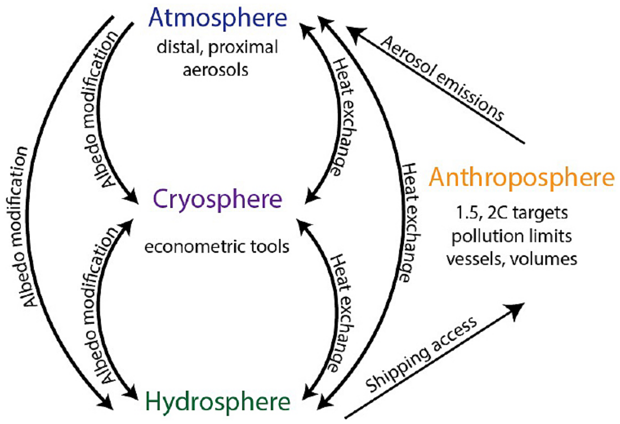

Figure 1: Couplings between Earth systems that are being modeled in ongoing and proposed research

limitations to these models include deficiencies within the model components (ice rheologies, cloud physics, upper ocean dynamics) but also emerging priorities for model development, such as the interactions between anthropogenic black carbon (BC) and albedo in ice and snow.

The Svalbard research stations are spearheading Arctic research through the state-of-the-art Earth System Model (ESM), NorESM (Bentsen et al, 2013), which is particularly sophisticated when it comes to the representation of aerosols and their impact on atmospheric radiation, surface albedo and clouds. BC emitted in the Arctic is likely to remain at low altitudes, causing Arctic surface temperature to be nearly five times more sensitive to BC emitted within the Arctic than to emissions from lower latitudes (Sand et al. 2013a). Sand et al. (2013b) examined the role of BC on the Arctic energy budget at the top of the atmosphere and at the surface in a slightly modified version of the CCSM4 (the Norwegian Earth System Model, or NorESM, Kirkevåg et al. 2013) and showed that the geographic distribution of sources inside and outside the Arctic made an important contribution to the magnitude of response. Later studies have explored the direct impact of Nordic BC sources in models (e.g. Hienola et al. 2016), the direct and indirect effects of all aerosols on sea ice cover (e.g. Gagne et al. 2015) and impact of Arctic shipping on direct radiative forcing and temperature (Fuglestvedt et al. 2014, Stephenson et al. 2018). Furthermore, Boeke and Taylor (2016) note that the seasonal flux of oceanic heat content is a significant contributor to Arctic amplification, carrying the memory of ice retreat though the winter season. Meanwhile, Stephenson et al. (2018) recently concluded that "trans-Arctic shipping will reduce Arctic warming by nearly 1 °C by 2099, due to sulfate-driven liquid water cloud formation" (Stephenson et al. 2018, p. 1). This means research is needed to investigate whether BC emissions from shipping contributes a positive feedback affecting the rate of retreat of Arctic sea ice (Figure 1). To quantify the contribution of Arctic BC emissions to polar amplification, its role in sea-ice-atmosphere feedback must be quantified. Research products supported through the Svalbard Strategic Grant project will be greatly enhanced by building models based on ground measurements of aerosol concentrations, as well as refined estimates of future emissions based on expected ship types, fuel types, and volumes.

Agenda

Both day-long workshops will be organized in conjunction with the annual Arctic Shipping Forum (ASF https://maritime.knect365.com/arctic-shipping-forum/) in Helsinki 2-5 April 2019 and in April 2021. ASF is the key industry event focused on Arctic shipping operations and relevant stakeholders of Arctic Shipping operating activities (researchers, decision-makers, NGOs, media etc.)
The first workshop will result in:

1. Understanding of knowledge needs from users of Arctic climate data for the Svalbard and North Barents Sea area;

2. New research questions for a project proposal that will fill further knowledge needs in ongoing research in Ny-Ålesund and UNIS, and the NSF CNH-funded project;
3. Better understanding of the opportunities and challenges of open data sharing
4. Contributions to the reduced environmental impact of Arctic shipping through policy recommendations for aerosol and black carbon emissions, and through improved financial risk assessments for shipping; and

Climate system couplings to shipping policy and investments in Svalbard and the High Arctic

Arctic Shipping Forum Helsinki April 2-5 2019

WEDNESDAY APRIL 3RD 2019

08.30	Registration and coffee
09.30	Chair's Welcome by SSF Representative
09.45-12:30	Workshop with users of climate and sea ice forecasts led by Dr Hughes and Dr Wagner from MET Norway (Tromsø)
12.30	Networking lunch
13.30-14.15	Project presentations • Nordland Research Institute: Climate system couplings to shipping policy and investments in Svalbard and the High Arctic • AWI Combined Aerosol Evaluation With Lidar And Comparison To In-Situ Aerosol Observations • UiO Mixed-phase clouds and climate (MC2) • AARI Studies Of Near-Surface Aerosol And Spectral Aerosol Optical Depth • Brown Univ. Modeling Risk From Black Carbon In A Coupled Natural-Human System At The Arctic Ice Edge
15.00-15.30	Coffee break
15.30-17.00	Roundtable discussion on synergies, data sharing, and future research collaborations
17.00-17.15	Review of meeting and close of workshop

The second workshop in 2021 will be a follow up of the first workshop that will:

1. Address the recommendation from the first workshop and if relevant other SSF funded workshop (period 2019-2020);
2. Present decision-makers with improved decision support tools based on atmospheric, sea ice, and shipping models, and identify further knowledge needs;
3. Evaluate past project proposals and hone in on research questions and methodologies as appropriate
4. Evaluate the data sharing platforms and processes;
5. Develop a comprehensive technical report for target groups

The tentative program for the first workshop is as follows, with the second workshop's agenda being informed by lessons from this first workshop, and by new research proposals and findings.

Tentative list of participants:

About 40 participants will be invited to each of the workshop, while workshop will be an open even for all interested parties. The invitation will be sent to directly to key Norwegian industrial and policy-making stakeholders from Svalbard and Oslo and to researchers who work with the similar topics. To secure the participarion of international industrial stakholders the workshop will be promoted at ASF web-page and a personal invitation will be sent to all key speakers (80+). The representatives from SSF and other relevant NFR-programs will be invited. Both workshops will be open for all interested parties. Participants that are invited to the first workshops:

Researchers (Confirmed): Trude Storelvmo (UiO, Scott Stephenson (U. Conn.), Amanda Lynch (Brown University), Michael Goldstein (Babson College), Nick Hughes (MET Norway), Penny Wagner (MET Norway), Håvard Karoliussen (NTNU), David Bailey (NCAR), Thomas Leirvik (Nord).

Researchers (Invited): Vladimir Radionov (AARI),

Christoffer Ritter (AWI), Harald Ellingsen, Kim

Holmén (UNIS), Ketil Isaksen (MET), Jackie Dawson (UOttawa)

Industrial stakeholders: Amund D. Ringdal (Norwegian shipowner organization); Frigg Jørgensen, Edda Falk (AECO); Kjetil Bråten (Port Authorities in Longyearbyen), Eva-Britt Kornfield (Cruise Network Svalbard); Roy Arne Rotnes (Norwegian Coastal Administration); Directorate of fisheries and all key speakers from Arctic shipping forum(80 +) https://maritime.knect365.com/arctic-shipping-forum/speakers

Decision-making: Anja Elisenberg (Norwegian Environmental Agency); Morten Wedege (The Governor of Svalbard); Soffia Gudmundsdottir (Arctic Council,PAME). Norwegian Ministry of Climate and Environment
Other organizations: Svalbard Science Forum; Barentsburg meteostation, Grumant (Arctic Travel Company), NFR (Polarogram, Klimaforsk), IMO (Polar Code)
All participants from the first workshop will be invited to the second one. The invitation will be also sent to key speakers of Arctic Shipping Forum 2021 and to other relevant organizations, suggested by project participants or SSF.

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