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List of Acronyms

Abbreviation/acronym	Description
AOAS	Arctic Ocean and Adjacent Seas
BC	Black Carbon
CAFF	Conservation of Arctic Flora and Fauna
CHNL	Center of High North Logistics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DFO	Department of Fisheries and Oceans (Canada)
ECA	Emission Control Areas
EEZ	Exclusive Economic Zone
GESAMP	The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) is an advisory body, established in 1969, that advises the United Nations (UN) system on the scientific aspects of marine environmental protection
HFO	Heavy Fuel Oil
H&M	Hull and Machinery
IACS	International Association of Classification Societies
ICCT	International Council on Clean Transportation
IMO	International Maritime Organization
IUCN	International Union for Conservation of Nature
IWC	International Whaling Commission
LNG	Liquid Natural Gas
MARPOL	The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes.
NEP	Northeast Passage
NM	Nautical Miles
NOAA	National Oceanic and Atmospheric Administration (USA)
NO_x	Nitrogen oxide
NPR	North Pole Route
NSIDC	National Snow and Ice Data Center
NSR	Northern Sea Route
NSRA	Norther Sea Route Administration
NWP	Northwest Passage
OC	Organic Carbon
PAH	Polyaromatic Hydrocarbon
PAME	Protection of the Arctic Marine Environment
PC	Polar Class
PCB	Polychlorinated Biphenyl
PM	Particulate Matter
POP	Persistent Organic Pollutants
P&I	Protection and Indemnity
RMRS	Russian Maritime Register of Shipping
SAR	Synthetic Aperture Radar
SO_2	Sulphur Dioxide
SO_x	Sulphur Oxide
TEU	Twenty-Foot Equivalent Unit (intermodal shipping container)
TPR	Transpolar Route
UNCLOS	United Nations Convention on the Law of the Sea
WSC	World Shipping Council
WWF	World-Wide Fund for Nature

Executive Summary

The Arctic is changing. Temperatures in the region are increasing causing a range of physical and environmental changes. Arctic sea ice is thinning and receding. As these changes expose potential opportunities and because the Arctic Sea provides shorter routes for global shipping, the international interest in the Arctic has increased. The growth of international interest towards commercial utilization of Arctic Seas is inevitable.

The traffic in the Northern Sea Route is continuously growing. Gas related mega-projects, located in the Russian Arctic, as well as governmental cooperative actions of the Russia and China to build the “Ice Silk Road”, will boost the near-future marine activities and shipping in the Northern Sea Route.

Commercial utilization of other trans-Arctic routes is still marginal, or practically zero. For the Northwest Passage, several areas are considering project proposals to build transhipment ports that might provide an as-yet undeveloped shuttle service across Arctic passages, including the Transpolar Route. Whether these schemes will go to fruition or not, remains to be seen.

Arctic shipping presents not only opportunities, but also challenges and threats. Sea ice, even if it is thinning, still creates major challenges for economically feasible shipping. Ice features, such as multi-year (icebergs, etc.) and compressive ice, which generate threats and hampers shipping, may exist in the encountered ice regime. The reasonable shipping season for non-specialised ice strengthened ships is currently only few months long. Marine (coastal) infrastructure, which is currently lacking, must be set up to enable safe and efficient trans-Arctic navigation.

The Arctic environment is vulnerable. To enable utilization of Arctic routes in an environmental-friendly manner it is important to consistently study the effects of shipping on Arctic nature. An understanding of Arctic environment, together with findings and learnings from anticipated future studies, can be utilised to plan and execute shipping so that the environmental impacts are minimized. In addition, these studies would improve the design of “greener ships” and enables the development of the services for “greener navigation” practices. Appropriate services, together with appropriate ships, ensure that Arctic shipping practices are conducted in the most environmentally friendly and sustainable manner in the future.

1 Introduction

The challenges associated with Arctic shipping are considered in this report. To provide context and background to these challenges, the status of the Arctic shipping activities today, as well as its future prospects, are considered in Section 2. Detailed consideration is then given to the challenges in Chapters 3-5. Conclusions, summarizing the key findings and learnings, are presented at the end.

The challenges considered in this report are divided into three fundamental parts. These parts and the respective key authors are listed below.

Part 1: Impacts of shipping to Arctic marine wildlife

This part is prepared by *Dr. Lauren McWhinnie* and *Dr. Kate Gormley* from Heriot-Watt University (Scotland, UK).

Part 2: Geo-economic & societal impacts of Arctic shipping

This part is prepared by Prof. *Frédéric Lasserre* from Laval University (Canada).

Part 3: Technical and economic challenges of Arctic Shipping

This part is prepared by *Sami Saarinen, Rob Hindley* and *Cayetana Ruiz de Almiron* from Aker Arctic Technology Inc (Finland).

In addition, contribution to the report contents have been given by:

Professor *Zhihua Zhang* from Shandong University (China). His input is incorporated to the contents of this report.

Christian Kinas and Doctor *Oliver Philipp* from Panasonic Business Support Europe GmbH (Germany). Their input is in Appendix 1.

Acknowledgements to all authors.

2 Arctic Shipping in General

In the recent years, interest in Arctic shipping has increased: exploitation of Arctic oil and gas reservoirs, global warming resulting in an increase in the ice-free navigable season on the shorter routes between North Pacific and North Atlantic Oceans compared to southern latitudes, as well as technological development of ice going vessels, are all contributing factors. As presented in Figure 2-1, the routes between these Oceans can be divided to the Northeast Passage (NEP), the Northwest Passage (NWP), and the Transpolar Route (TPR). Today only the Northeast Passage, of which the Northern Sea Route (NSR) forms part, is currently used for commercial transportation, whereas the NWP and the TPR (also referred as "North Pole Route") are predicted to be utilized for commercial shipping later in the future. The decreasing trend of ice extent and ice thickness, driven by global warming, increases the interests towards utilization of these routes in shipping. However, even as the ice conditions in the Arctic become more navigable for shipping at a general level, difficult ice conditions persist and ice-caused challenges to shipping will be encountered in the future. In addition, intra and inter-seasonal ice variability, environmentally sensitive areas, political and jurisdictional disputes, lack of modern infra (deep-water ports, search & rescue capabilities) all generate additional challenges for Arctic Shipping. Analysis, storage, and distribution of big data from diverse sources (e.g., meteorology/climate, ocean, remote sensing, environment, economy, computer-based modelling) applied with modern technology aids (like satellite technologies, etc.) and software algorithms are needed to plan shipping activities arctic waters and exploit of Arctic routes in shipping.

The Northeast Passage is a sea route connecting the Far East and Europe, by travelling along Russia's and Norway's Arctic coasts through the Chukchi, East Siberian, Laptev, Kara, Pechora and Barents Seas. Its total length is 3300 – 3700 NM (from Barents Sea to Bering Sea). The route is restricted to about 14,5 meters of depth. As described later in this section, the shipping activities in this passage have increased remarkably during previous years. Several large-size industrial projects have been established along coastal regions of Northern Russia (mainly at the western segment of the route) during last 10 years. Locations of key existing oil and gas projects in Northern Russia are presented in Figure 2-1 (yellow dots), together with main transit routes in the Arctic.

The Northwest Passage is a term used for a collection of navigational routes running along the northern coast of North America via waterways through the Beaufort Sea, Canadian Arctic Archipelago, Baffin Bay and Davis Strait. The representative length of the route is approximately 3200 - 3700 NM (from Labrador Sea to Bering Sea). Traffic intensity in this route is relatively low.

Although the summer/autumn seasons in the Arctic are forecast to become significantly more favourable for shipping, the probability of encountering ice in the Canadian Arctic Archipelago is still significant during the short summer navigation period. The region often contains strong old or multi-year ice floes which remain present throughout the summer.

The Transpolar Route (TPR) is not a passage as such but a theoretical route of about 2800 NM (from Norwegian Sea to Bering Sea) long that connects the Bering Sea and Norwegian Sea directly through the Fram Strait and across the North Pole. Although the Transpolar Route is much shorter than the Northeast and Northwest Passages, it is presently inaccessible due to the presence of thick multiyear sea ice. However, some preliminary studies to exam its commercial utilization in the future have lately been carried out.

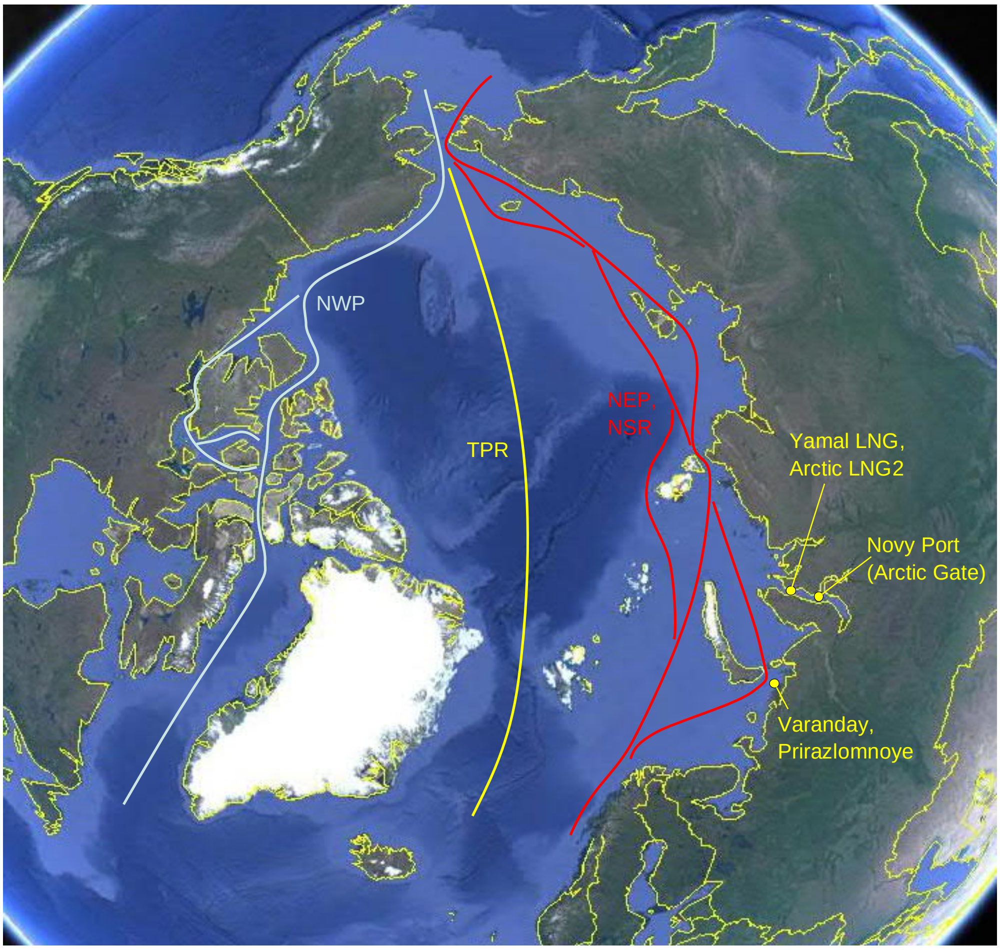

Figure 2-1. Main transit routes in the Arctic.

Global warming and ice melting

Over the past 30 years, the Arctic has warmed at roughly twice the rate as the entire globe, a phenomenon known as “Arctic amplification” (see Figure 2-2). The projected 2-4 °C increase in the global mean temperature by the end of the century will lead to a 2-9 °C increase in the Arctic region, which will result in the rapid decline of the extent and thickness of sea ice in the Arctic. The Arctic Ocean is predicted to be free of summer ice within the next 20-25 years. The combination of melting Arctic ice and related economic drivers are triggering and facilitating Arctic shipping by a longer navigation season (Wang & Overland, 2012)

According to the National Snow & Ice Data Center (University of Colorado, USA) the air temperature at high latitude has increased by almost 4 °C during the last 50 years. WWF correspondingly reports that the average temperature of the Arctic has increased 2.3°C since the 1970s (WWF, 2021).

The mean surface air temperature trend over the period from 1960 to 2019 is illustrated in Figure 2-2 below (NSIDC, 2021).

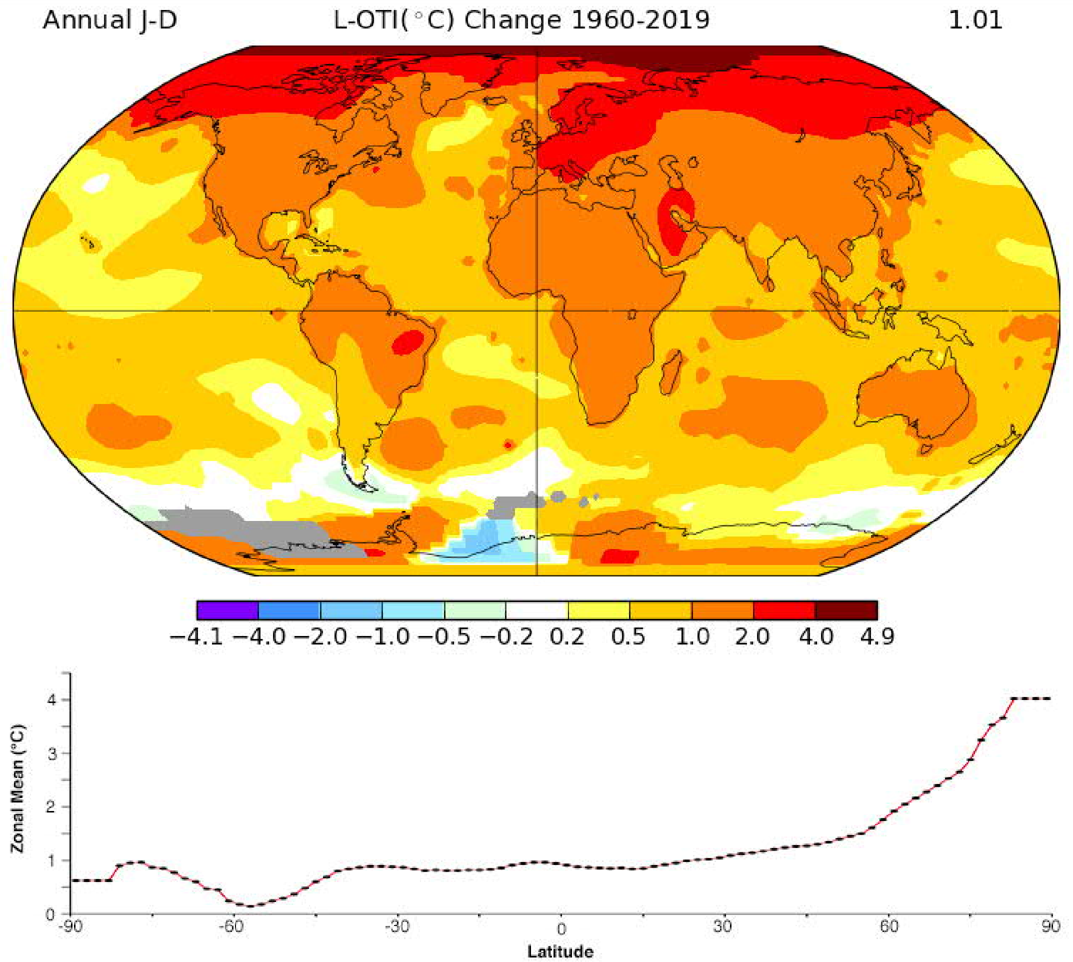

Figure 2-2. Trends in mean surface air temperature over the period 1960 to 2019.

The variation of Arctic sea ice follows the same pattern every year. The ice cover expands from late September until in reaches a maximum in March/April after which melt begins. The minimum ice extent is reached around mid-September. As can be seen in Figure 2-3, the ice extent has clearly shrunk during last decades especially in the summer and autumn seasons. As of early 2020, the lowest extent in the satellite record occurred in September 2012. September sea ice minima in 2007, 2016, and 2019 are all statistically tied for second lowest (NSIDC, 2021).

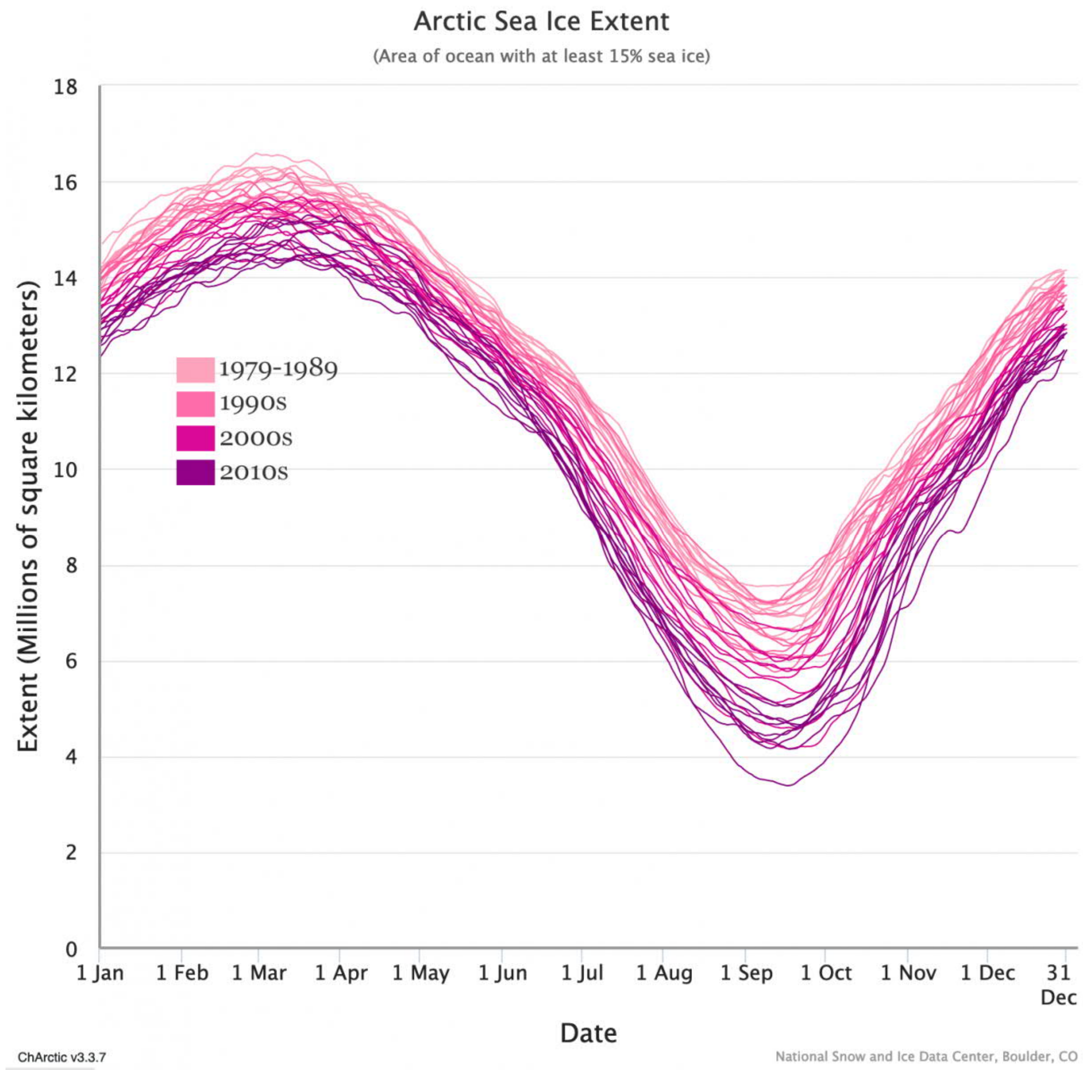

Figure 2-3. Yearly seasonal variation of Arctic sea ice extends.

The reduction in sea ice extent in the Arctic has stimulated shipping activities along the Northeast Passed and along the Northern Sea Route in particular. The navigational distance between Asia and Europe is 5000-7000 NM shorter than the route via the Cape of Good Hope and 2000-4000 NM shorter than the predominant route via the Suez Canal. The difference of routes between South Korea and Central Europe via the Suez Canal and the NSR is illustrated in Figure 2-4 ,where the blue track refers to the Northeast Passage and the red track route through the Suez Canal (Wikipedia, 2021).

Figure 2-4. Visualization of the route alternatives between South Korea and Central Europe.

Figures presenting the growth of NSR transportation in previous years are presented below. As can be seen in the Figure 2-5, most of the transportation is associated with destinations or origins located within the NSR, while a minor part of transportation is pure transit throughout the entire NSR (Aker Arctic Technology, 2020). However, an increase of pure NSR transit cargo during last few years can also be seen, as presented in Figure 2-6 (CHNL, 2021). The chart indicates an increasing trend of cargo volumes during previous years although these are still very low total volumes compared to cargoes shipped via southern routes. Figure 2-7 (CHNL, 2021) correspondingly visualises the seasonal variation of shipping utilizing the NSR. As can be seen, the traffic is concentrated in the Summer-Autumn season when the ice cover extent is minimum and ice conditions along NSR are relatively easy or the route is free of ice.

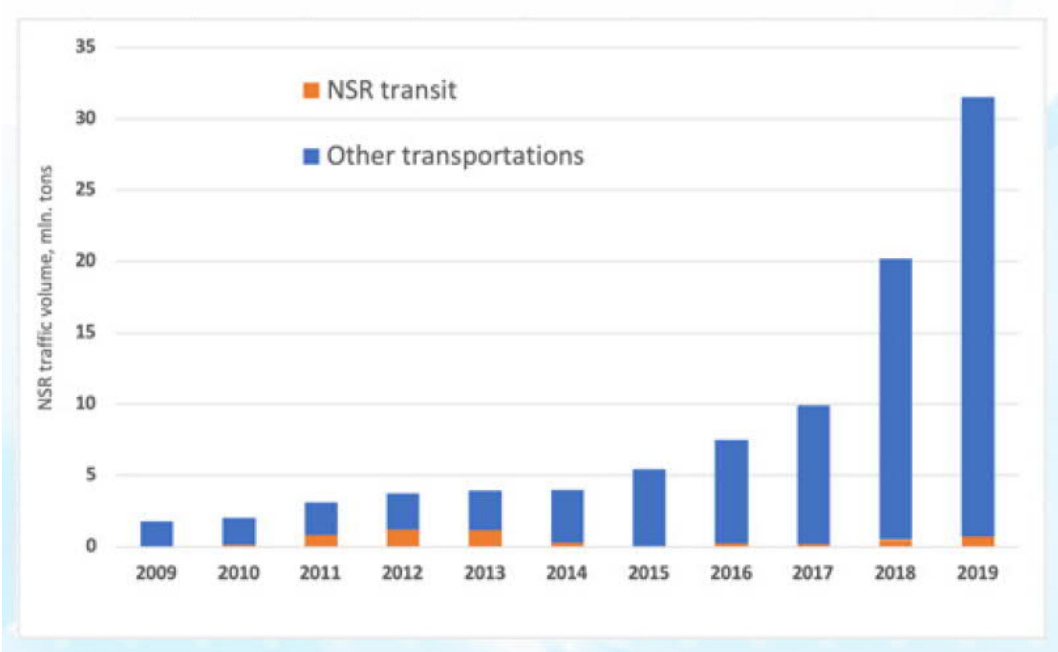

Figure 2-5. Development of shipping volumes at the NSR

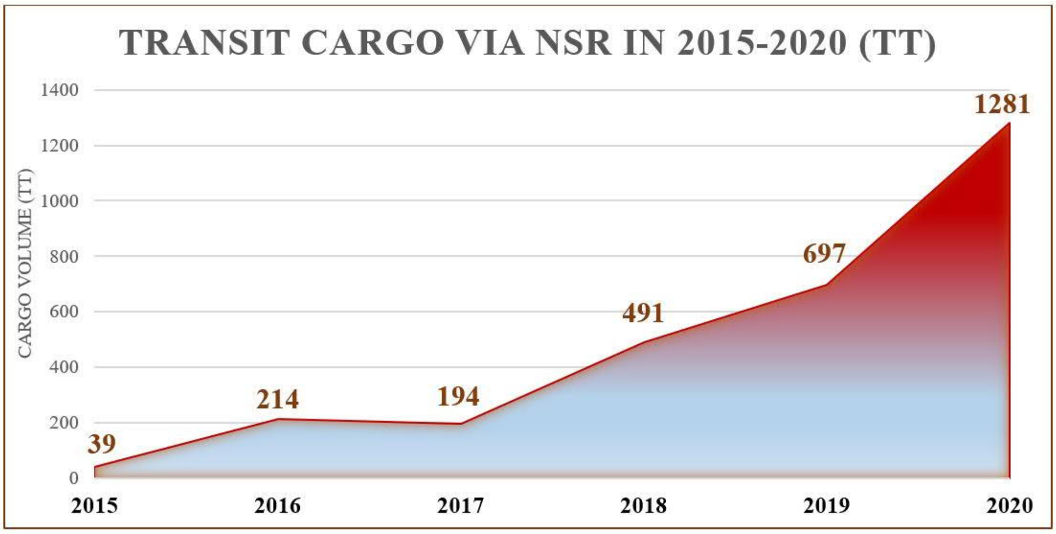

Figure 2-6. Grow of transit cargo in NSR during 2015 -2020.

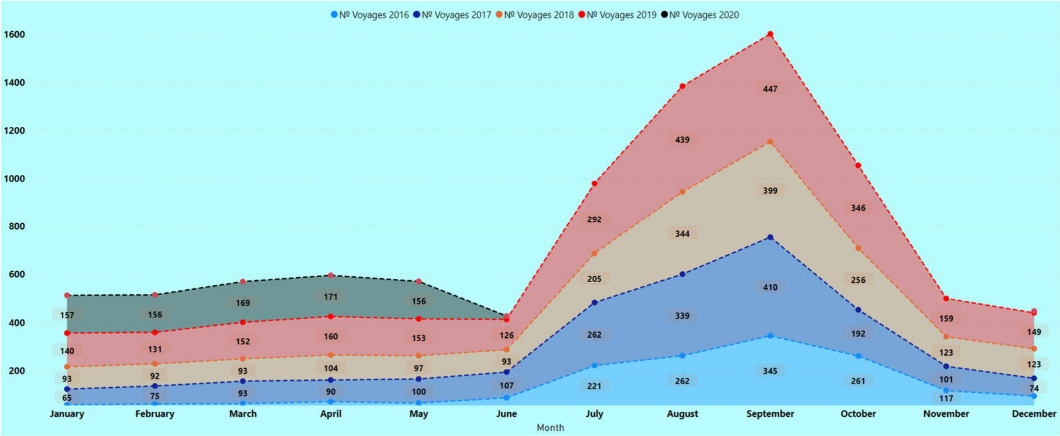

Figure 2-7. Number of voyages per month along the NSR during 1/2016-5/2020.

In this context, it should be noted that for the first time in history, a large-capacity cargo vessel, LNG Carrier “Christophe de Margerie”, completed a transit passage along the eastern sector of the Northern Sea Route in February 2021. The lateness in the ice season for this voyage was unprecedented as conditions have usually been unnavigable, even for ice strengthened ships during later winter /spring. The journey started from Jiangsu (China) and ended about 11,5 days later at the Sabetta LNG terminal (Ob Bay, Russia). From Cape Dezhnev to Sabetta, the gas carrier was escorted by the “50 Let Pobedy” icebreaker. The voyage covered a total distance of 2,500 nautical miles. The most challenging part of the voyage involved passing through ice hummocks in the Chukchi Sea and the East Siberian Sea (Sovcomflot, 2021). As shown in Figure 2-8 the route was fully covered by ice including up to 2 m thick first year ice during the trip. Sabetta is marked with yellow dot. Colour codes: Brown = second-year or multi-year ice; Green = 0,3 – 2 m thick first year ice; Magenta = 0,1 – 0,3m thick young ice; Dark Blue = very thin new ice (< 0,1 m), Light blue = Open water.

Even though ice cover is continuously shrinking, the ice associated challenges in the Arctic will be also met in the future. Therefore, ice conditions and environment along the routes should be continuously monitored and studied. Traffic management and infrastructure along the routes should be developed simultaneously with increasing traffic to enable safe, efficient and greener navigation routines in the Arctic. The first step in this development is to identify the key challenges and threats associated with Arctic shipping today. Such challenges, especially related to the environmental, geo-economic and social impacts as well as technical issues, are introduced in the following chapters of this paper.

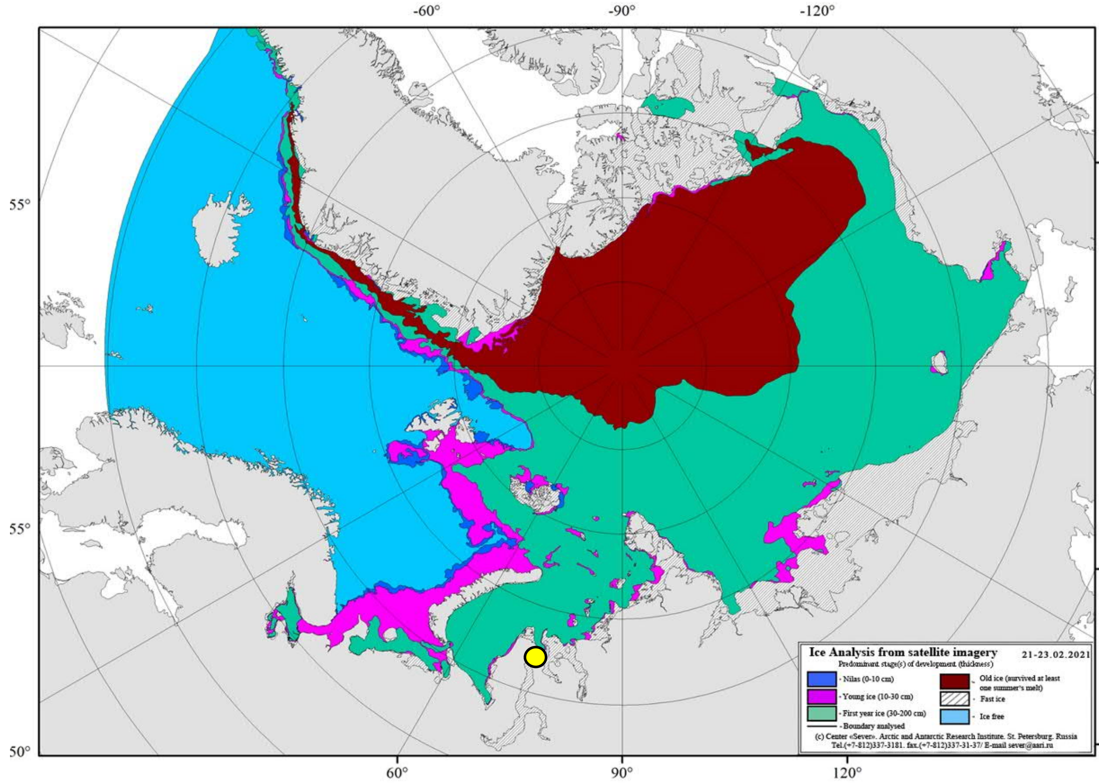

Figure 2-8. Ice conditions in Central Arctic and Russian Arctic during the trip of Christophe de Margerie. (AARI, 2021)

3 Part 1: Impacts of shipping to Arctic marine wildlife

3.1 Summary of Arctic Wildlife

As environmental conditions change and human activity continues to increase in the Arctic marine environment, it becomes more important than ever to have a clear understanding of the abundance and distribution of the many and varied wildlife that are present (permanently or temporarily). This will ensure that the impacts of human activities can be minimized; conservation measures can be deployed and managed to protect the most vulnerable species and habitats; human activities and industrial/economic developments occur sustainably; and that indigenous communities and their way of life are preserved, consulted, and supported now and in the future.

This section provides a high-level summary of the wildlife that is found in the Arctic marine environment and some associated challenges and opportunities that they face. More in-depth information on Arctic wildlife is available in the Conservation of Arctic Flora and Fauna (CAFF) Arctic Biodiversity Assessment 2013 and the associated status reports (CAFF, 2013).

3.1.1 Marine Mammals

The Arctic is home to seven endemic marine mammals, which are dependent or highly associated with sea ice for part of the year:

- Cetaceans
  - narwhal (*Monodon monoceros*)
  - beluga whale (*Delphinapterus leucas*)
  - bowhead whale (*Balaena mysticetus*)
- Pinnipeds
  - ringed seal (*Pusa hispida*)
  - bearded seal (*Erignathus barbatus*)
  - walrus (*Odobenus rosmarus)*
- Bear
  - Polar bear (*Ursus maritimus*)

There are an additional four species of ice seals that depend on sea ice for whelping in the southern Arctic in the spring but are generally pelagic or use subarctic waters for the rest of the year: the spotted seal (*Phoca largha*), ribbon seal (*Phoca fasciata*), harp seal (*Pagophilus groenlandicus*), and hooded seal (*Cystophora cristata*). In addition to the 11 ice-dependent/ associated marine mammals, there are approximately 24 other species of marine mammal that use the Arctic seasonally, for foraging in the late spring and summer (Laidre &

Regehr, 2018). These include spotted, ribbon, harp, hooded, northern Fur, grey, harbor seals; Stellar sea lion; North Pacific right, North Atlantic right, grey, blue, fin, sei, minke, humpback, sperm, Baird's beaked, Stejneger's beaked, Cuvier's beaked, northern bottlenose, killer, Long-finned pilot whales; white-beaked, Atlantic white-sided dolphins; Dall's, harbor porpoise; and sea otter.

Table 3-1 provides a summary of the global population status and distribution of the endemic Arctic marine mammals. The International Union for Conservation (IUCN) Red List of Threatened Species provides a vulnerability rating for species (as listed in Table 3-1) However, it should be noted that these statuses are applied to the global population and does not consider the vulnerability of sub-populations/sub-species. As shown in Table 3-1, all the endemic Arctic species have multiple sub-populations. This is largely driven by the nature of the sea ice in the Arctic, which historically has isolated these populations. Although some species are listed globally as of 'least concern' by IUCN, several sub-populations in the Arctic may in fact be threatened or critically endangered. [Table 3-1 Sources: (Laidre, et al., 2015); (IUCN, 2020); (Laidre & Regehr, 2018), (CAFF, 2013)].

The known population trend and distribution for many Arctic marine mammals is largely unknown, either through lack of research, lack of data, data is out of date or due to their elusive behaviour. With reducing sea ice, there are several opportunities and challenges for Arctic marine mammals. Sub-populations may have the opportunity to begin mixing, therefore potentially reducing a sub-population's vulnerability; allowing populations wider foraging/breeding areas; access for research may improve, allowing for a better data gathering and improved knowledge of population trends. Challenges of retreating sea ice include loss of habitat (especially for hunting polar bears and breeding/nursing seals, increased human activities (e.g., shipping) and increased predation, to name a few (discussed in more detail in Section 3.3).

Arctic communities interact in some way with marine mammals, directly through subsistence hunting (for food, clothes and secondary products) or fishing, or indirectly via shipping and other activities that overlap with marine mammal habitat (Hovelsrud, et al., 2008). Hunting activities, yields, methods and target species vary between communities, but largely include the core Arctic species listed above. (Hovelsrud, et al., 2008) also outlines the cultural, social, and economic significance of certain marine mammals and that climate change and increasing anthropogenic impacts may have serious consequences on the needs of these communities.

Table 3-1. Endemic Arctic marine mammals, their status and distribution.

Species	Estimated Global Population	No. Known Arctic Subpopulations/ Subspecies/ Stocks	ICUN List Status (as of 2020) and Global Trend	Distribution
Polar Bear	20-25k	19	Vulnerable Population Global Trend - unknown	Throughout ice-covered Arctic regions
Narwhal	100k	11	Least Concern Population Global Trend - unknown	Atlantic Arctic in the eastern Canadian high Arctic, waters around Greenland, Svalbard, and Franz Josef Land
Beluga Whale	150k	19	Least Concern Population Global Trend - unknown	Circumpolar
Bowhead Whale	<20k	4	Least Concern Population Global Trend - unknown (Svalbard-Barents Sea/Spitsbergen subpop. Critically Endangered)	Discontinuous circumpolar
Ringed Seal	Low millions	9	Least Concern Population Global Trend - unknown	Circumpolar
Bearded Seal	500k	9	Least Concern Population Global Trend - unknown	Patchy circumpolar
Walrus: Atlantic Walrus Pacific Walrus	 20k 129k	16	Vulnerable Population Global Trend - unknown	Discontinuous circumpolar

3.1.2 Seabirds

The Arctic is seasonally populated by approximately 200 species of bird (of which the majority are migratory). There are 64 species of seabirds (birds which spend a proportion of their time at sea, primarily feeding); 44 species of seabird and 59 species of shorebird (associated with coastal areas, but some sea ducks, divers, geese and swans may spend some time at sea) that breed (23 in the high Arctic and 41 exclusively in the low Arctic) in the Arctic. In both polar regions, diving seabirds reach their maximum diversity in sub-polar latitudes, and the highest densities of breeding seabirds occurs in Arctic waters (CAFF, 2013).

Seabird communities in general are well studied, particularly using seabirds as an indicator for environmental change (primarily through their sensitivity to prey availability), and the known spatial distribution of many Arctic seabirds has improved over recent years. Like marine mammals, there are several opportunities and challenges that face seabirds in the light of recent and future environmental change. Retreating sea ice and coastal glaciers may see a reduction in some ice associated species (such as the ivory gulls); however, this reduced ice cover, will see an influx of other species (e.g., horned puffin in the Beaufort Sea). Changes to prey species (e.g., zooplankton) as sea ice cover changes will see seabird populations change (i.e., many seabirds have specific diets, and if their prey is removed, it is possible that the birds will leave an area, rather than adapt to the new prey available). Increased predation (due to retreating sea ice) may also have an impact on Arctic seabird (CAFF, 2013). It is not possible to give details on all Arctic seabirds here, but a summary of status and distribution of some notable species (identified as breeding in the Arctic and either vulnerable or near threatened on the IUCN Red List is listed in Table 3-2 [source: (IUCN, 2020); (CAFF, 2013); (Strøm, et al., 2019); (Birdlife International, 2020); (O'Hanlon, et al., 2020)].

Human activities have several impacts on seabirds (e.g., fisheries by-catch), but the biggest threat to seabirds is from the potential for oil spills (primarily related to shipping and oil and gas operations) and other pollution (e.g., microplastics). Seabirds spend time at sea – either resting on the water surface or diving into the water for feeding. In the event of an oil spill, seabirds are vulnerable to the oily surface (see Section 3.3.7 for more details).

Table 3-2. Example of Arctic distributed seabirds and their status.

Species	Estimated Global Population	ICUN List Status (as of 2020) and Global Trend	Distribution
Ivory gulls *(Pagophila eburnea)*	58,000-78,000 Individuals	Near Threatened Population Global Trend - decreasing	Circumpolar 85% of global pop nest on the Svalbard, Franz Josef Land and Severnaya Zemlya archipelagos and associated islands Davis Strait and northern Labrador Sea is an internationally significant wintering area for the species. Arctic-wide metapopulation.
Yellow-billed loon (*Gavia adamsii*)	11000-21000 individuals	Near Threatened Population Global Trend - decreasing	Breeds in the Arctic in Russia, Alaska and Canada. Winters at sea mainly off the coasts of Norway, western North America, and the eastern coast of Asia, including the coasts of Japan, North Korea, South Korea, and China.
Spectacled Eider (*Somateria fischeri*)	360,000-400,000 individuals	Near Threatened Population Global Trend - decreasing	Breeds along the coasts of north-east Siberia, Russia, east from the Yana Delta to Cape Schmidt, Beaufort Sea coast of Alaska's North Slope and the Yukon-Kuskokwim Delta, Alaska, USA. 90% of the breeding population is thought to inhabit the Russian range.
Common Eider (*Somateria mollissima*)	c. 3,300,000-4,000,000 individuals	Near Threatened Population Global Trend - unknown	Holarctic distribution, being present in both Eurasia and North America. However, its distribution is not continuous across the Holarctic
Long Tailed Duck (*Clangula hyemalis*)	3,200,000 to 3,750,000 individuals	Vulnerable Population Global Trend - decreasing	This species has a circumpolar range, breeding on the Arctic coasts of North America (Canada, Alaska, U.S.A. and Greenland), Europe (Iceland and Norway), and Asia (Russia) - wintering at sea further south.
Steller's Eider (*Polysticta stelleri*)	c.130,000-150,000 individuals	Vulnerable Population Global Trend - decreasing	Breeding in Alaska and Russia. Summer in Russia, northern Norway and adjacent Russian waters, and south-west Alaska. Winter in the Bering Sea, northern Japan, north-east Atlantic Ocean and the Baltic Sea.
Leach's Storm petrel (*Hydrobates leucorhous*)	6,700,000-8,300,000 individuals	Vulnerable Population Global Trend - decreasing	Wide breeding range, but Arctic wise in Alaska, Canada, Iceland and Norway.
Velvet Scoter (*Melanitta fusca*)	141,000-268,000 individuals	Vulnerable Population Global Trend - decreasing	Breeds in Scandinavia, from Norway and Sweden, into Finland and Estonia, and western Siberian Russia to the River Yenisey, and winters mostly in the Baltic Sea and along the coasts of Western Europe.
Black-legged Kittiwake (*Rissa tridactyla*)	14,600,000-15,700,000 individuals	Vulnerable Population Global Trend - decreasing	Breeds in the North Atlantic, from northern central Canada and north eastern U.S.A. east through Greenland to western and northern Europe, and on to the Taymyr Peninsula and Severnaya Zemlya (Russia).

Atlantic Puffin (*Fratercula arctica*)	12,000,000-14,000,000 individuals	Vulnerable Population Global Trend - decreasing	Population in Iceland and Norway, account for 80% of the European population. Found throughout the North Atlantic Ocean, from north-west Greenland (to Denmark) to the coastline of Newfoundland (Canada) and Maine (USA) in the west, and north-west Russia.

3.1.3 Other Flora and Fauna and the Food Web

3.1.3.1 Fish and Sharks

Of the 16,000 global fish species, 633 are known to occur in the Arctic Ocean, with 15 species considered to be rare and endemic to the Arctic, with an additional 63 considered to be true Arctic generalists. Overall, the status of many Arctic marine fish is unknown and it is thought that about 95% have not been evaluated for threat/vulnerability (CAFF, 2013). Fish species endemic to the Arctic Ocean and adjacent seas (AOAS) are the ice cod (*Arctogadus glacialis*) and polar cod (*Boreogadus saida*); 49 species of cartilaginous fishes (21 shark species, 27 skate species and 1 rabbit fish species), spatial distribution varies, with some sea areas devoid of these fish.

Fish in the Arctic Ocean are an important part of the ecosystem and food web. Some species live within the water column (pelagic) and others live close to the seafloor (demersal). Fish are important predators on plankton and bottom-dwelling animals (benthos; (Norcross & Iken, 2016)). Fish are a key food source/prey for marine mammals, seabirds and humans, particularly the Arctic cod. Climate change is a specific concern for Arctic cod because its young life stages depend on sea ice as a habitat, and this central species in the Arctic food web may be severely impacted by the ongoing and projected sea ice loss (Norcross & Iken, 2016).

Arctic fish may be sensitive to changing environmental conditions, particularly the ones which prey on sea ice dependent plankton/algae or use sea ice for breeding. Retreating sea ice may reduce the prey and breeding habitat availability for these fish and increase predation. However, as before, opportunities exist for other species, as the sea ice retreats, opening new foraging habitats and increasing abundance of non-sea ice plankton and algae species. Regarding human activities, fish are again vulnerable to impacts from oil spills, leading to toxicity and contamination (particularly when considered prey or subsistence catch); and some fish may also be sensitive to anthropogenic noise.

3.1.3.2 Seaweed and Plankton

There are 21 species of endemic seaweed species in the Arctic and approximately 15-20% of zooplankton found in the Arctic is endemic (CAFF, 2013). The distribution of marine invertebrates in the Arctic is not only associated with the open waters, but also with the sea ice, with some specialized algae and invertebrates living exclusively on and under the sea ice. The biodiversity of sea ice in terms of marine invertebrates is low, in comparison to the surrounding water column (which is considered to have high biodiversity when compared globally) due to low temperatures and high salinity. Across the arctic the most common amphipod occurring under the sea ice are *Apherusa glacialis*, *Onisimus glacialis*, *O. nanseni* and *Gammarus wilkitzkii*, which are important prey species for fish, particularly the polar cod (which in turn is an important food source for the ice seals). Climate change is of particular concern to calciferous marine invertebrate (ones that form calcium carbonate shells) as ocean acidification will reduce the amount of calcium carbonate available in the water and increased acidification will lead to the shells being dissolved.

Regarding marine invertebrates and plants, although too numerous to cover in detail here, they are a fundamental part of the Arctic food web, and any changes or impacts to these foundations, ultimately has an impact on the higher organisms.

3.1.3.3 Food web

The Arctic food web is made up of primary producers (seaweeds, algae and phytoplankton), consumers (primary consumers e.g., zooplankton, secondary consumers, grazers and top consumers (e.g., apex predators etc.) and decomposers (e.g., microorganisms that break down and recycle waste and organic matter). The Arctic food web is most vulnerable to climate change (see Section 3.1.4), although human activities may also cause significant impact to the food web through over exploitation (which has been witnessed through hunting of marine mammals for example and overfishing) and pollution.

In many impact assessment situations, it is important to consider the "cumulative impacts", not necessarily from multiple stressors/activities, as we define cumulative impacts in Section 3.3, but from a whole ecosystem perspective (e.g., including the whole food web), therefore accounting for impacts that may happen over different spatial and temporal scales. An impact, particularly one arising from a catastrophic pollution event, may have significant impacts in the food web, and ecosystem for many years (e.g., *Exxon Valdez* oil spill in Alaska, 1989, see Section 3.3.7; (Colegrove, et al., 2016)).

3.1.4 Climate Change and Human Activities

Arctic amplification is a phenomenon where the rate of climate warming is more rapid compared with the average rate of global climate warming. Over the last 30 years, the Arctic has warmed at a rate roughly twice that of other regions (NSIDC, 2020). In the marine environment in the Arctic, the concerns include the melting sea ice, warming waters and ocean acidification.

The extent of sea ice in the Arctic has been recorded by the National Snow and Ice Data Center (NSIDC) since the 1979, with the lowest extent of winter sea ice being recorded in 2017. The 2020 sea ice extent represented the 11th lowest recorded extent (since 1979) and reached its maximum on 5th March 2020. Entering the northern hemisphere winter in December 2020, sea ice extent remained far below average, dominated by the lack of ice on both the Pacific and Atlantic sides of the Arctic Ocean; the average October 2020 sea ice extent was the lowest on record and the average November 2020 extent was the second lowest (NSIDC, 2020). It is predicted that the Arctic sea could lose its sea ice cover entirely by 2035 (Guarino, et al., 2020).

Given the rate of warming and loss of sea ice in the Arctic, the implications on marine wildlife are many. There is evidence of north ward expansion of some boreal marine invertebrate species (CAFF, 2013); fish are also likely to move northward (some species are particularly sensitive to changes in temperature; for example, some fish stocks in the Barents Sea are moving north at up to 160 kilometres per decade as a result of climate change (WWF, 2020); loss of ice habitat for ice dependent (sympagic) flora and fauna (many of which are unique to the Arctic and important food web species) ;and coastal erosion - a particular threat to indigenous communities and wildlife that live on the coasts. This erosion is accelerated due to the retreat and loss of land-fast ice (Borunda, 2020).

The opening of the Arctic through the loss of sea ice also sees the likely increase in invasive, non-native and opportunistic species – which often out-compete their true Arctic counterparts, change predation rates (as seen by increased presence, both in geographic range and time spent in Arctic waters by killer whales for example, see Section 3.3.4 and altering the Arctic ecosystem and biodiversity.

Finally, retreating sea ice brings with it the opportunity for people to expand and diversify their activities and exploitation of the Arctic's marine environment, particularly shipping, extractive industries (oil and gas, aggregate, mining etc.) and tourism (cruise ships etc.).

3.2 Arctic Shipping/Vessel Activities

Vessel activities that may have an impact on the marine environment in the Arctic, include transportation of cargo; fishing vessel activities (commercial and recreational/local); vessels related to oil and gas exploration and production (e.g. survey, supply, cargo vessels); military vessels; other offshore and coastal developments or extractive industries (e.g., marine renewables, aggregate extraction); tourism (e.g., cruise ships and wildlife watching); harbor and coastal vessels (e.g., tugboats, coastguard); recreational vessels; and indigenous community related vessels; all of which present several challenges for the environment and Arctic wildlife.

Overall, when we consider shipping, we must also consider the potential environmental impacts that may arise from the associated shipping infrastructure, such as the construction of ports, harbours and marinas and the long-term presence of these structures. These impacts may include the temporary construction impacts (e.g., noise, debris, construction traffic, suspended sediments/turbidity) and longer-term impacts (e.g., marine biofouling, potential for invasive species, alteration to water movement and persistent pollutants from heavy traffic use in the area).

The use of vessels for other activities in the Arctic also carry their own suite of environmental impacts, such as, dredging and trawling for seafood from fishing vessels, potential disturbance of wildlife on tourism/wildlife watching cruises (if not conducted responsibly), disturbance of wildlife through survey activities (e.g., shooting seismic, deep positioning thrusters, anchoring etc.) servicing of offshore energy structures and platforms, mines, and removal of seabed aggregate.

Shipping figures for the first ten months of 2020 suggest that shipping in the Arctic increased, despite the coronavirus pandemic, with a total of 26.37 million tons of goods being shipped on the Northern Sea route, an increase of 2.9 percent compared with the same period in 2019 (Staalesen, 2018a). In 2020, the Northern Sea route opened in May and it is reported will be largely open through December 2020 due to the warm Autumn, the longest open season to date (Shiryaevskaya, et al., 2020). Reports in mid-January 2021 of Russian tankers traversing the North Sea Route with no ice breaker escort, confirm these predictions (Smith, 2020).

The development of the blue economy (WWF, 2016) in the Arctic is at a critical stage, with the need to develop and enhance social and environmental management strategies, that may allow for the sustainable development of the marine environment and which will also adequately protect the important and sensitive Arctic ecosystem.

In order to focus the scope of this report, it will concentrate on the environmental impacts of shipping activities that only involve the vessel moving from point A to point B (e.g., transportation /travelling /traversing /transiting through the Arctic) and will not consider any other environmental impacts that may be associated with the activities that occur onboard or from a vessel (e.g., fishing, seismic, explosives etc.).

3.3 Environmental Impacts of Shipping on Arctic Wildlife

Levels of human activities (e.g., shipping, fishing, oil and gas) in the Arctic marine area are increasing, which will ultimately result in more frequent and severe threats and impacts to Arctic marine wildlife (Reeves et al., 2014). Environmental impacts of a project or activity can be grouped into three broad categories: i) direct impacts – impacts that are a direct result of a project activity or decision. These are usually predictable, based on planned activities/routes and knowledge of the marine ecosystem and can to some extent be managed or mitigated for; ii) indirect impacts - impacts that are less predictable as they derive from interactions with multiple factors and stakeholders; and could be described as a 'by-product' of an activity and these tend to have a much larger spatial footprint (Biodiversity Consultancy, 2013); and iii) cumulative impacts are "the incremental impact of an action when added to another past, present and reasonably foreseeable action" (Piet, et al., 2017), derived from European Commission guidelines, 1999) and therefore this also includes impacts from multiple activities. Some impacts can be considered both direct and indirect, depending on the environmental receptor and stressor, and their temporal and spatial extent. Table 3-3 provides a summary of potential direct and indirect impacts of shipping in the Arctic marine environment.

Table 3-3. Direct and indirect Impacts from shipping on Arctic wildlife and the marine environment.

Impacts of Shipping in the Arctic Marine Environment	
Direct Impacts	
Collisions/ship strikes with marine mammals	Direct hits to marine mammals (cetaceans and pinnipeds) by vessels, resulting in injury or death and behavioural changes (avoidance, increased dive times etc.) Impacts can be at an individual or population level.
Noise disturbance to marine mammals that use sound for communication and navigation (e.g., Cetaceans, pinnipeds, some fish and crustaceans)	Excessive noise can result in physical injury, behavioural changes and in severe cases death depending on level of exposure, noise source and species sensitivity. Acoustic masking can also have consequences for communication and maintenance of mother-calf relations, foraging success and increase likelihood of predator detection. Impacts can be at an individual or population level.
Disruption to migratory patterns or routes; and/or abandonment of important areas/habitats	This may result from the introduction of noise which results in behavioural or avoidance impacts; or through the physical presence of vessels (especially in large quantities), or contamination of water/habitat (e.g., due to a spill) which restricts or does not allow for migratory passage. Species may temporarily or permanently leave/abandon important areas/habitats if significantly disturbed (e.g., by noise, physical presence or contamination).
Breaking sea ice	May result in the loss (habitat destruction or modification) of calving, resting, feeding areas for marine mammals and other marine wildlife e.g., seals/walrus, fish, seabirds. May contribute to the loss of ice algae (food source and carbon sink).
Physical impacts from loss of ship or cargo	Impacts seabed through potential loss or damage to seabed habitats (e.g., coral reefs, sea pen communities). Potential for ingestion of cargo by some marine wildlife, leading to injury or death (particularly plastics).
Potential accidental events/Spills/hazardous or toxic substances/transportation of oil (incidental, operational and illegal discharges)	If an oil/chemical spill is encountered, this may result in injury or death of animal. Behavioural changes may also occur (see 'Disruption to migratory patterns or routes; and/or abandonment of important areas/habitats').
Indirect Impacts	
Breaking sea ice	Impacts travel and hunting capabilities of indigenous communities as they cannot travel over broken ice. This may lead to fractured communities, loss of livelihoods, and loss of subsistence. Changes to ice flows, making ice movement more erratic and less predictable – this may lead to an increase in ice trapping incidents.
Collisions/ship strikes with marine mammals	Significant incidents of death due to ship strikes, could ultimately lead to a population's decline or loss.
Atmospheric emissions (air pollution through emissions and particulate matter from engine exhaust gases and cargo tanks)	Carbon Dioxide and Greenhouse gases: climate change, resulting in loss of sea ice and associated knock-on impacts (e.g., see 'breaking sea ice'), increased vessel traffic etc. Stormier conditions during ice-free season. Black carbon: contributes to climate change. On ice or snow black carbon and particulate matter reduces the surface's ability to reflect sunlight and therefore accelerates melting. These impacts ultimately have global consequences.

<table>
<tr><td colspan="2">Physical impacts from loss of ship or cargo</td><td>If lost cargo is not recovered (not including hazardous substances/cargo herein, see ‘release/discharge of substances’ below), then introduction of a hard substrate into an area of previously only soft substrate, may lead to colonization by non-native/invasive species, thereby potentially altering the local ecosystem and potential ingestion of lost cargo/microplastics.
The potential loss of habitat (direct impact) may also result in the loss of the associated habitat communities (e.g., fish) which are important to the local and wider food web (including large predators and communities).</td></tr>
<tr><td colspan="2">Introduction of invasive species (ship biofouling, ballast water and associated sediment)</td><td>May lead to the rapid spread of the invasive species throughout the region – potentially leading to the loss of native species, loss of grazers or predators (if the invasive is not a suitable food source), and loss of livelihoods (if invasive is not suitable for hunting and therefore removes the community’s food source). There is also the potential for the introduction of non-endemic diseases/parasites etc., due to the Arctic’s relative isolation.</td></tr>
<tr><td colspan="2">Noise disturbance to other marine wildlife</td><td>Excessive noise may scare, injure or cause behavioural/physiological changes to other marine animals, e.g., fish/cephalopods – which may in turn have a direct impact on for example predators, if prey species are scared away.
Impacts can be at an individual or population level.</td></tr>
<tr><td rowspan="3">Discharge of pollutants to Sea</td><td>Potential accidental events/Spills /hazardous or toxic substances/transportation of oil (incidental, operational and illegal discharges)</td><td rowspan="3">Any release of oil, chemicals or waste into the marine environment could result in many potential impacts:
• Injury to and death of wildlife
• Contamination of prey (resulting in bioaccumulation up the food chain)
• Ingestion of litter
• Physiological changes to wildlife (long term/chronic e.g., infertility)
• Loss of subsistence for local communities
• Damage to offshore and coastal habitats and communities

Impacts can be at an individual or population level.</td></tr>
<tr><td>Discharge of waste/oil/chemicals (operational and illegal discharge – raw sewage, litter)</td></tr>
<tr><td>Release of toxic chemicals (e.g., anti-fouling paints, leaching heavy metals from anodes)</td></tr>
<tr><td colspan="2">Disruption or loss to indigenous community way of life</td><td>Any number of impacts listed above may result in the loss or disruption to indigenous communities, e.g., impacts to hunting species, subsistence, travel, pollution of environment etc.</td></tr>
</table>

The following sections outlines these potential impacts in more detail and primarily focuses on aquatic marine wildlife that have the potential to come into direct contact with shipping activities (e.g., marine mammals and fish) and seabirds that spend time at sea (surface or diving) in relation to oil spills.

3.3.1 Collisions/Ship Strikes

One of the most clearly defined and direct impacts of shipping on Arctic marine wildlife, is the potential for vessel collisions/strikes. That is, when a vessel makes direct impact with an animal in the water, or while on ice. The resulting impact from the collision may range from minor injury or behavioural change to death.

(Schoeman, et al., 2020) reports that at least 75 marine species globally are at risk of ship strikes including large and small whales, dolphins, porpoise, dugongs, manatees, whale sharks, sharks, seals, sea otters, sea turtles, penguins and fish. To date, most studies have focused on larger marine mammals, particularly North Atlantic right whale (van der Hoop, et al., 2012), fin whales (Carrillo & Ritter, 2010), blue whales (Szesciorka, et al., 209), humpback whales (Hill, et al., 2017) and sperm whales (references in (Schoeman, et al., 2020)). This disproportionate number of studies would indicate that larger marine mammals are most prone to ship strikes, however, smaller animals are still at risk, and the collision reports with smaller marine animals although scarce, is likely due to a reporting bias rather than lack of frequency (Schoeman, et al., 2020). In the Arctic, the potential risks to marine mammals are widely acknowledged and the seven endemic Arctic marine mammal species are presumed to be at most risk from increased vessel traffic (Hauser, et al., 2018). A recent study on killer whales in the eastern Pacific Ocean showed that deaths as a result of human interactions impacted all age classes. Identification of vessel strike-related trauma demonstrates that human interaction is a significant cause of morbidity or mortality in killer whales and that ship strikes pose a significant threat to killer whale, especially endangered populations (Raverty, et al., 2020).

The International Whaling Commission (IWC, 2011) states that the risk of collision is defined as “the probability that a collision occurs, combined with the probability that such a collision will lead to a serious outcome (i.e., major injury, mortality or damage to vessel”. A collision risk analysis requires knowledge of animal and vessel distribution patterns and specific vessel (e.g., size and speed) and animal (e.g., time spent at or near surface, behavioural response to vessels etc.) related factors (Schoeman, et al., 2020); and the probability of a collision increases when areas of higher shipping activity overlap with higher animal density.

Specific impacts of ships collisions with marine mammals include sharp and blunt force injuries (which may be lethal immediately on impact or days-months later); and longer-term consequences may include locomotive impairment and reduced fitness, potentially preventing effective foraging and may ultimately lead to starvation; open wounds and broken bones may lead to increased energy expenditure (*i.e*., less energy available for growth and reproduction; (Schoeman, et al., 2020)) and potential for infection and disease.

The Australian Marine Mammal Centre’s National Marine Mammals database holds records of 84 individual marine mammals (all cetaceans), being struck by vessels (during 74 incidents) between 1998-2012 (average 3/year). In the UK, the UK Cetacean Stranding's Investigation Programme has confirmed 32 cetacean deaths as a result of ship strikes between 1990 and 2014 (representing 0.9% of investigated deaths - the most common cause being bycatch/entanglement; average 2/year). In the USA, 292 records of confirmed or possible ship strikes involving large whales were recorded from 1975-2002 (average 11/year; of which 16.4% resulted in injury and 68% were fatal; (Jensen & Silber, 2003)). A report in Alaskan waters reported 108 confirmed and probable ship strikes to whales between 1978-2011 (average 3/year; (Neilson, et al., 2012)); also, in Alaska, 13 whales between 1988 and 2007 (2-3% of 459 bowheads landed as part of subsistence hunts) bore signs of possible or confirmed ship strikes (Reeves, et al., 2012); 24 right whales (45 examined from 77 deaths between 1970 and 2007 on the east coast of the USA, showed evidence of ship strike (Reeves, et al., 2012); and 30 cetacean-vessel collisions were reported between 2004-2011 (average 4/year) in British Columbian waters ((Wild Whale, 2013); Table 3-4). It should be emphasized that the number of whale strikes reported, and deaths registered as a result of ship strikes, likely represent a very small percentage of the actual number of animals that are struck. [Table 3-4 source: listed in Table; * confirmed or possible.]

Table 3-4. Summary of global ship strike statistics (average numbers rounded up).

Country /Region	No. of Ship strikes *	Year Range	Average No. Strikes per year	Marine Animal	Reference
Australia	84	1998-2012	3	Cetaceans	(Australian Marine Mammal Centre , 2020)
UK	32	1990-2014	2	Cetaceans	(ZSL, 2014)
USA	292	1975-2002	11	Large whales	(Jensen & Silber, 2003)
USA (Alaska)	108	1978-2011	3	Whales	(Neilson, et al., 2012)
Canada (British Columbia)	30	2004-2011	4	Cetaceans	(Wild Whale, 2013)
Arctic (Bering-Chukchi-Beaufort Sea)	20	1990-2012	1	Bowhead whales	(George, et al., 2017)
USA (Alaska, Barrow and Kaktovik subsistence hunt landings)	13	1988-2007	1	Bowhead whales	(Reeves, et al., 2012)
USA (east coast)	24	1970-2007	1	Right whales	(Reeves, et al., 2012)
USA/Canada (west coast)	9	2004-2013	1	Killer whales	(Raverty, et al., 2020)

As previously mentioned, studies on ship-strikes with other marine animals (not just cetaceans) is limited. In the Arctic specifically, (Wilson, et al., 2019) estimated that in the Caspian and White Sea, the potential collision risk with seal pups in the path of ships transiting seal breeding ice were 9.6% and approximately 1.4 to 1.9% respectively (% of pup population). They also reported that the median areas of danger for seals in water surrounding vessels ranged from approximately 1500m^2 to 7800m^2, and in areas where vessel speed was greater than 5 knots, seals in the water were prone to come under the drawing forces of the vessels (Wilson, et al., 2019).

(Hauser, et al., 2018) undertook a comprehensive assessment of the combined effects of vessel exposure (likelihood of encountering a vessel) and sensitivity (to the vessel e.g., noise of ship strike) across all populations of Arctic marine mammals under increasingly navigable Arctic sea routes during open-water conditions. Their results (focusing on the North West Passage and Northern Sea Route) showed that of the subpopulations that overlap with the sea routes, the Eclipse Sound narwhal was most vulnerable to vessel traffic (as a result of high exposure to the North West Passage and biological/species-specific traits that increased vulnerability) and the Hudson Bay-James Bay ringed seal was least vulnerable. In summary, the results showed high vulnerability scores for narwhal, walrus, bowhead and beluga subpopulations. Intermediate vulnerability for bearded seals and low vulnerability for polar bears and ringed seals (Hauser, et al., 2018).

Arctic bowhead whale susceptibility to ship strikes can be demonstrated by evidence of wounds and scarring consistent with vessel collisions, found on about 2% of the whales taken by Alaskan Native subsistence hunters (Reeves, et al., 2012). Indirect evidence that large vessels negatively impact bowheads is derived from studies on their near relatives, North Atlantic right whales, with vessel strikes being their most significant cause of mortality (Reeves, et al., 2012). Endangered North Atlantic right whales are especially vulnerable to vessel strikes as their habitat and migration routes are close to major ports and often overlap with shipping lanes (NOAA, 2020)There is the potential that this is the fate awaiting the Arctic bowheads (where the western Arctic populations has been steadily recovering, post hunting depletion), as shipping increases, if measures to protect them and reduce potential collisions are not implemented effectively.

The IWC plan to mitigate ship strikes to cetacean populations: 2017-2020 report (IWC, 2017) identified a list of high-risk areas where ship strikes are common. In the Arctic, these areas include the north-east coast of Sakhalin Island (for western gray whale), Eastern Bering Sea (for North Pacific right whale) and the general US and Russian Arctic (potential threats to bowhead whale). The 2020-2022 ship strike workplan outlines plan (in collaboration with relevant stakeholders) for developing proposals for ship strike reduction measures in these high-risk areas.

Several knowledge gaps have been identified. Studies on the risk of ship strikes to other (non-cetacean) marine animals are limited. Therefore, the assumption that smaller animals (e.g., seals) and cetaceans (e.g., some smaller whales, dolphins and porpoise) are more agile and faster moving, and as a result are less likely to be struck, is largely unfounded. For example, the Australian ship strike database reports that 25% of ships strikes occurred to dolphins or porpoise (46% were whales and 29% were unidentified). Data presented by (Raverty, et al., 2020) demonstrates that even the agile killer whales are still susceptible to ship strikes.

The under reporting of small cetacean or non-cetacean strikes may also be related to vessel size. Some larger vessels may not be aware of striking an animal, particularly if the strike does not result in damage to the vessel, and if the animal is relatively small (e.g., in comparison to the larger whales). This also includes a need to understand the risk to ice breeding seals and walrus during their pupping season (Wilson, et al., 2019). Under reporting of large whale strikes will also be an issue and therefore the true extent of ship strike threat to marine mammals is not known.

Using the St Lawrence River Beluga whales as a proxy for other Arctic cetacean species (particularly narwhal given their biological similarities) – the impact of ship strikes has been significant. Following the ban on commercial whaling, there has been no recorded recovery of the population (DFO, 2020). The St Lawrence River has high levels of shipping activity (Reeves, et al., 2014) that overlaps the population's range. As a result, in 2016, this population of Belugas was listed as endangered (Species at Risk public registry, Canada and the Committee on the Status of Endangered Wildlife in Canada).

The long-term physical and population level consequences of ship strikes is also poorly understood and there are large data gaps on Arctic marine mammal subpopulation status, trends and distribution, which contribute to the uncertainty of risk and vulnerability assessments (Hauser, et al., 2018).

With adequate mitigation and management measures, which are well-informed and based on solid scientific data and evidence, a number of these risks can potentially be reduced or avoided. Ship strike reporting systems, stranding databases and modelled risk analysis help identify populations for which ship strikes may exceed population recruitment rates.

3.3.2 Noise Disturbance

Although this section focusses on direct and indirect impacts to wildlife, noise should be considered as a direct, indirect, and cumulative impact. This is because anthropogenic noise can be highly pervasive and there is no way to 'remove' other sources of underwater noise when examining the impacts of one activity such as shipping. For example, (Nieukirk, et al., 2012) reported that air gun sounds were recorded up to 4000km from seismic survey vessels in the North Atlantic. This noise could ultimately impact all marine wildlife within that range, to varying degrees, albeit temporarily; but when considered in combination with all the other noise generating activities that happen within that range, the level of noise a recipient is exposed to then has the potential to dramatically increase. The nature of noise produced via ship propulsion (low-mid frequency noise) means that it is more likely to propagate further and suffer less attenuation than high frequency noise. Therefore, the potential area over which it will result in an impact or likely contribute to cumulative noise budgets is significant.

Underwater noise can be categorized as: i) 'acute', noise generated through activities such as military sonar, seismic activities, oil and gas exploration and seabed construction; activities that are temporary, and the noise will stop when the activity stops; and ii) 'chronic,' noise that is continuous, persistent and/or spatially extensive such as the noise generated by shipping (Von Mirbach, 2019).

Ambient underwater noise levels in the Arctic are relatively low (compared to the world's other oceans), however the underwater marine environment in the Arctic is undoubtably becoming noisier, due to the direct increase of human activities and developments, the reduction of sea ice coverage and increasing ocean acidification ((Reeves, et al., 2014); (PAME, 2019)). However, it should be noted that seasonal fluctuations to ambient noise may be attributed to ice coverage extent. During the ice-covered season, ambient noise is dampened/muffled by the ice. As the ice coverage reduces and anthropogenic activities increase, the Arctic will become noisier (Insley, et al., 2017).

(Halliday, et al., 2020) have conducted a review of underwater noise and marine mammals; and a recent state of knowledge report on underwater noise (PAME, 2019) both give an extensive overview of issues and impacts associated with underwater noise in the Arctic. These reports have been reviewed and the highlights and impacts related specifically to vessel noise is summarized in Table 3-5.

Table 3-5. Overview of Underwater Noise in the Arctic.

Summary of Underwater Noise in the Arctic: A State of Knowledge Report (PAME, 2019); Underwater noise and Arctic marine mammals: review and policy recommendations (Halliday, et al., 2020); and references therein. *root-mean-squared, ** median	
Sound propagation	High frequency sound waves that hit sea ice attenuate by scattering (repeated reflection). Near surface sounds waves will not propagate as far as waves travelling in deeper or ice-free waters. Layering of freshwater and temperatures (thermocline) refracts sound waves up and down, creating the Arctic sound channel – with sound getting trapped in certain layers of water (100-300m) – therefore propagating farther than if they were not trapped. Propagation in the sound channel depends on noise frequency. Ocean acidification can also reduce absorption of sound waves (400-5000Hz) and allow sound to travel farther.
Ambient sound	Ambient noise sources include physical processes (geophony; ice, wind, earthquakes etc.), biological sounds (biophony; marine mammal communication, fish grunts etc.) and anthropogenic sounds (anthrophony; vessels etc.). Ambient sound varies throughout the year and elevated ambient noise can be caused during marine mammal mating seasons (to attract mates). For northern polar sea, on average, the Arctic Ocean has the lowest levels of ambient noise, compared with that in the Greenland and Beaufort Seas. Shipping has a much larger overall impact on ambient sound levels than for example seismic surveys (relative to the number of seismic surveys), adding a median 3.5dB (40-315Hz) to ambient sound levels. The signal-to-noise ratio is greater in the Arctic due to low ambient sound, which may elicit a greater response from animals.
Vessel noise	Typical vessel noise ranges have been reported to be between 159-178dB_{rms*} in non-polar regions (average 178dB_{rms*}). Vessel noise in the Arctic is poorly reported, and mostly focuses on icebreaking activity, which is greater than other vessel noise – and can be louder than 200dB_{med}** (0.01 to 20 Hz). One research vessel transiting in the Barents Sea reported 176dB_{rms*} (0.063 to 20Hz). Noise levels will depend on vessel type and speed.
Marine mammals	Marine mammals can be grouped as: 1) low frequency cetaceans (bowhead, fin, grey and minke whales) range 7Hz-35kHz; 2) mid frequency cetaceans (beluga and killer whales, narwhals) range 150Hz-160kHz; 3) high frequency cetaceans (e.g., harbor porpoise) range 200hz-180kHz; and 4) Pinnipeds in water (e.g., ringed seals) range 75Hz-75kHz (Walrus range 100Hz-40kHz). All Arctic pinnipeds (excluding walrus) are phocids (earless seals), therefore their hearing is more acute underwater. Bowhead whales (endemic): 50-1000Hz in summer; higher vocalization >2000Hz in winter when they sing. Beluga and Narwhal (endemic): 400-15,000Hz; echolocation clicks 10-12kHz. Seals: species specific, but range100-10,000Hz (bearded seals produce sound within this whole range; ringed seals <1000Hz) Fish (only Arctic cod confirmed to make noise): grunts 100-200Hz. Bowheads and bearded seals reported to elevate ambient noise during breeding seasons. Therefore, these different groups of marine mammals have varied sensitivity to anthropogenic noise. Severity of the physical impact increases the closer to the noise source and exposure to chronic/long term noise can both result in behavioural change, physical injury (hearing damage, collision due to avoidance) and death. Behavioural changes include, avoidance of an area, increased vigilance, stress, decreased foraging (significant biological implications), change in signal amplification and amplitude.

	Studies on vessel impacts reported Bowhead whales react to vessel noise by avoidance and changing their diving behaviour. Limited studies on belugas and narwhals, show both species are reported to be sensitive to intense noises from icebreaking and shipping. Seals are reported to be more tolerant to shipping noise than all three whale species.
Marine mammal – species specific responses to shipping noise	*Bowhead Whales*: movement away from and changes in diving cycle in response to vessels approaching. Show stronger reaction to noise whilst migrating. *Belugas and Narwhal*: beluga have strong reaction to ice breaking, with avoidance responses within 50km of the ice breaker; while Narwhal may respond to ice breaker noise with a "freeze" response, and avoidance for up to 48hrs. Beluga vocalization may decrease due to decreased calling rates or fleeing in response to vessel presence. Belugas may increase heart rate ("acoustic startle response") in response to noise disturbance. *Harp Seal*: decreased vocalization in response to boat noise (potential acoustic masking within 2km of seal) *Minke Whale*: less sightings when vessel traffic and noise increases, so avoidance inferred. *Note: species listed here are those covered by the two summarized reports and is not necessarily representative of all species that need to be accounted for when considering future shipping impact assessments.*
Fish	Acoustic impacts have only been studied in two Arctic fish species: Arctic cod and shorthorn sculpin. The impacts from vessels include altering their home range size and movement patterns. Non-Arctic studies on other fish species have shown that underwater noise may cause barotrauma (damage to swim bladder; may cause injury or death), impaired hearing sensitivities, auditory masking (when the ability to detect or recognize a sound is degraded by the presence of another sound) and change in behaviour.
Invertebrates	There have been no studies on the impacts of underwater noise on Arctic marine invertebrates. However, other non-Arctic studies have shown that vessel noise can impact the behaviour of lobsters, crabs and prawns, impact on the biochemistry and physiology of crabs and prawns, change how sediment dwelling invertebrates' function in their environment (e.g., nutrient cycling) and low-frequency noise can damage the hearing in cephalopods.
Knowledge gaps	• Limited geographic range of the studies (large areas of the Arctic have no studies related to underwater noise). • Limited number of Arctic species studied (7 of the 11 Arctic marine mammals not studied for noise impacts; and only 2 of 633 fish species studied); (need real-time studies) • Limited studies on impacts of vessel noise on belugas and bowheads (most studied species for other noise sources) • Measurements of ambient underwater noise is not standardized • Source levels not measured for many activities/vessel types/vessel speeds etc. • Measurements of source level not standardized • No studies were found to have documented chronic/cumulative impacts of noise on Arctic marine wildlife or cumulatively with other stressors (majority of studies focus on acute responses) • Very limited availability (if any) of data/evidence for hearing sensitivities/tolerances for Arctic marine wildlife • Lack of information on areas with the most vessel traffic (or future traffic) - these areas need increased monitoring
Policy and assessment considerations	• Vessel traffic and shipping are not generally covered by environmental impact assessments (only if considered within a project specific EIA, e.g., oil and gas vessels) • Other management measures needed, for example transportation corridors or protected areas to reduce or limit extent of underwater

	noise from shipping, quieter technology, quiet zones, speed reduction, seasonal protection, adaptive management etc.

Low-frequency noise from large ships (20–200 Hz) overlaps acoustic signals used by baleen whales (e.g., Arctic endemic bowhead whales; (Ahonen, et al., 2017)), and increased levels of underwater noise have been documented in areas with high shipping traffic. This level of exposure may be associated with chronic stress in baleen whale species (Rolland, et al., 2012). Studies of humpback whales in Japan showed that their singing reduced in the presence of vessel noise, vacating areas nearest to the shipping lanes, with most whales not resuming their vocalizations until half an hour after the ship has passed (Tsujii, et al., 2018). Other species have also been documented to change their vocalization rate and/or the energy of their calls in response to the presence of vessel noise both of which may have energetic or fitness consequences for that individual or the wider population, if more than one animal adopts this behaviour for a prolonged period (Weilgart, 2007).

For cetaceans, the importance of communication between animals during periods such as the breeding season (bowheads; (Stafford, et al., 2012)) and calving (beluga; (Vergara, et al., 2010)) is well recognized. For endemic species in the Arctic these periods usually occur in the summer months and temporally overlap with peak months for transmitting vessel traffic. It is also known that introduction of ship noise has the potential to result in acoustic masking of these types of vocalizations across a wide range of species and can essentially reduce the space over which they are able to listen ((Erbe, et al., 2016); (Putland, et al., 2018)). Interference with vocalization that are linked to communication can have a potential impact on breeding success and in extreme cases separation of mothers and calves leading to mortalities ((Parks, et al., 2019); (van Parijs & Corkeron, 2001)). One study on humpback whales also highlighted the introduction of vessel noise can result in mothers having to increase the loudness or their call rate in order to maintain connection with their offspring and that this could have wider implications for their fitness as these normally discrete communications, if louder or more frequent will be more likely to alert potential predators (i.e., killer whales to their presence; (Videsen, et al., 2017)).

(Erbe, et al., 2019a)(and references therein) provides a summary of known impacts and knowledge gaps on the impacts of shipping (and other sources of) underwater noise on marine mammals in Antarctica. Studies summarized included reporting increased stress levels in North Atlantic whale (or similar species); effects on foraging, (e.g., lower descent rates and fewer side-roll feeding events per dive) on humpback whales; and noise source avoidance and predicted masking of communication sounds in killer whales. More generally, (Erbe, et al., 2019b) review of the impact of ship noise on marine mammals, gives an overview of species-specific responses as summarized below:

- Bowhead whales: avoidance, interruption of foraging, socializing, and playing behaviour, less time spent at surface.
- Gray whales: increased vocalization rate.
- Humpback whales: increase amplitude of vocalization, less frequent vocalization, cessation of singing in vessel presence, decrease in dive time, avoidance, cessation of foraging activities, decrease in communication range.
- North Atlantic right whales: lack of behavioural response (a possible reason for high ship strike rates), increased stress levels (from physiological examination), shift to vocalization frequency and duration, "gunshot" call susceptible to masking by vessels.
- Fin and minke whales: decrease in communication range, masking compensation (changes to vocalization range).
- Beluga whales: loss of pod integrity, commencement of rapid movements, shallow dives, change to vocal behaviour, increasing avoidance in heavy shipping areas (e.g., St Lawrence Estuary, Canada), shift to higher frequencies.
- Narwhal: changed locomotion, fall silent.
- Sperm whale: fewer clicks during vessel passes, decreased surface time, respiration interval and number of ventilations (avoidance, no response and attraction depending on the context of the underwater noise).
- Killer whale: less foraging, increased surface-active behaviour, changes to respiration, swim speed and direction, increased vocalization duration.
- Dolphins: displacement, changed site occupancy, altered movement patterns, increase to time spent travelling (decreasing resting and socializing), alterations to dive patterns, alteration to whistle characteristics/frequency range, duration, increase in whistle production rates.

Reported responses of whales to increased noise include habitat displacement, behavioural changes and alterations in the intensity, frequency and intervals of calls (Rolland, et al., 2012). Behavioural responses to increased noise may include slower descent rates and fewer side-roll feeding events per dive, which may ultimately reduce foraging success (as recorded in humpback whales in the western North Atlantic; (Blair, et al., 2016)).

Results of a study on gray whales in the Gulf of California (Findley & Vidal, 2002) and other studies (references in (Findley & Vidal, 2002)) reported behavioural changes (e.g., changes in vocalizations), preceded the abandonment/avoidance of lagoons during underwater noise experiments and in the presence of fishing vessels running at high speeds in the lagoons, confirmed the disturbing effects of high-level underwater noise on these whales.

Evidence is emerging that when ship traffic is reduced, the levels of stress or impact to marine mammals' species is also reduced. This was noted by (Rolland, et al., 2012) following the events of 11th September 2001 (reduced ship traffic in Bay of Fundy, Canada); and recent evidence suggests that numbers of Indo-Pacific humpback dolphins in the Pearl River Estuary between Hong Kong and Macau increased after ferry (approx. 200 ferries per day) activity ceased in response to the Covid-19 pandemic (Davidson, 2020). These examples suggest that background vessel noise is reducing the world for these animals and robust management measures are needed to limit noise impacts.

Impacts of noise on other marine species have also been documented. A critical literature review by (Edmonds, et al., 2016) outlined that physiological sensitivity to some underwater noise among Norway lobster (Nephrops Norvegicus) and closely related crustacean species, although overall data is lacking. A review by (Tidau & Briffa, 2016) also identified studies documenting the impact of noise on crustacean species (freshwater and marine). Response to noise included increase in some behaviours (e.g., locomotion) and stress, reduced and slower antipredator behaviour, changes in foraging, suppressed behaviours with an ecological function (bio irrigation), and changes to intraspecific behaviour (e.g., agonistic encounters), although again suggesting that knowledge was lacking.

Research on the impacts of anthropogenic noise on fish is also limited, however the available studies suggest that fish may be subject to the same range of impacts (although impacts and severity differ between species) e.g., behavioural responses furthest from the source, with an increasing likelihood of physiological impacts, hearing damage, injury, and death with increasing proximity as other taxonomic groups (Radford, et al., 2014); and prey fish may be caught more readily when impacted by passing motorboats (Simpson, et al., 2016).

3.3.3 Disruption to migratory patterns/abandonment of important habitats

The introduction of new and/or permanent shipping routes in the Arctic, could be compared to the construction of a new road on land – it creates a new and potentially very dangerous obstacle to animal movement (Pirotta et al., 2018) and disturbance to habitats. Marine animals use both the water (cetaceans and pinnipeds) and ice (polar bears) to seasonally migrate around the Arctic. Migrations are in response to feeding, breeding and nursing/calving needs. Arctic cetaceans are migratory, often following genetically based migration routes and exhibiting site fidelity to productive regions with extensive summer foraging opportunities (Hauser, et al., 2018).

The eleven endemic marine mammal species (3 cetacean, bowhead whales, Beluga whales and narwhal, 7 pinnipeds and the polar bear) are also joined by at least another five cetacean species (e.g., minke whale, fin whale, grey whale, humpback whale, killer whale) that migrate into Arctic waters during the ice-free summer and autumn months, principally to feed (Moore & Reeves, 2018).

Pinnipeds rely on the sea ice to rest, breed and mate, and therefore migrate in response to the seasonally changing sea ice conditions. It is likely therefore, that as Arctic waters become ice free for longer, seal migration range will probably decrease in response, with the seals needing to stay close to the ice-covered areas.

There are geographic “bottle-necks” in/out of the Arctic (e.g., Bering Strait and eastern Canadian Arctic), which are used by both seasonally migratory marine mammals and vessels. The marine mammals that use these routes are two to three times more vulnerable to the impacts of shipping (e.g., noise, strikes etc.) as they represent potential high conflict areas (Hauser, et al., 2018) - the more vessels using a migratory route, the more chance of coming into contact and impacting migratory marine mammals.

Increased noise (see Section 3.3.2 for more details) from shipping and the physical presence of more vessels may also lead marine mammals to abandon or avoid migratory routes or preferred habitats (e.g., foraging or calving areas). Cetaceans, and particularly those that have high site fidelity, are at risk of significant population impacts, as seen in the gray whale population in the Gulf of California, Mexico, reported by (Findley & Vidal, 2002). Their study suggested that the increased presence of high-speed vessels (mainly fishing vessels) and increased shipping traffic are likely responsible for the decrease in gray whales using calving/nursery lagoons in the Gulf. This study was based on gray whale observations from the 1950’s to 1995, and suggests that no gray whales have returned to calve at these sites since the mid-1980's. This movement of gray whales from these areas may lead to an increase in gray whale populations elsewhere. This evidence suggests that there is the potential for similar abandonment or avoidance of important areas in the Arctic, as shipping levels increase.

3.3.4 Breaking sea ice

One of the most notable and well documented environmental change/challenge in the Arctic marine environment over the last decade or more, is the state of the sea ice (loss, summer break-up and sea-ice free winters). Marine wildlife (considering primarily birds and marine mammals here) in the Arctic area see the sea ice as either an opportunity (e.g., evolving ways in which to exploit its presence - on ice hunting/foraging, breeding, resting, migration etc.) or see it as a challenge/barrier, that needs to recede or be broken in order to move into an area (e.g., breathing/feeding holes, in water migration and feeding etc.; (Ainley, et al., 2003). Inevitably, there will be both winners and losers in the event of the Arctic becoming ice-free. Moore, 2016 outlines that the ‘new normal’ (retreating sea ice and increased primary and secondary production) conditions in the Pacific Arctic may provide endemic-Arctic bowhead whales with optimal foraging opportunities, confirmed via observations of seasonal ecology in core-whale-use areas and improved body whale condition.

In the Arctic, ringed seal, bearded seal, polar bear, bowhead whale, narwhal, ivory gull and Ross's gull are all classed as ice-obligate species (reliant on sea-ice for hunting, breeding, resting etc.). Harp seal, hooded seal, walrus, minke whale, beluga, thick-billed murre and black guillemot are ice-associated (evolved specific adaptation to allow them to exploit sea ice habitat). For gray whale, killer whale, northern fulmar, eider species, oldsquaw duck and dovekie, ice is largely a barrier ((Tynan, et al., 2010); (Moore & Huntington, 2008)).

Shipping may contribute to breaking sea ice via two routes. Firstly, and most significantly, increased atmospheric pollution/emissions/particulate matter from vessels, may lead to increased rates of global warming and accelerated sea ice loss (see Section 3.3.6 for more details). Secondly, vessels (ice breaking) travelling through areas of fragile/thin ice, may accelerate ice loss or not allow ice to completely freeze (when it would have done so, if vessels weren't present). Although it is estimated that ice breaking vessels only contribute a miniscule amount to summer sea ice loss (NSIDC, 2020); there is the potential that the resulting impacts may be harmful for marine wildlife (marine mammals, as summarized below). A 2017 WWF report (WWF, 2017) provides a review of various literature on the impacts of shipping through Arctic sea ice, and the highlights are summarized below.

- *Ice Entrapment:* although ice entrapment is a natural cause of death in marine mammals, it has been speculated that ice breaking by vessels has been responsible for a few ice entrapments events. The open water behind the vessel confuses marine mammals and lead them to become trapped then the water eventually refreezes. Ice breaking may also lead animals to delay their winter migration, putting them at risk of entrapment. These entrapments may become more frequent as shipping continues later into the year.

- *Habitat destruction and/or fragmentation:* ice is used as resting, breeding and nursery habitat by seals and walrus. Ringed seal pups are concealed in lairs until they are about 6 weeks old. These lairs are vulnerable to destruction by ice breaking activities as they are not highly visible (usually a small ice hole or adult on the ice), therefore they are not easily avoidable. Seal pups can also be flushed into the water by the vessel wakes, and their survival is species dependent (e.g., some pups can tolerate the water from about 4 days (larger hooded seal pups) while others may not be tolerant before 6 weeks). Separation of mother and pup, displacement from natal site and whelping site breakage may also occur. This causes stress to the mother, may impact lactation and ultimately have impacts on pup survival. Species with whelping site tenacity are more vulnerable to habitat destruction than those species that only use the ice to haul-out. Navigation back to the nursery sites for mothers following at sea feeding may also be impeded by ice breakage.

- *Open passages*: open areas of water left by ice breaking activities can lead to the increased presence of non-endemic species (e.g., killer whale) or introduction of new marine species (e.g., invasive/non-natives, see Section 3.3.5) to an area. This may be particularly pertinent when considering predators, primarily killer whales. These open corridors may give these predators greater access to wintering grounds (used by beluga, bowheads, narwhal and seals/walrus) and for more of the year (Breed, et al., 2017).

- *Noise:* less sea ice leads to more noise, as the noise can travel further in open water (see Section 3.3.2 for more details on noise impacts).

- Ship Strikes: less sea ice may lead to some animals (e.g., seals and walrus, particularly pups and nursing mothers) spending more time in water which will put them at increased risk from noise and ship strikes (see Section 3.3.1 for more details on ship strike impacts).

- Oil spills: an oil spill in an ice-covered area can be hard to detect and clean up. In sea-ice, oiling of breathing holes puts the animals that use then at particular risk, especially as they have no other alternative (see Section 3.3.7 for more details on oil spill impacts).

In addition, to the impacts outlined above, another impact to consider is the potential fragmentation to polar bear hunting grounds. Polar bears' main prey are ringed and bearded seals, primarily those which are on ice (rather than in the water). If the bears hunting grounds are destroyed through ice breakage, then their hunting range is reduced, leading to increased competition between bears, movement onto land (where food is scarce; and potential conflict with communities) and possible starvation (Laidre, et al., 2020). Polar bears also use the ice for seasonal movement, mating and in some areas maternal denning. Reductions in optimal ice habitat result in reductions in body condition, survival, reproduction, and abundance (Laidre, et al., 2020).

An opportunity also exists for other marine mammals that are not reliant on the sea ice (e.g., non-endemic cetaceans) to move into the ice-free areas, potentially increasing their range (e.g., subarctic species of baleen whales; (Moore, 2016)). Increased primary and secondary production (as a result of sea ice loss) opens new feeding opportunities for endemic and seasonally migrant cetaceans (Moore & Reeves, 2018). This however is not without its impacts – and may lead to intra-species competition for feeding/breeding grounds; a change to the overall ecosystem due to the potential alteration to the food web; exposure to more diverse human activities; and potential changes to subsistence hunting ((Reeves, et al., 2014); (Moore, 2016)).

Although not a specific impact of shipping, but an important impact to note here; less sea ice also means that there is less ice for food-web foundation organisms like krill, algae and plankton to live (sea ice algae contribute up to 50% of primary productivity in the central Arctic Ocean; (Gosselin, et al., 1997)), which may have a knock-on effect throughout the whole food chain – leading to less prey (e.g., fish) and less predators (e.g., seals) (NMLC, 2018).

This has a massive impact on the whole marine ecosystem balance in the Arctic and may lead to the loss of species and/or the introduction of non-natives; or decreasing seal population, for example, may lead to an increase in fish population (e.g., cod), which may ultimately lead to an increased fishing industry.

3.3.5 Physical impacts from loss of ship or cargo and Invasive Species

Physical impacts to the marine environment may be as a result of a vessel being lost to the seabed or grounding (physical presence, not spill of oil), and/or the loss to the seabed of a vessels cargo. In 2020, the World Shipping Council (WSC) reported an average of 1,382 containers were lost at sea each year, between 2008-2019. This represents a significantly small amount (less than one thousandth of 1%) of the approx. 226 million containers shipped each year (WSC, 2020). In some cases, lost cargo can be recovered, in others, the cargo is not recovered.

The resulting loss of cargo can have some unintended environmental consequences. These include:

- *Loss or damage to habitat*: cargo or vessel may be lost over areas of habitat/seabed that is of particular importance, either from a conservation perspective (e.g., sea pen communities) or habitats that have significant importance to the food web or support specific populations of species. Loss or damage of this habitat could have a negative impact, particularly where the habitat is important to a population of a species. For example, if a habitat supports a large prey fish population, that ultimately supports a particular marine mammal population; if the habitat is lost, and the fish leave the area, the marine mammal is also forced to abandon their “feeding” area too. The resulting loss may also impact on indigenous communities (if they hunt the “lost” population); or move the predation pressures elsewhere.
- *Creation of habitat*: hard substrate (e.g., cargo containers) may be added to areas of previously soft substrate (e.g., sand or mud) - therefore creating an unnatural substrate. Many marine flora (e.g., seaweeds) and fauna (e.g., mussels, corals) require a hard substrate on which to attach and grow. This potential impact can be both negative and/or positive. Over time, as the newly attached organisms multiply to create new habitats (e.g., a coral reef), this may ultimately support higher organisms such as fish (native or non-native) and potentially culminating in a positive impact on the overall food web and contribute organic matter to the sediment (potential to increase productivity), and on fishing communities, for example. Inversely, a potential negative impact might be introduction of invasive species (see below for more details).
- *Ingestion of cargo*: ingestion of marine litter/items lost at sea may be an issue for larger marine animals depending on the type of lost item

(considering larger items or foreign material/marine litter, >2.5cm, not including “micro” here). It is widely documented that marine litter has negative impacts on marine mammals, primarily due to ingestion and entanglement and it is reported to be ingested by many species of marine mammals, such as baleen whales, beaked whales, dolphins and porpoises, and seals (Panti, et al., 2019).

– *Creation of microplastics* (and other non-biodegradables or heavy metals): any non-biodegradables materials (particular focus on plastics; although some “biodegradable” plastics are also contributors to the microplastic problem) lost at sea, take a long time to degrade (100’s of years). Plastic degradation over time, creates microscopic particles (e.g., microplastics; a particularly important research topic at present; (Zantis, et al., 2021); (Moore, et al., 2020)). These particles are ingested by marine animals at all levels of the food web, causing a mechanical hazard if ingested (eaten, uptake via cells/tissue or exposure through gills) and toxicity. The long-term toxicity impacts of microplastics in-particular are currently not known (GESAMP, 2015). Although impacts could include contamination of meat, reduced fertility, impaired tissue/organ function and death, as seen with long term heavy metal toxicity studies (e.g., (Das, et al., 2003); (Rosa, et al., 2008)).

The overall risk of causing an impact to the environment as a result of lost cargo or vessel is relatively low when considering single events (in relation to the size of the Arctic ocean). However, when considered cumulatively, this impact could become more significant, especially as the Arctic shipping are restricted in area, areas become busier, and the potential for lost cargo increases.

Of particular interest when considering this, is the potential for the creation of “stepping-stone” habitats for invasive or non-native species (invasive species being defined here as a species that may cause harm or out compete native species; non-native species defined here as species that are not native to an area, but do not cause harm or are perhaps beneficial). That is, the creation of new hard substrate that could either be colonized by invasive or non-native species, and which create a corridor for its wider spread through the region. This has been reported for other marine structures such as marine renewable devices (Adams, et al., 2014), decommissioned oil and gas structures (Olenin & Minchin, 2019), wrecks and other marine infrastructure (ports, marinas etc.; (Mineur, et al., 2012)).

As the sea ice retreats and the Arctic ocean warms, these potential stepping-stones may become more relevant for the introduction of invasive and non-natives (climate migration) into the Arctic region. The specific impact of this in the Arctic is currently a knowledge gap and therefore recommendations on policy, management and mitigation of this impact is further required.

Invasive and non-native species may be introduced into the Arctic marine area via several routes, e.g., biofouling on ship hulls, ballast water and climate migration. The introduction of invasives as a result of biofouling and ballast water are well known and studied, with several international and national measures in place, to minimize this route of introduction (e.g., amendments to Ballast Water Management Convention entered into force on 13 October 2019); (Seebens, et al., 2013). Climate migration in the Arctic may also allow for the introduction of new species (see Section 3.1.4 for more detail).

3.3.6 Atmospheric Emissions

Shipping is known to contribute significantly to global warming/climate change and health impacts through emission of many pollutants (e.g., carbon dioxide, methane, nitrogen oxides, Sulphur oxides carbon monoxides and particulate matter including organic carbon and black carbon). Although shipping in the Arctic at present only contributes a relatively small proportion to global atmospheric pollution, that is likely to increase (Schröder, et al., 2017) and local/regional impacts in the Arctic may be more significant due to the unique and sensitive environment.

However, shipping is statistically the least environmentally damaging mode of transportation, when its productive value is considered (accounting for the movement of 90% of global trade, (IMO, 2020)). The International Convention for the Prevention of Pollution from Ships (MARPOL) 73/78 Annex VI Regulations for preventing air pollution from ships includes a global Sulphur limit of 4.5% for heavy fuel oil burned by ships and has established special areas (Emission Control Areas; ECAs) where certain Sulphur oxide (SOx) and nitrogen oxides (NOx) emission are further regulated (IMO, 2020). At present, there are no ECAs in the Arctic ocean (the closest being the Baltic Sea), however, that may change as shipping in the Arctic increases. A global shipping inventory for 2015 emissions is shown in Table 3-6.

(Corbett, et al., 2010) outline a baseline emissions inventory for shipping in the Arctic for 2004 by vessel type (Table 3-6). This is compared with the 2015 global emissions inventory for all ships (Global emissions were not available for 2004). Emissions data is also presented in the “Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025” report (ICCT, 2017).

Table 3-6. In-Arctic Shipping emissions estimates by vessel type for 2004 (metric ton per year).

Vessel Category	2004 Emissions Inventory (mt/y) Source: (Corbett, et al., 2010); (Arctic marine Shipping Assessment Database, 2009); (Johansson, et al., 2017).						
	CO2	BC	OC	SOx	NOx	PM	CO
Container ship	2400000	260	790	10000	58000	3900	5500
General cargo ship	2000000	220	670	34000	49000	3300	4600
Bulk ships	1200000	130	410	21000	30000	2000	2800
Passenger vessels	1100000	120	380	19000	27000	1900	2600
Tanker	900000	100	300	15000	22000	1500	2100
Government vessels	380000	40	130	6000	9000	630	880
Tug and barge	40000	4	12	600	863	59	82
Offshore service vessel	10000	1	4	183	263	18	25
2004 Transit Total	8030000	875	2696	105783	196126	13307	18587
Fishing	3200000	350	1080	10000	58000	1100	7500
In-Arctic Total	33630000	3675	11336	185783	660126	22107	78587
2015 Global Total (All ships)	831300000	-	-	9690000	20880000	1490000	1350000
% of 2015 global shipping emissions inventory	4	-	-	2	3	1	6

(Corbett, et al., 2010) reported that by 2050 (under their two future scenarios, Business as Usual and High Growth) container shipping will account for between 50-61% of all shipping in the Arctic. From the figures presented in Corbett *et al*. (2010), on the percentage of shipping and future scenario emissions projections for 2050, the emissions per vessel category have been further calculated and presented in Table 3-7.

Table 3-7. In-Arctic Shipping emissions estimates by vessel type for 2050 (metric ton per year) under "business-as-usual" and "high growth" future scenario

Future Emissions (mt/y) Source: extrapolated and calculated from figures presented in (Corbett, et al., 2010). Note: Tugs and offshore vessels not included as numbers were 0% as per (Corbett, et al., 2010).							
Vessel Category	CO_2	BC	OC	SO_x	NO_x	PM	CO
2050 "Business-as-Usual" Scenario							
Container ship	12000000	1350	1500	23000	214500	5000	28000
General cargo ship	2160000	243	270	4140	38610	900	5040
Bulk ships	2400000	270	300	4600	42900	1000	5600
Passenger vessels	1440000	162	180	2760	25740	600	3360
Tanker	2640000	297	330	5060	47190	1100	6160
Government vessels	480000	54	60	920	8580	200	1120
Fishing	2880000	324	360	5520	51480	1200	6720
Total	**24000000**	**2700**	**3000**	**46000**	**429000**	**10000**	**56000**
2050 "High Growth" Scenario Emissions							
Container ship	26230000	2867	3172	81130	458720	10980	60390
General cargo ship	3440000	376	416	10640	60160	1440	7920
Bulk ships	3440000	376	416	10640	60160	1440	7920
Passenger vessels	2150000	235	260	6650	37600	900	4950
Tanker	3870000	423	468	11970	67680	1620	8910
Government vessels	430000	47	52	1330	7520	180	990
Fishing	3440000	376	416	10640	60160	1440	7920
Total	**43000000**	**4700**	**5200**	**133000**	**752000**	**18000**	**99000**

Heavy fuel oil (HFO) is the most used marine fuel in the Arctic (60% of fuel consumed in the geographic Arctic (at or above 58.95oN as defined by (ICCT, 2017)), the combustion of which is highly polluting, resulting in high levels of Sulphur dioxide (SO2), heavy metals, volatile organic compounds and black carbon particles (Zhang, et al., 2019). Although black carbon is a relatively small proportion of emissions (Table 3-7), it has unique properties that can significantly influence snow and ice albedo (reflectivity of sunlight) and further accelerate Arctic sea ice melt (Zhang, et al., 2019). If black carbon is deposited on ice or snow, sunlight is absorbed by the darker material (rather than being reflected into the atmosphere; (Stephenson, et al., 2018)). The absorption of solar radiation leads to warming, and results in ice/snow melt - the more solar radiation that is absorbed, the faster the melt. Per unit of mass, black carbon may have a climate warming impact that is 460-1500 times stronger than CO2 (Climate and Clean Air Coalition, 2015).

As of the 1st of January 2020, new IMO regulations state that the allowable amount of Sulphur content in fuel is reduced to 0.5% m/m, however there are knowledge gaps around the behaviour of these alternative low-Sulphur fuels in the cold Arctic waters (PAME, 2020). However, in the limited time that these regulations have been implemented, a study has found that use of these very low Sulphur fuels, may increase black carbon emissions by 10 to 85% (IMO, 2019). More research is therefore needed to properly examine and quantify these impacts.

Reporting of global shipping emissions is limited; with shipping being the least regulated transportation modes in terms of emissions, which consequently makes access to quality spatial and temporal data difficult (ICCT, 2017). Better data is needed to be collected in order to make more informed decisions regarding fuel use and to implement effect mitigation and management strategies for shipping in the Arctic. There also needs to be improved global co-operation regarding shipping emissions, as more non-Arctic countries are predicted to participate in Arctic shipping (Zhang, et al., 2019).

Our understanding of how atmospheric emissions directly impact marine wildlife is lacking, with no studies to suggest bioaccumulation of contaminants from atmospheric emissions in marine mammals. However, one study demonstrates that killer whale population (near whale watching vessels) may be inhaling concentrations of air pollutants that have the potential to cause serious adverse health effects (Lachmuth, et al., 2011).

3.3.7 Discharge of Pollutants to Sea

Pollutants from shipping discharged to sea can include operational discharges (e.g., ballast, cleaning and sanitary waters, litter), accidental spills and discharges (e.g., oil or chemical spills) and other hazardous substances (heavy metal leaching from anodes, leaching of anti-fouling paints); and pollutants released to sea come in many forms including, for example, Persistent Organic Pollutants (POPs), Polychlorinated Biphenyls (PCBs), Polyaromatic Hydrocarbons (PAHs) and heavy metals.

The presence of POP contaminants (chronic pollution) in the tissues of marine mammals and their potential impacts on populations has been documented over the years (see references in (Simmonds, 2017)), with particular interest in the Arctic on the beluga whales of the St Lawrence River. Specific impacts may include issues with reproductive health (infertility, abortion, fetal abnormalities, calf mortality) and even cancers (as in the case of the belugas; (Simmonds, 2017)). The persistence and bioaccumulation/biomagnification of pollutants in the food chain is well established, and marine mammals feeding in more polluted waters are more vulnerable, with toothed whales, killer whales, sharks, bears (and humans) at the top of the food chain being most at risk (Simmonds, 2017).

It is also possible for pollutants to enter the marine environment via the ship-air-sea-interface as described by (Endres, et al., 2018). Exhaust gas cleaning systems (aka "Srubbers"). In short, wet scrubbers use seawater as a cleaning media for SO_x producing sulfurous acid, sulfuric acid, and calcium sulfate. The SO_2 dissolves and is removed from the exhaust gas. The resulting wash water is acidic (pH 3), hot and contains several contaminants (e.g., PAHs, heavy metals and nitrate). The need to remove SO_x from shipping emissions in this manner is a cost-effective response to the low-Sulphur fuel requirements (see Section 3.3.6).

One of the most significant threats to Arctic marine wildlife is from an oil spills (generalized to include fuel and chemical spills here too), with initial impacts being classed as acute and long-term exposure/bioaccumulation classed as chronic. Although major oil spills are not necessarily a regular occurrence in the Arctic (65 shipping related spills in the Arctic between 1970 and 2011; <1 per year; (PAME, 2016); the most famous of which is likely the *Exxon Valdez* oil spill in Alaska, 1989, which had long-term impacts on the environment ((Peterson, et al., 2003); (Matkin, et al., 2008)), this may increase as anthropogenic activities like shipping and oil exploration increase; their impact can be catastrophic – with the unique environmental conditions in the Arctic impeding response and clean-up efforts and making the oil-environment interactions unpredictable or significantly damaging. Impacts may also extend to indigenous communities' food security and livelihoods (PAME, 2019).

Depending on the type of substance spilled, the environmental conditions in the Arctic can lead to a slow rate of degradation due to the low temperatures, limited evaporation (typically less than 10%) and limited dispersion in the water column (PAME, 2019). Increased turbidity and wave action can also lead to the creation of oil-in-water emulsions, which are not only harder to remediate, but which also increase the "volume" of the oil spilled (Fingas & Fieldhouse, 2006). In addition, oil and other substances spilled in ice covered areas can lead to trapped oil under the ice surface and the potential for wider spatial distribution if the ice breaks off and drifts, complicating spill tracking and clean-up operations (Aune, et al., 2018). Small spills may rely on natural attenuation to remove the spill from the environment whereas larger spills require human intervention via a variety of clean-up methods, the use of which depends on location, type and size/volume of spill and proximity to the shoreline (Aune, et al., 2018). The behaviour of oil spilled under ice will vary, depending on the local ice conditions, in particular under-ice roughness (Fingas & Hollebone, 2013).

However, knowledge on the true extent of the impacts of oil spills in Arctic waters is limited, due the lack of field and experimental data and lack of data on species' vulnerability/sensitivity to and probability of encountering a spill. In addition, extrapolating general oil spill impacts from a single Arctic spill is problematic (Nevalainen, et al., 2018) due to the vast and varying nature of the

Arctic marine environment and the sea ice. The risk of oil spills to marine wildlife differs between species, spatial locations and seasons. In addition, although risks of heavy fuel oil spills are considered more impactful, lighter fuel oils still pose significant risks as these oils can pollute larger areas compared with heavy fuels (Helle, et al., 2020).

Seabirds are particularly vulnerable to oil spills as spills on the water's surface may cause direct toxicity through ingestion and hypothermia as a result of the birds' inability to waterproof their feathers, which may ultimately lead to their death. Seabirds are also indirectly impacted by oil spills, through displacement from foraging habitats and reduced food availability where prey species are affected (O'Hanlon, et al., 2020).

Marine mammals are impacted by oil spills in varying ways. Polar bears are at risks from oil spills as they are reliant on their fur to protect them from the extreme Arctic temperatures. Oil significantly reduces the insulating value of the fur, and if not removed it is unlikely that the bear would survive. Polar bears are also likely to ingest oil via grooming or foraging oil contaminated seals (Helm, et al., 2015). Seals spend time at sea foraging and may come into contact surface oil at these times, although data of impacts is limited (or sample sizes very small). As seals and walrus use blubber for insultation, it is thought that external oiling is unlikely to have a significant impact, although contact via the eyes and ears, for example, may cause significant damage. As with seals, data and evidence of impacts for cetaceans is again limited, but their blubber will protect them for significant external damage. The most significant impact for cetaceans and seals, will be the at the surface when they need to breathe, and they may inhale oil and toxic vapours. In addition, marine mammals with high site fidelity will be most vulnerable if a spill occurs within their habitats, or those Arctic marine mammals that use sea ice breathing holes (Helm, et al., 2015).

Impacts of ballast water are largely linked with the potential for the introduction of invasive or non-native species (see Section 3.3.5), however, ballast water can still contain quantities of fuel and other substances (although this should be well managed), that may cause significant impacts in areas of high activity and where ballast water release sites overlap with areas used by marine mammals and seabirds.

The level of impact of an oil spill in the Arctic will be influenced by both spatial and temporal variables. Many marine animals (fish, seabirds and mammals) are present in the water throughout the year, however, during migrations and open water seasons, the number of individuals and variety of species will increase. Therefore, if an oil spill was to occur during these times, there will be more animals effected, and in the case of migratory seasons, whole populations. In addition, seals, during the pupping season will be onshore, where an oil spill will have a huge impact if it washes ashore. Seal pups are vulnerable at this stage as they rely on fur to keep warm and feeding from their mother, who if oiled, will lead to oil ingestion. In addition, oil spills that occur during the Spring phytoplankton bloom will also have an impact on foraging animals, either through ingestion of the oil, or starvation.

Large parts of the arctic region are not adequately prepared for large accidents and spills, and Arctic oil spill response and preparedness for worst-case scenarios remains a weakness (Atkisson, et al., 2018).However, emergency response in the Arctic has improved slightly in the last decade through the addition of available vessels and helicopters, but response times may be too long and the capacity limited if major incidents occur (Marchenko, et al., 2018). The remoteness and challenging environmental conditions in the Arctic make response to certain areas difficult often hindered by harsh weather conditions and seasonal periods of darkness (PAME, 2019), however, as shipping increases and waters become ice free, accessibility and speed of response may be improved; and management and mitigation (e.g., oil spill response plans) for oil spills will hopefully improve via the responsibility of the shipping industry.

3.4 Summary and Next Steps

The Arctic marine ecosystem is sensitive to environmental change and particularly vulnerable to anthropogenic impacts as a results of climate change and rapid development. Levels of human activity are increasing in the Arctic marine area, which will ultimately result in more frequent and severe threats to the Arctic's marine wildlife. The level of impact from shipping will vary, based on the receptor or receiving environment, and the type of impact (direct, indirect or cumulative) and its severity/exposure.

Some of the impacts on marine wildlife, associated with shipping (not necessarily just in the Arctic), are relatively well understood, with some being considered temporary or short-term e.g., behavioural disturbance. However, knowledge on the long-term or permanent (both chronic e.g., ship strikes and acute e.g., noise exposure) impacts of shipping are lacking (e.g., the impact at population and/or individual level, there is limited knowledge about the many populations that make up different marine mammal stocks). This is particularly apparent in the Arctic, as extensive shipping has been limited through the region until more recently, and more research is therefore needed to truly understand these impacts and threats.

Looking to the future, there is the need to consider what effective management measures could be put in place to minimize the impact of shipping on the Arctic wildlife. Whilst ensuring that developments and increasing anthropogenic activities are managed sustainably and with greater consideration of the environment.

The next steps are to consider what mitigation, management and conservation measures are currently utilized within the Arctic in relation to marine wildlife, shipping and associated impacts (e.g., Marine Protected Areas, exclusion zones, speed restriction zones, other management tools etc.); gain an understanding for the appropriateness and applicability of such measures in an Arctic setting (considering such issues as transboundary management and physical limitations due to sea ice) and their potential adaptability; explore different spatial management scenarios (e.g., identifying area of ecological significance, assessing areas for shipping/wildlife intensity etc.); what recommendations could be made to enhance these measures (e.g., industry guidelines); and outline opportunities for future management options (e.g., stakeholder engagement, mechanisms for introducing policy/management frameworks, Marine Spatial Planning).

Assessing the impacts of shipping on the marine environment is a global issue, and as such, several management and mitigation measures have been explored and implemented in the seas around the world. Those developing and working in the Arctic have an opportunity to use lessons learned from around the world to proactively manage the environment and ensure that future Arctic shipping is conducted in a manner that has minimal impact on marine wildlife.

4 Part 2: Geo-economic & societal impacts of Arctic shipping (Laval Univ., Shandong Univ.)

4.1 Contrasting Trends in Arctic Shipping (prepared by Frédéric Lasserre)

Ever since the impact of climate change on Arctic sea ice began to be discussed in international forums at the turn of the century, several comments were published to the effect that diminishing sea ice would quickly translate into the development of massive transit routes across the Northwest Passage (NWP), the Northern Sea Route (NSR) and the Arctic Bridge linking Churchill on the shores of Hudson Bay and Murmansk. Twenty years later, Arctic shipping did indeed expand significantly, but the actual picture is significantly different from what analysts projected. Destinational traffic appears to be the driver of Arctic shipping expansion, while transit traffic remains marginal. What are the main features of Arctic shipping presently, and how did the industry adapt, depending on the area? Results show contrasting evolutions along the NSR, in the Canadian Arctic, and in Greenlandic waters.

This chapter is based on the analysis of figures from three different sources, which implies methodological issues since the data does not display the same elements ((Lasserre & Alexeeva, 2015); (Lasserre, 2019)). In the Russian Arctic, data about vessel movements and characteristics were gathered from the Northern Sea Route Administration[1] and from the Center for High North Logistics.[2] For the Canadian Arctic, the Ministry of Transportation agency for the Northern Canada Vessel Traffic Services Zone Regulations provided the author with annual detailed ship movements. For Greenlandic waters, data was provided by the Danish Joint Arctic Command based in Nuuk.[3]

4.1.1 A definite increase in Arctic shipping

Figures below indicate that vessel movements are definitely increasing substantially in the Arctic. From 2009 to 2019, traffic was multiplied by 1.92 in the Canadian Arctic; by 1.97 in Greenlandic waters; and by 1.58 between 2016 and 2019 in waters of the Northern Sea Route.[4]

[1] NSRA, nsra.ru
[2] CHNL, www.arctic-lio.com
[3] Joint Rescue Coordination Center/JAC, Nuuk, https://www2.forsvaret.dk/eng/Organisation/ArcticCommand/Pages/ArcticCommand.aspx
[4] The Northern Sea Route comprises Russian Arctic waters between the Kara Gate and the Bering Strait. Thus, traffic in the Barents Sea is not included in NSR figures, nor traffic in Russia’s Arctic Pacific waters.

Table 4-1. Vessel movements in the Canadian Arctic, number of voyages, NORDREG zone.

Vessel movements in the Canadian Arctic, number of voyages, NORDREG zone. Source: figures compiled by the author from data submitted by NORDREG, Iqaluit.									
	2009	2011	2013	2014	2015	2016	2017	2018	2019
Vessels cumulated dwt, million metric tons	1.02	1.28	1.39	1.43	1.8	2.79	3.54	4.38	5.16
Voyages	225	319	348	302	315	347	416	408	431
Of which:									
Fishing boats	65	136	137	119	129	131	138	139	137
Cargo or barges	109	126	127	108	120	147	188	197	223
Of which:									
General cargo	23	38	35	32	34	36	50	48	59
Tanker	23	30	28	25	27	23	24	29	28
Dry bulk	27	23	27	33	36	53	72	89	106
Tugs and barges	36	33	36	18	23	35	42	31	30
Pleasure crafts	12	15	32	30	23	22	32	17	19
Cruise/passenger	11	11	17	11	18	20	19	21	24
Government vessels (icebreakers, navy)	21	20	17	23	16	20	22	18	20
Research vessels	7	11	20	10	9	6	13	13	8
Others					3	3	6	3	

Table 4-2. Voyages to and from Greenlandic waters.

Voyages to and from Greenlandic waters. Source: Joint Arctic Command, Nuuk									
	2009	2011	2013	2014	2015	2016	2017	2018	2019
Container, general cargo	159	184	141	155	135	150	151	113	146
Passenger, cruise	96	113	130	122	105	222	249	372	241
Bulk	12	0	0	2	1	88	132	155	188
Tankers	57	60	24	29	22	20	31	36	40
Fishing vessels	54	145	124	120	123	144	142	168	149
Research vessels	62	44	20	31	24	32	33	20	10
Other ships	59	73	48	88	122	131	143	209	228
Offshore	0	61	6	0	0	0	0	0	4
Government vessels	12	17	12	13	13	13	19	5	3
Total	511	697	507	559	564	800	900	1078	1009

Table 4-3. Vessel movements in NSR waters.

Vessel movements in NSR waters, number of voyages. Source: CHNL				
	2016	2017	2018	2019
Volume transported, million metric tons	7.265	10.713	20.18	31.53
Voyages in NSR waters	1 705	1 908	2 022	2 694
Of which:				
Tanker	477	653	686	799
LNG tanker		13	225	507
General Cargo	519	515	422	546
Container	169	156	150	171
Icebreaker	58	101	232	231
Supply		57	104	169
Research	91	87	85	93

Within the general and substantial increase in vessel traffic in these three areas, contrasting trends can be observed from these figures.

In the Canadian Arctic, growth in traffic was mainly driven by fishing vessels (+106.2 percent between 2009 and 2019) and cargo ships (+122 percent), of which dry bulk experienced the fastest expansion (+288.9 percent), driven by mining activities, and general cargo (+156.5 percent), driven by community supply.

Bulk traffic has benefited from the exploitation of Arctic or subarctic mines such as Voisey's Bay (Labrador), Raglan (Quebec), and Mary River (Baffin Island, Nunavut); this traffic has largely made up for the drying up of traffic to and from Churchill since the port closed down in 2016 before reopening up in 2019. For instance, Baffinland Iron Mines shipped 920,000 tons of ore from its mine in Mary River through its port of Milne Inlet the first year of activity in 2015, then 4.1 million tons in 2017 (Maritime Magazine, 2018) and 5.1 million tons in 2018 (Debicki, 2019). The company eventually intends to reach an annual volume of 12 million tons.

In Greenland, cruise traffic (+151 percent), fishing (+176 percent) and bulk traffic (+1,467 percent) largely drove traffic expansion, whereas container and general cargo stagnated. Research vessel traffic decreased 83.9 percent and offshore vessel traffic decreased 93.4 percent from 2011 to 2019, anticipating a decline in interest for offshore oil and gas development.

In Russia, tanker traffic increased 67.5 percent between 2016 and 2019. LNG tanker went from nil to 507 voyages, and icebreaker voyages increased 238 percent. Tanker traffic experienced a sustained growth with the oil and gas developments in the Kara Sea (Prirazlomoye and Varandey oil terminals) (Agarcov, et al., 2020) and on the Yamal peninsula and Ob Bay, with Sabetta and Novy Port main terminals and the impending opening up of Arctic LNG 2 terminal ((Staalesen, 2018b); (Katysheva, 2020)). With the programmed opening of coal and lead and zinc mines, bulk traffic should experience a fast growth in the Russian Arctic as well,[5] whereas fishing, concentrated in the Barents and Bering Seas, does not appear in these statistics.

It is apparent that the main driver for the expansion of shipping in the three areas is natural resources exploitation, including mining, oil and gas, and fishing. Community resupply in Canadian waters and cruise ship traffic in Greenland also experienced sustained growth.

However, contrary to popular belief and widespread expectations, transit traffic remains very limited along Arctic passages in Canada and Russia.

4.1.2 Transit traffic remains weak

Despite the ongoing melting of sea ice, transit traffic remains rather limited along the Northwest Passage and the Northern Sea Route, here again with differentiated pictures.[6]

[5] Nickel ore is shipped in containers from the port of Dudinka, thus the apparently high container traffic that in fact largely reflects shipments of mineral and metallurgical semi-transformed products, besides limited reefer shipments of fish from Kamchatka to Arkhangelsk and St-Petersburg.

[6] A methodologic note is necessary here. The term transit is interpreted differently by the various administrations that collect and publish figures describing transit along Arctic passages. In Canada, figures are collected by the Canadian Coast Guard section responsible for the enforcement of the Northern Canada Vessel Traffic Services Zone Regulations (NORDREG). The definition used by NORDREG for transit is a movement between Baffin Bay to the Beaufort Sea. Robert Headland and his team at the Scott Polar Research Institute use a definition whereby transits are counted between the Labrador Sea and Bering Strait. This difference does impact figures since a vessel servicing the community of Inuvik from Montreal will be counted as a transit by NORDREG but not by the Scott Polar Research Institute. This is why the SPRI counts 32 transits in 2017 (33 for NORDREG), and 3 in 2018 (5 for NORDREG) for instance. In Russia, figures are collected by the Northern Sea Route Administration, then formatted and published by the Center for High North Logistics (CHNL), a private association and therefore not an official Russian administration. CHNL bases its figures on the NSRA definition of transit, which is a voyage between the Bering Strait and the Kara Gate. Thus, a ship from Kamchatka to Murmansk will be counted a transit by CHNL despite the fact the ship is still in Russian Arctic waters. Other voyages, like those carried in 2009 by heavy lift vessels *Beluga Foresight* and *Beluga Fraternity* in 2009, are counted as transits by CHNL from South Korea despite the fact they unloaded their cargo at Yamburg before proceeding to Germany, thus making their voyages a destinational voyage. On these methodological issues, see (Lasserre & Alexeeva, 2015), (Lasserre, et al., 2019). For this paper, it was decided to work with official NORDREG figures and semi-official CHNL figures.

Table 4-4. Transit traffic along the Northwest Passage, 2006-2019.

Transit traffic along the Northwest Passage, 2006-2019. Source: figures compiled by the author from data submitted by NORDREG, Iqaluit											
Vessel type	2006	2008	2010	2011	2012	2013	2014	2016	2017	2018	2019
Icebreaker	2	1	2	2	2	2	4	3	2	2	1
Cruise	2	2	4	2	2	4	2	3	3	0	5
Pleasure boat	0	7	12	13	22	14	10	15	22	2	13
Tug	1	0	1	0	2	0	0	0	3	1	1
Cargo ship	0	1	0	1	1	1	1	1	2	0	5
Research	1	1	0	1	1	1	0	0	1	0	0
Other	0	0	0	0	0	0	0	1	4	0	0
Total	6	12	19	18	30	22	17	23	33	5	25

Table 4-5. Transit traffic along the NSR, 2006-2019.

Transit traffic along the NSR, 2006-2019. Source: CHNL data compiled by author.												
Vessel type	2006	2008	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Icebreaker	0	0	0	2	3	2	2	1	2	0	1	0
Government ship	0	0	0	1	0	1	1	3	1	0	0	0
Cruise	0	0	1	1	0	1	3	1	1	0	0	0
Tug, supply vessel	0	1	4	4	5	1	1	4	4	1	2	0
Commercial	0	2	6	31	38	64	24	15	11	24	23	32
Research	0		2	2	0	2	0	0	0	0	0	2
Fishing	0	0	0	0	0	0	0	0	0	2	1	3
Total official transit	0	3	13	41	46	71	31	18	19	27	27	37
Volume transported, million metric tons	0	na	0.11	0.82	1.26	1.18	0.27	0.04	0.21	0.19	0.49	0.70
Total volume handled in the NSR, million metric tons	na	2.2	2.1	3.2	3.7	3.9	4.0	5.4	7.3	10.7	20.2	31.5

In both cases, there is a definite trend towards an expansion but with differentiated details. Transit numbers across the Northwest Passage were higher at the beginning of the period, experienced growth until 2012, witnessed a moderate decline, expanded again until 2017, then collapsed in 2018, only to recover in 2019. Figures show that both in terms of voyages and tonnage, transit represents a very small share of total traffic along the NSR, despite the recent increase in tonnage in 2018 and 2019. Transit traffic was initially very moderate, then expanded up to a high of 71 voyages in 2012, then collapsed to 18 in 2014 to recovery gradually to 37 in 2019. This decline, and later stagnation at low levels in transit traffic along the Northern Sea Route, is clearly out of step with media forecasts announcing the advent of heavy traffic along Arctic routes. This is due to several factors ((Balmasov, 2016); (Doyon, et al., 2017)):

- The decline in oil and fuel prices, which makes the search for possible reductions in transit costs less attractive for shipping companies.
- The decline in commodity prices, which makes Arctic resources less attractive, both for exploitation and for initial investment for transport with specialized vessels. The impact of this element may decrease as new oil, gas, and mining sites open along Siberia’s Arctic shore.
- The continuing global decline in both bulk and container freight rates, which discourages shipping companies facing overcapacity from investing in new ice-bound vessels.
- The priority deployment of Russian icebreakers to infrastructure projects, notably the terminals linked to the oil and gas project on the Yamal Peninsula or Ob delta. The lower availability of icebreakers has dissuaded some carriers from hiring their vessels for lack of guaranteed escort.
- A confusing tariff schedule for the services of the Northern Sea Route, sometimes considered opaque by maritime carriers.

The composition of this traffic also differs by region. Commercial cargo ships represent the largest share of transit traffic along the NSR, whereas transit along the NWP is largely composed of pleasure boats, with commercial vessels comprising between zero and two units (except for five in 2019). Among the elements that explain this very weak interest for transit traffic along the NWP, let us mention a higher ice concentration in summer (NSIDC, 2019), the absence of promotion of the NWP as opposed to a very proactive stance in Russia, and a higher level of equipment and infrastructure along the NSR, including ports that can harbor ships in cause of damage. Icebreaker support also varies greatly, with Canada having only nine Arctic-capable icebreakers as opposed to Russia’s five nuclear and 37 diesel icebreakers.

This comparison between total and transit traffic underlines the fact that destinational traffic (ships going to the Arctic, stopping there to perform an economic task and then sailing back) remains the driving force in Arctic shipping. This destinational traffic is fuelled by the servicing of local communities, the exploration for natural resources and their exploitation, including mining, oil and gas, and fishing.

Another feature of Arctic traffic is the recurrent seasonality. Most traffic takes place between June and October, inclusive.

Table 4-6. Share of voyages carried out between June and October included, percent of total.

Share of voyages carried out between June and October included, percent of total. Source: compiled by author from NORDREG, CHNL and JAC data.							
	2013	2014	2015	2016	2017	2018	2019
NSR	na	na	na	69.8	68.7	64.1	61.2
Canadian Arctic	86.5	88.7	86.7	87.1	88.5	89.2	88.2
Greenland	77.7	77.5	80.7	84.5	71.5	86.6	87.5

The seasonality is less pronounced and is declining along the NSR, in large part because several oil and gas projects included investments in high ice-class vessels for year-round shipments, especially from Varandey oil terminal as well as Sabetta port. In 2019, 1,245 out of 2,694 of transits (46.2 percent) were carried out by ships with an ice class Arc 6 or greater (Polar Class 5), of which 1,032 were carried out by commercial ships and 214 by icebreakers (CHNL, 2020); among these voyages, 866 were carried out by tankers or LNG tankers. This clearly underlines the business model resting on year-round shipping developed by the oil and gas industry with regard to Arctic hydrocarbon development. However, for now other segments of the shipping industry have not really developed year-round activity in NSR waters and thus maintain a seasonal approach, as is very obviously the case in Greenland and Canadian Arctic waters.

4.1.3 Towards a new business model

The literature abounds with cost analyses that pledge Arctic commercial transit shipping is profitable, although several other articles state the contrary (Theocharis, et al., 2018); (Theocharis, 2019); (Lasserre, 2019). There is an increasing discrepancy between academic research, with an emphasis placed on transit shipping, and the reality where destinational shipping is on the rise but transit shipping remains very weak. This has led some authors to suggest that shipping companies analyse the market more broadly, and not merely on a single-trip cost basis. This should come as no surprise since it is a basic principle in business management that strategic analysis does not rest exclusively on a cost-based approach ((Porter, 1991); (Lorange, 2009); (Stopford, 2009)). Authors ((Buixadé Farré, et al., 2014); (Lee & Kim, 2015); (Lasserre, 2019); (Lasserre & Pelletier, 2011), (Lasserre, et al., 2016);

(Sarrabezoles, et al., 2016)) have underlined that shipping companies also take into account strategic business elements such as:

- The high financial risk for bulk carriers, working on a tramp basis, stemming from the difficulty to secure long-term contracts to make up for higher ice-class construction and exploitation costs.
- The high commercial risk for liner shipping (container, general cargo) to develop seasonal and ice-prone routes given their major just-in-time business constraint.
- The non-tariff barriers to entry imposed by insurance companies regarding ship equipment, ice class, crew experience, now enshrined in the Polar Code.

A way to circumvent these business constraints would be to build transhipment hubs at both entry points of Arctic passages, where cargo could be loaded onto regular ships, while enabling shipping companies exploiting Arctic routes to consider investing in ice-class vessels with greater capabilities, so as to develop year-long service. Indeed, a technical constraint for Arctic shipping is that high ice-class vessels are more expensive to build and operate, but are also often less seaworthy in open, rough waters (Baudu, 2019), thus making their exploitation in non-Arctic waters less attractive. The implementation of this transhipment system would, according to its promoters, eliminate these technical and business impediments to the growth of Arctic commercial shipping.

Several ports have thus been considered for the development of transhipment hubs, with various advantages and capacities. For the NSR, Murmansk is already acting as such a hub on the western entrance; the Norwegian port of Kirkenes is dreaming about such a possibility, especially if the Kirkenes-Helsinki railway is eventually built (Lasserre & Têtu, 2020). On the eastern entrance, Zarubino in Primorie Province or the more northern port of Petropavlovsk are options. These two NSR possibilities are the most serious since they are actively supported by the shipping companies involved in oil and gas development in the Yamal area and by the Russian government with its Northern Sea Transport Corridor scheme (Staalesen, 2020).

For the Northwest Passage, several areas are considering project proposals to build transhipment ports that might provide an as-yet undeveloped shuttle service across Arctic passages, including the Transpolar Route: Nome in Alaska is promoting its hub vision; Halifax, Nova Scotia; St-Pierre on the eponymous French island; and Portland, Maine have all been considered. Whether these schemes will go to fruition or not remains to be seen.

4.2 China perspective

Compared with the Suez route, the navigation shortcuts via the Arctic waters can cut traditional transit times between East Asia and Europe by about 10 days and reduce navigational distance by 3000-4000 miles. Moreover, the economic benefits will become greater for the mega vessels that are unable to pass through the Suez Canals and must navigate around the Cape of Good Hope. At the same time, to prevent the mean global temperatures from rising more than 2° C, global transportation must reduce its carbon emission footprints by 2.6% per year during 2020-2050. Compared with traditional southern routes, maritime transportation via Arctic Northeast passage could reduce carbon emissions by 49%-78**%.**

Currently, due to unpredictability, seasonality and nonregularity of navigation, Arctic sea routes are possibly more economical for bulk cargo vessels than for container vessels, since the later depend more on precise schedules for loading, shipping, and unloading to keep costs down. When the transit time in the Arctic is not a key impact factor affecting benefits, because the fuel consumption and related carbon emissions of vessels at low speed is much less than that at high speed, the operators may select lower than the standard speeds. This approach to achieve reduction in fuel consumption may be higher than the decreased costs due to the reduction in navigational distances. So, for shipping low-value raw materials, it is prudent to use reduced speed instead of shorter transit times, which will also help to mitigate global warming**.**

Unlike via the Suez or via the Panama Canal, there are no similar canal fees for Arctic navigation routes. The main costs for Arctic maritime transportation consist of fuel costs, icebreaking costs, operating costs, and vessel depreciation costs. Fuel costs depend mainly on sea ice conditions and navigational distance/speed. The trans-Arctic transportation may avoid passing through politically unstable and piracy affected regions and reduce transit times significantly, but lack of intermediate markets along Arctic passages may restrict seriously shipping via these routes. At the same time, it is important to note that the exploitation of trans-Arctic transportation may be seriously conflicted with some ambitious climate change mitigation strategies which will reverse the decreasing trend of Arctic sea ice cover, and then prevent future exploitation of trans-Arctic maritime transportation.

With the recent increases in international trade of goods between Europe and China, the related transportation section consumes huge amounts of fuels and contributes substantial quantities of global carbon dioxide emissions. Arctic maritime transportation not only can reduce transit times and costs but can also help to achieve the objective of reducing carbon emissions from shipping transportation in China. Although China is not a littoral Arctic country, as the largest international trader, trans-Arctic maritime transportation has considerable impacts on China and will play an increasing role for green and sustainable development of China. Recently, China is incorporating trans-Arctic maritime transportation into “the Belt and Road Initiative” which will boost trade by massive investments in roads, ports and other infrastructure between

Asia and Europe. In July 2017, the Chinese government and the Russian government announced plans to cooperate on Arctic passages and to build the "Ice Silk Route". Both governments would cooperate to improve infrastructure construction and to explore oil/gas resources and eco-tourism resources along Arctic coastline, which could partially solve the dilemma of the lack of intermediate markets along Arctic Northeast Passage.

5 Part 3: Technical and economic challenges of Arctic Shipping

5.1 General

The key challenge, when addressing in practice all technical and operational challenges of Arctic shipping, is associated with cost. This is due to multiple reasons which are elaborated on in this section. For example, the fuel cost during ice navigation is higher than in open water navigation because ice causes additional resistance to the ship's hull, requiring the use of higher engine power. The impact of ice on the ship's hull and propulsion system (through the propeller) causes loads that exceed those when operating in a seaway, the ships thus require extra strengthening leading to the increased weight and size (and/or reduced cargo capacity) and increasing the newbuilding cost. Variability of ice conditions during the voyage, risks of uncontrolled interaction events with ice as well as possible environmentally sensitive areas on the route (requiring rerouting) tend to increase cost as well. Together, this result in higher building and operational costs of an ice going vessel compared to an equivalent vessel designed for operation in ice free water.

Technical, operational, and economic challenges regarding Arctic shipping are introduced in this chapter. All of these are very case-specific, strongly interconnected and controlled by multiple regulations and standards. The costs associated with Arctic shipping are heavily affected by ship itself and actual ice conditions which in turn varies depending on the season, severity of the winter and location. Therefore, the challenges presented in following sections, should be considered as representative, based on existing operational practices.

5.2 Technical challenges and effects on costs

5.2.1 Identification and understanding of ice conditions

Sea ice is the greatest obstacle affecting Arctic maritime transportation. Ice conditions offshore are dynamic, varying and reforming continuously. The main factors affecting navigation include the ice extent, ice concentration, ice thickness, ice type (e.g. level ice, ridged ice, brash ice, first-year ice, multi-year ice, etc.), partial concentration of each ice type and floe size. Identification and prediction of such conditions along the planned ship route in advance is difficult. On the other hand, in most of the cases waypoint navigation (directly between point A and point B) is not efficient. Difficult ice conditions (e.g. compressive ice areas, compacted and ridged ice, etc.) should be avoided because they may significantly slow down the navigation speed and sometimes the vessel may even get totally jammed in ice (see Figure 5-2). Correspondingly, easier ice conditions, even it means increased navigation distance, are preferred. This is termed tactical ice navigation and it is illustrated in Figure 5-1.

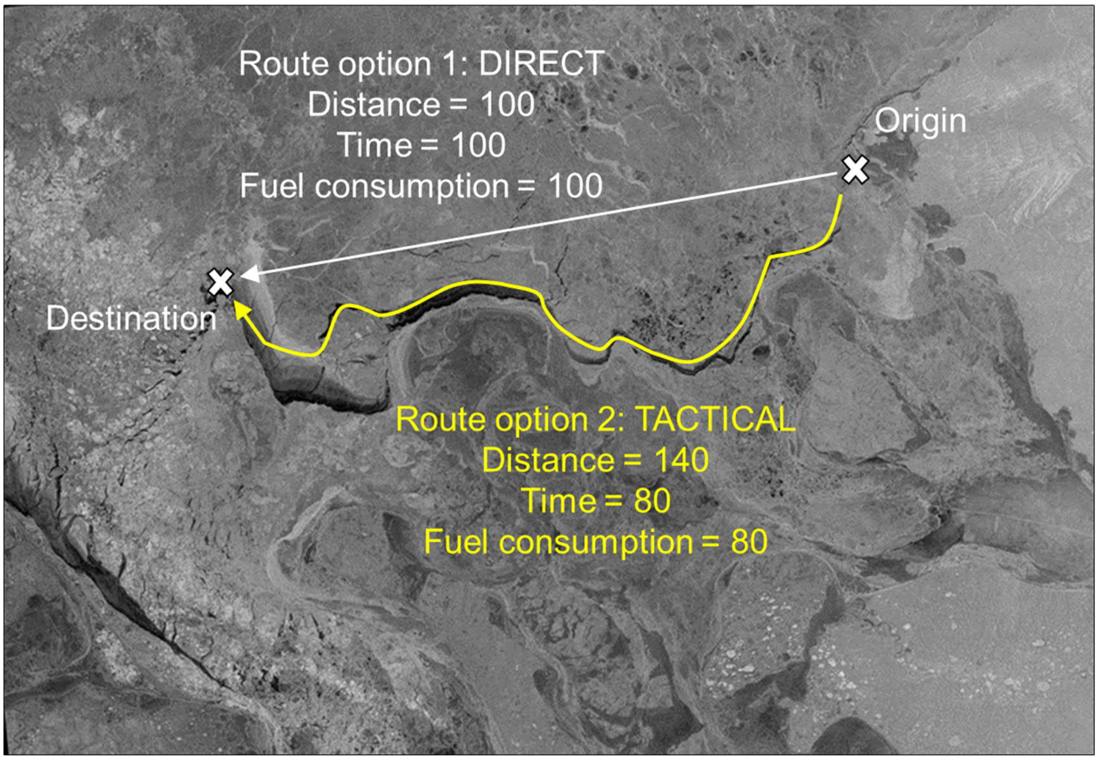

Figure 5-1. Illustration of importance of appropriate route selection in icy waters. Utilization of open water leads (dark areas along yellow line) enable fuel and time savings. The figure is illustrative and not based on real case.

Due to harsh climatic conditions and poor infrastructure, in consideration of sparse and inefficient ground observation sites, state-of-the-art satellite based remote sensing techniques have become the most efficient and accurate approach to monitor large-scale variability of Arctic sea ice conditions. Utilizing a combination of multiple active and passive microwave, visible, and infrared satellite data sources currently provides the only efficient means to obtain information on the expected ice conditions on the route ahead.

Due to the restricted spatial resolution, icebergs and multi-year ice floes, which can cause serious damages to vessels, are difficult to be detected and monitored by satellites with passive microwave radiometers. Satellites with Synthetic Aperture Radar (SAR) have high spatial resolution (30-100m), which can be used to track icebergs and large-size multi-year ice floes. However, due to the narrow swath width of SAR, which leads to low temporal resolution, it is very difficult to make near real-time monitoring. Therefore, it is essential, to combine all active/passive microwave remote sensing data and other kinds of observational data to track sea ice motion. In the longer-term, more satellites should be launched so that at any time, every region along the Arctic routes can be covered. In general, latest developments associated to satellite image availability and quality provides new possibilities to significantly improve real-time recognition of ice conditions and ice conditions prediction. These possibilities could be utilized in planning of arctic shipping activities and real-time routing in ice covered waters.

AN additional challenge connected to the utilization of satellite images is related to the significantly limited communication possibility with ships navigating in remote Arctic waters. The file size of satellite images is typically large thus sending such images to the ships through limited communication channel requires a lot of time. Expenses related to this transmission may also be significant.

Thus, lack of services related to the detection and planning of most efficient routes through ice, even the appropriate technology exists already, exist today. This leads to inconveniences in estimating transit times, fuel consumptions during the voyage, arrival times and overall logistical chain in general. For shippers, unreliable transit times and therefore unreliable lead time reliability can cause issues on supply planning. This will not only cause cost for carriers, but also for shipper. Those cost could come up through express services necessary at on-carriage from port to customers and through potential penalties due to delayed arrival of goods.

5.2.2 Ice resistance

Ice generates extra resistance on the ship's hull as it moves through ice. The magnitude of this resistance depends mainly on the ice thickness, ice strength and ship hull geometry and ship speed. In principle, the ship speed in ice may be remarkably lower than in open water even when all available propulsion power is utilised. The vessel's speed may occasionally drop close to zero and the vessel may get totally stuck in ice. Figure 5-2 shows an example of a situation where multiple vessels are jammed and unable to proceed in ice. Another example difficult ice event is presented in Figure 5-3.

Due to ice resistance the time required for voyages increases, thus increasing the fuel costs and other time related expenses per voyage. To achieve and maintain an appropriate speed in ice, the machinery power of an ice going vessel is typically higher than the power of a similar sized vessel designed for operation in ice free waters (an "open water vessel"). This naturally increases the ship price compared to such an open water vessel due to increased engine size and overall ship lightweight.

The magnitude of the challenges described above are highly dependent on the ship design itself and the additional costs connected to Arctic navigation can be significantly decreased with the appropriate design of such ice going vessels. However, such specialised designs are typically optimised for certain ice conditions and/or specific routes which can make them inefficient in open water and thus uncompetitive against ships designed for open water. The balance of designing for reduced ice resistance whilst still retaining close to parity of efficiency with "open water ships" is one technical challenge that has a significant impact on the economic case for a ship owner: if the ship can be operated efficiently in ice, but the ship cannot be utilised throughout the year in ice then for the rest of the year that ship is inefficient, costly to run and difficult to find work for.

Figure 5-2. Several vessels jammed in ice and waiting for the icebreaker assistance in the Gulf of Finland in March 2011. (Source: Aker Arctic)

Figure 5-3. Nuclear-powered icebreaker escorting a cargo ship through an ice pack in the Kara Sea while heavy compression and ridging stop other vessels following in its wake, in April 2015. (Source: Aker Arctic)

5.2.3 Ice loads and classification

Ice generates additional loads on the ship hull and propulsion machinery which typically exceed the loads generated from waves when operating in a seaway. Consequently, a vessel operating in icy waters needs to be reinforced. This is done by defining the anticipated ice loads on the different areas of the ship's hull and on the propulsion components (principally the propeller, with the loads then transferred along the propeller shaft) with respect to the ice conditions (thickness, strength) that the vessel will operate in and how the ship is expected to operate. The reinforcement of these areas and components is then done according to the defined loads. Hull strengthening is most often done by increasing the hull plate thicknesses and the thickness and density of the supporting frames behind the shell plate. Correspondingly, the propeller strength (thickness) is increased and the rest of the propulsion components reinforced at a higher level, forming a pyramid of strength of the various shaft line components from the propeller to the prime mover. All these reinforcement measures require additional material increasing the lightship weight and the newbuilding price of the ship. In turn increased lightship weight means reduced deadweight (cargo carrying capacity) for a ship of a certain size. For ships designed for heavy ice conditions (higher ice loads), it is often necessary to utilise special steels with higher strength properties than those used on "open water" ships, to limit the impact on the lightship weight. These materials are however more expensive and thus a balance between utilisation of special steels and loss of deadweight is a challenge.

The scientific understanding of the loads imposed on ships due to interaction with ice is still incomplete. In particular, the ice failure mechanics at the point of contact between ice and the ship is not fully understood. Furthermore, the natural variability of ice, the orientation of the ice when in contact, etc. means that ice loads are stochastic in nature. Although some engineering models exist for predicting the ice load magnitude on a ship operating in certain ice conditions these are semiempirical in nature, relying on a relatively limited set of full-scale measurement data for validation.

To address this issue, standards have been developed by various national and international organisations which specify a certain strength level for operation in specific sea areas, during specific seasons, based on semi-empirical data and experience of damage. These standards usually adopt nominal descriptions of the ice conditions that the ship is intended to operate in. The standards often divide the strength level required by arbitrary steps, which are called ice categories or ice classes. Consequently, often a ship is strengthened to a certain ice class or ice category which is selected by the ship owner (or designer) based on their understanding of the expected ice conditions, and national regulations which may stipulate a certain ice class. Higher ice classes typically provide increased independency (need for the icebreaker assistance decreases), wider time and geographical ranges to navigate in the Arctic waters.

Under UNCLOS Article 234 coastal states have the right to regulate ships operating in ice covered waters within the EEZ to ensure ship safety and environmental protection. Often the approach to regulation is for the coastal state to divide their sea areas into zones, categorized by the historic prevailing ice conditions, and regulate access to these zones or areas by requiring a certain ice class for ships to enter, dependent on the season.

The relevant categories of Russian ice class rules and international Polar Class Rules, which are often applied for the commercial Arctic shipping, are presented below. The nominal descriptions of ice conditions associated to the presented categories are given in Table 5-1 (IMO, 2010) and Table 5-2 (RMRS, 2020). The categories between considered ice classes are roughly comparable. However, since some of the underlying engineering assumptions behind these rules are partially different, the categories should be considered only “referentially” comparable, but not completely equivalent.

Table 5-1. Ice conditions per ice class category according to Polar Class IMO

Polar Class	Ice descriptions (based on WMO Sea Ice Nomenclature)
PC 1	Year-round operation in all polar waters
PC 2	Year-round operation in moderate multi-year ice conditions
PC 3	Year-round operation in second-year ice which may include multi-year ice inclusions.
PC 4	Year-round operation in thick first-year ice which may include old ice inclusions
PC 5	Year-round operation in medium first-year ice which may include old ice inclusions
PC 6	Summer/autumn operation in medium first-year ice which may include old ice inclusions
PC 7	Summer/autumn operation in thin first-year ice which may include old ice inclusions

Table 5-2. Ice conditions per ice class category according to RMRS

Ice class	Description[1]
Arc9	In summer/autumn navigation — voyage in all areas of the World Ocean. In winter/spring navigation in Arctic — voyage in very close floating ice and in compact multi-year ice of up to 3,5 m thickness and in freezing non-arctic seas without restrictions.
Arc8	In summer/autumn navigation — voyage in all areas of the World Ocean. In winter/spring navigation in Arctic — voyage in close floating second-year ice up to 2,1 m thickness and in freezing non-arctic seas without restrictions
Arc7	In summer/autumn navigation — voyage in all areas of the World Ocean. In winter/spring navigation in Arctic — voyage in close floating first-year ice up to 1,4 m thickness and in freezing non-arctic seas without restrictions
Arc6	In summer/autumn navigation in Arctic — voyage in open floating first-year ice up to 1,3 m thickness. In winter/spring navigation in Arctic — voyage in open floating first-year ice up to 1,1 m thickness. Year-round voyage in freezing non-arctic seas
Arc5	In summer/autumn navigation in Arctic — voyage in open floating first-year ice up to 1,0 m thickness. In winter/spring navigation in Arctic — voyage in open floating first-year ice up to 0,8 m thickness. Year-round voyage in freezing non-arctic seas
Arc4	In summer/autumn navigation in Arctic — voyage in open floating first-year ice up to 0,8 m thickness. In winter/spring navigation in Arctic — voyage in open floating first-year ice up to 0,6 m thickness. Year-round voyage in freezing non-arctic seas in light ice conditions
Ice3	Regular voyage in open floating ice-cake ice of non-arctic seas up to 0,7 m thickness
Ice2	Regular voyage in open floating ice-cake ice of non-arctic seas up to 0,5 m thickness
Ice1	Episodical voyage in open floating ice-cake ice of non-arctic seas up to 0,4 m thickness

[1]The value of ice thickness given in the Table is indicated on condition of fulfillment of the minimum requirements of the RS Rules for ice classes **Arc4 — Arc9**.

For each ice class, an ice thickness may be assigned greater, but not exceeding the value for the next higher ice class on condition of application of relevant design solutions confirmed by the Register during review of the technical design documentation of the ship under construction or plan approval documentation of the ship.

The effect of an ice classification on the newbuilding costs depends on several factors thus simple and generally applicable rule for it cannot be given. For example, ice class upgrade often requires, in addition to hull and propulsion reinforcement, also propulsion power upgrade to ensure that the vessel can navigate with reasonable speed in intended ice conditions. The percentual increase of the newbuilding also depends on the vessel type. Using 170k LNG Carrier designed for open water operation (no ice class) as a reference, an approximate increase in shipbuilding price for an Arc 4 LNG Carrier would be 10%; and for a Arc7 LNG Carrier 70%.

5.2.4 Icebreaker assistance

Arctic shipping is often assisted by icebreakers. In principle this means that an icebreaker navigates in front of the assisted vessel (or vessels which proceed in “convoy”, Figure 5-4) and breaks ice in advance so that it is easier for the assisted vessel(s) to follow icebreaker and proceed in ice. Icebreaker assistance can be arranged on a regular/seasonal basis as a part of a shipping scenario where the vessels are not designed for independent navigation in all anticipated ice conditions along the route. It may also be needed occasionally if the vessel (even it is designed for independent ice navigation) gets jammed in unexpectedly difficult ice conditions or if the vessel’s speed drops unreasonably low.

Icebreaker assistance may take time (waiting for the icebreaker, waiting other vessels to join to convoy, etc.) and it is charged by the operator of icebreakers thus increasing the costs. On the other hand, sometimes assisted navigation may save fuel of the assisted vessel, because the power needed during assistance may be much lower than without assistance. The net impact of assistance to the costs is very case specific.

Icebreaker assistance also includes an increased risk of collisions. This is because sometimes, depending on the type of assistance, the distance between the icebreaker (or icebreaking tug at the port area) and assisted vessel may be small, and if the icebreaker rapidly decelerates due to a change in ice conditions, the assisted vessel may not be able to stop in time to avoid collision with the icebreaker's stern. The same applies also to ships proceeding in convoy. Examples of different icebreaker assistance types are presented in the Figure 5-4 and Figure 5-5 (ARCOP, 2006). Accidents and ship collisions are further considered in Section 5.2.5.

Figure 5-4. Icebreaker assisting two ships as a convoy

Figure 5-5. Close towing. The bow of a towed ship is fastened to the icebreaker stern by a towing line

Representative cost estimates for icebreaker assistance on the NSR are presented below. The costs are estimated for an Arc5 container ship of about 10 000 TEU and an Arc7 container ship of the same size. The assisted routes, seasons and ice classes are considered representative examples of assisting events thus giving an overall insight into the variation of NSR assisting costs. The estimations are calculated according to NSRA information and apply to the assisting services of the Russian state icebreaking company "FSUE Atomflot" (NSRA, 2020).

Table 5-3. Examples of assisting costs at the NSR

Class	Period	Assisted area/route	Cost
Arc5	Summer-Autumn	East-Siberian and Laptev Seas	230 000 EUR
Arc5	Summer-Autumn	Throughout NSR(1	290 000 EUR
Arc7	Summer-Autumn	Laptev Sea	190 000 EUR
Arc7	Winter-Spring	Throughout NSR(1	790 000 EUR
1) Bering Strait – Barents Sea			

5.2.5 Ice associated accidents and uncontrolled ice events

Many Arctic areas include multi-year ice and glacial ice obstacles (e.g. icebergs, bergy bits, growlers, thick floes) which are sometimes difficult detect in advance and which are much stronger than first-year ice. High speed collisions with such objects may cause substantial damage to ships, even those with ice class. An example of a growler is presented in Figure 5-6 . These small glacial ice features are especially challenging to be identified in advance because they are small, and they may be hidden between the waves. Examples of ice damages are presented in Figure 5-7 (Canadian Coast Guard, 2012) and Figure 5-8 (TRAFI, 2018).

It is worthy of mention in this connection that the hazardous ice features mentioned above may also exist in regions where no regular ice cover exists (like “Iceberg Alley” located in south Labrador Sea offshore Newfoundland and north-western Atlantic Ocean). In any case, notwithstanding if there is ice cover or not, navigating with high speed in the regions where multi-year ice or glacial ice may exist increases the risk of damage.

Vessels may also get jammed in ice (ref. Figure 5-2) especially if ice conditions in the area around the vessel are compressive. The compression may cause dents to the ship hull or in the first case, even damage the ship hull dangerously.

Jamming in ice may also lead to the dangerous situation if the ice cover moves. Then the vessel which is jammed in moving ice and thus unable to control her movements, starts to drift with ice. This may consequently lead to the situation where the vessel drifts with ice to the shallows and results in grounding.

Figure 5-6. Growler among waves.

The consequence of collision with multi-year ice features can be decreased by slowing down the navigation speed, while the frequency of encounter can be reduced utilizing latest technologies to detect the hazardous obstacles in advance. However, utilising these measures, together with possibility of getting jammed in ice, cause an increase in transit time, consequent delays in shipments and thus extra expense.

Figure 5-7. Ice damage to the bulb of a merchant vessel

Figure 5-8. Damage caused by ice on the bilge keel of a merchant vessel

Ice may also induce ship collisions with other ships and structures. For example, sometimes the ice resistance may reduce suddenly which may lead to a loss of directional control. This increases the risks of collision with other vessels nearby or with terminal structures and berths. Especially during icebreaker assistance, the risk of collision with assisting icebreaker and assisted vessel may, in specific circumstances, be significant.

Statistics on accidents occurring in the Northern Baltic (2007- 2013) indicate that approximately 75 % of accidents happen at the ports and Archipelagic waterways, and 25 % on the open sea. Correspondingly almost 60% of accidents happen during independent navigation while approximately 20% of accidents are associated with icebreaker escorting and convoys. The remaining 20% of accidents are associated with "cutting loose" operations where the icebreaker breaks ice around a vessel which has become beset in ice (e.g. due to compressive ice) (Goerlandt, et al., 2016). (Hänninen, 2018) correspondingly reports that about 80% of all winter accidents in the same area are due to collision with other ships.

Compared to open water navigation, challenges and risks described in this section tend to increase the insurance costs. The risks of some of the events previously described can be significantly minimized by using well-trained/experienced ship officers, ships designed for the purpose of operating in the Arctic as well as appropriately planned and managed operations.

5.2.6 Cold weather

In general, cold weather sets multiple specific requirements for ship systems and equipment. Freezing air together with sea spray may cause significant ice accumulation on the decks and rigging of ships (i.e. "icing"). The machinery, associated systems and equipment as well as vessel outfit need to be "winterized" so that they tolerate freezing ambient air temperatures without losing their functionality. This means, for example, utilization of specific materials and/or different heating and ice removal arrangements. Provision of these solutions increases the operational and capital costs of shipping in cold temperature regions. An example of "icing" is presented in figure Figure 5-9 (NOAA, 2015).

Figure 5-9. Deck outfit icing

The cold weather may affect the physical and mental functions of humans. This is the case especially with people who are not familiar with cold weather. For example, working for too long in freezing weather with insufficient clothing may lead to an increased risk of human errors and cause health problems for the crew members. Appropriate training and familiarization of the crew to the cold weather, proper tools and clothing and as well as sufficient manning (to limit the time of working periods) naturally increases the expenses (compared to open water vessels).

5.2.7 Environmentally sensitive areas

Some areas in icy waters are environmentally sensitive (due to vulnerable animal or vegetation populations, traditional hunting/fishing seasons of indigenous people, etc.) thus navigation in such areas may be, continuously or temporarily, restricted. Avoiding these areas where favourable navigation areas are rare in any case may cause additional challenges for shipping. Examples of environmentally sensitive locations, which should be considered when navigating and/or planning routes in the Canadian Arctic Archipelago are presented in Figure 5-10 (Transport Canada, 2018). Environmental challenges are further considered in Chapter 3.

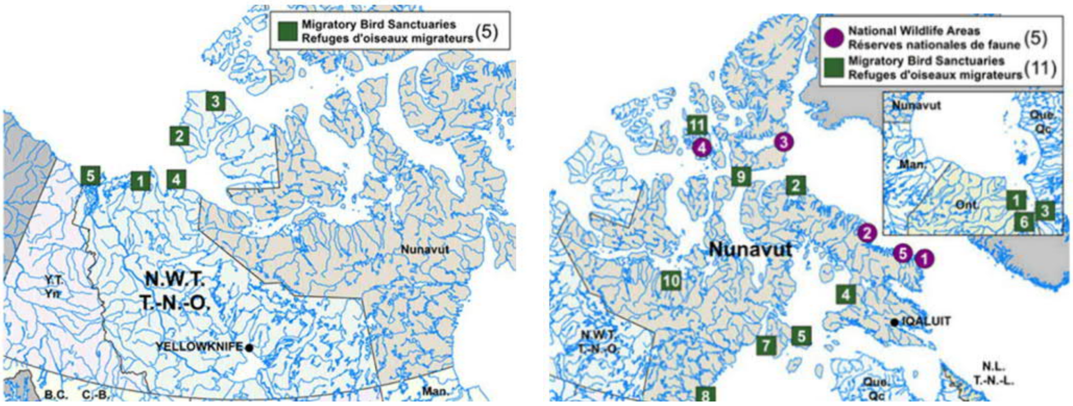

Figure 5-10. Maps of protected areas along the Canadian Arctic coastline

5.3 China perspective

Unlike via the Suez or via the Panama Canal, there are no similar canal fees for Arctic navigation routes. The main costs for Arctic maritime transportation consist of fuel costs, icebreaking costs, operating costs, and vessel depreciation costs. Fuel costs depend mainly on sea ice conditions and navigational distance/speed. The Arctic icebreaking fee depends on vessel size, ice class, the route, etc. The main operating costs include manning, H&M (Hull and Machinery) insurance, P&I (Protection and Indemnity) insurance, repairs and maintenance, administration and other costs. Compared with the savings in fuel costs via Arctic routes, there will be increased costs in vessel depreciation and icebreaker services. Except for sea ice conditions, harsh weather conditions and intermittent fog will probably significantly increase fuel costs and operating costs.

Compared with traditional routes, navigating the Arctic will have higher risk levels. The main risks influencing factors along Arctic navigation routes can be classified as meteorological factors, marine hydrology factors and ship performance factors. In meteorological factors, wind speed can impact the vessel's navigation speed and the associated course controls; low air temperature may lead to ice on decks and on associated equipment. In marine hydrology factors, sea ice concentration and thickness are the most essential aspects, while the sea temperature and wave height will also have some impacts. Icebergs and ice floes often force vessels to reduce navigational speeds significantly and may even cause vessel accidents. Ship performance factors mainly include ship speed and engine power.

At present, the scarce availability of Arctic transportation data makes it difficult to both identify and quantify risks compared to the traditional routes via the Suez Canal. Moreover, the seasonal/inter-annual variations and uncertainties of sea ice conditions along the Arctic routes make this kind of risk assessment more complex. Economic and risk assessments of trans-Arctic routes are at the early and immature stage.

6 Conclusions

The Arctic is changing. Temperatures in the region are increasing causing a range of physical and environmental changes. Arctic sea ice is thinning and receding. As these changes expose potential opportunities, and because the Arctic Sea provides shorter routes for global shipping, the international interest in the Arctic has increased. Recent years have indicated a significant increase of interest, not only among “traditional Arctic countries”, but also among global Asian traders (such as China, Japan, South Korea, etc.) to utilize Arctic sea routes for commercial purposes. The continued growth of international interest towards commercial utilization of the Arctic Seas is inevitable.

Certainly, Arctic shipping presents opportunities, but also challenges and threats. Sea ice, even when thinning, still creates major challenges for economically feasible shipping. The reasonable shipping season for most of the ships is currently only a few months long (typically from mid-summer to mid-autumn). Some experimental voyages outside this season have however been conducted on Northern Sea Route, although with very specialised vessels. An extreme example of such is the LNG carrier Christopher De Margerie’s voyage from Jiangsu (China) to Sabetta LNG terminal (located at Yamal Peninsula, western Siberia) through the eastern segment of the Northern Sea Route in February 2021.

Much attention has been given to the exploitation of the vast hydrocarbon reservoirs located in the Arctic. Gas related mega-projects, like Novatek’s on-going “Yamal LNG” and near-future “Arctic LNG2”, will accelerate the near-future marine activities and shipping in the Russian Arctic. These projects, together with other smaller projects, will certainly generate valuable information regarding the opportunities and challenges associated with Arctic shipping. Findings from these activities could be applied, not only to shipping on the Northern Sea Route, but also to shipping in Northwest Passage and Trans Pole Route, whose commercial usage today is marginal or practically zero.

Although trans-Arctic marine transportation is on the rise, it is still far from being an explosion. Infrastructure and marine services must be set up for safe, secure, and efficient operations of trans-Arctic navigation. This includes for example sea ice monitoring and forecasts, search and rescue services, experienced crews and ship owners, appropriate shipping technologies that can be safely used in ice prone waters, improved traffic systems, seaport facilities and navigation aids, as well as international governance and cooperative mechanisms.

The Arctic environment is vulnerable. Therefore, to enable utilization of Arctic routes in environmental-friendly manner, it is important to study the effects of shipping to the Arctic nature. The current understanding of the Arctic environment, together with findings and learnings from future studies, can be further applied to plan and execute shipping so that the environmental impacts are minimized. In addition, an environmental focus drives the design of "greener ships" and enables the development of services for "greener navigation" practices. Such services, together with appropriate ships, could ensure that Arctic shipping practices are conducted in the most environmentally friendly and sustainable manner in the future.

China's perspective

With the recent increases in international trade of goods between Europe and China, the related marine transportation section consumes huge amounts of fuels and contributes substantial quantities of global carbon dioxide emissions. Arctic maritime transportation not only can reduce transit times and costs but can also help to achieve the objective of reducing carbon emissions from shipping transportation in China. Although China is not a littoral Arctic country, but being the largest international trader, trans-Arctic maritime transportation has considerable impacts on China and will play an increasing role for green and sustainable development of China. Recently, China is incorporating trans-Arctic maritime transportation into "the Belt and Road Initiative" which will boost trade by massive investments in roads, ports and other infrastructure between Asia and Europe. In July 2017, the Chinese government and the Russian government announced plans to cooperate on Arctic passages and to build the "Ice Silk Route". Both governments would cooperate to improve infrastructure construction and to explore oil/gas resources and eco-tourism resources along Arctic coastline, which could partially solve the dilemma of the lack of intermediate markets along Arctic Northeast Passage**.**

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Annex 1

Panasonic

Research of the usage of the Northern Sea Route for Container transport

1

As with reference to the arctic transit route, Panasonic (Europe) is mostly interested in using it for commercial purposes for ocean container traffic.

As the information shared by Frederic Lasserre clearly shows in table below the container vessel movements on the Northern Sea Route (NSR) has stayed in stationary level during present years

	2016	2017	2018	2019
Container	169	156	150	171

Ref: Table 4-3 in the report

Panasonic (Europe) is shipping considerable number of Containers per year from Asia to Europe. Majority of those containers are shipped to northern Europe, mainly Hamburg port, which potentially could also be shipped through the NSR (Northern Sea Route).

Panasonic

2

Advantages regarding NSR shipping, which we consider as a shipper:

- no lead time improvement, but reliability of schedule since no commercial delays should be happening such as:
  - congested ports en-route
  - no re-loading of containers in connection ports
  - no need of passing of Suez Canal
  - no piracy or war risk
- exclusive position as one of the first "users" of the newly introduced route
- possibly lower freight rates due to tailor made setup based on the needs of the shippers and not the mass market

Disadvantages regarding NSR shipping, which we consider as a shipper:

- as far as we are aware the NSR still cannot be used throughout the year
- still possibly long way to go to materialize the NSR for commercial container purposes
- possible risk for "stuck in ice" situation and the therefore unpredictable length of delay until a icebreaker has reached the container vessel

We as Panasonic do not operate own vessels and would never do so, but as a shipper with a constant volume from Asia to Northern Europe we consider that it is very interesting to observe if it develops to a commercial usable stage.

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Vladivostok – Vostochny – Busan (Korean, Japanese and PRC cargo) - Bremerhaven – St. Petersburg (P1P)

NORTHERN SEA ROUTE GENERAL OUTLOOKS:

Ice-free navigation window – 3 months (mid-Jul till October) and it is growing (vessels are subject to Polar Code compliance);

Distance abt. 8 500 nm vs. 12 000 nm via SUEZ;

No challenges associated with Suez passage, no piracy or war risks;

No ship size restrictions – possible to scale up in future (vessels are subject to Polar Code compliance);

The NSR receives utmost support from Russian government as priority geopolitical project;

In 2017 NSR transited 10,7 M tons (7,5M tons in 2016) of cargo – mainly hydrocarbons, ores and North Russia supplies. By 2021 the flow is forecasted to reach more than 40 M tons/year.

[1] China National Petroleum Corporation

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Maersk –Venta, Crew -28 staff (specially trained)
3600 TEU ice-class Maersk Line vessel;
(7 vessels are planned to build in China)
Vladivostok – 23 Aug
Vostochny – 24 Aug
Busan - 28 Aug
Bremerhaven – 23 Sep
St. Petersburg (PLP) -28 Sep
Busan → Bremen – 25 days
Busan → St. Petersburg – 30 days
Loaded only ~ 1900 TEU (~ 600 TEU ref with Russian fish, ~ 1300 TEU with car s/parts, electronics & etc.)
Had to do ~2 ice channeling by Rosatomflot icebreaker
~80% of containers was unloaded in Bremerhaven (for EU customers)
Main purpose of the trip: to show technical and organizational possibility to deliver cntrs via NORTHERN SEA ROUTE
Economics of the route was not discovered
Future perspective was not announced
MAERSK LINE
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