MARINE INVASIVE ALIEN SPECIES IN ARCTIC WATERS

PHASE I REPORT

MAY 2025

ARCTIC COUNCIL

PAME
Protection of the Arctic Marine Environment

CAFF
Conservation of Arctic Flora and Fauna

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CHAPTER 3: ***The co-leads are currently working on updating the list of species based on comments received to date and will revise the relevant figures and tables accordingly***

This report is under final editorial review and layout.

PAME
Protection of the Arctic Marine Environment

CAFF
Conservation of Arctic Flora and Fauna

ARCTIC COUNCIL

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Abbreviations

To be included

1. Summary

This project is part of a joint effort between The Conservation of Arctic Flora and Fauna (CAFF) and the Protection off Arctic Marine Environment (PAME) Working Groups to implement actions related to the Arctic Invasive Alien Species Strategy and Action Plan.

With warming climate and increasing ship traffic there has been a growing interest and concern regarding the potential for introduction of Non-Indigenous Species (NIS) and Invasive Alien Species (IAS) to and into Arctic waters. For Arctic marine species the report assessed that ships are the most common source for the introduction of Invasive Alien Species (IAS) and Non-Indigenous Species (NIS) in Arctic marine systems, through organism entrainment in ballast water and biofouling of outer surfaces.

Based on a comprehensive review of available information in over 60 databases and 100 primary publications this report presents a list of species /taxa known to NIS and IAS. The report present details on individual species/taxa detections in 18 different Arctic Large Marine Ecosystems (Arctic LMEs). The list includes higher total number than in other previous studies in the Arctic waters while numbers of species/taxa recorded in the current report are like those found in The European Marine Observation and Data Network list.

The assessment in the report indicates that ship traffic to and into the Arctic waters has significant increase in period year 2013 to 2024. The number of unique ships entering the Arctic area has increase by around 37%. This corresponds to approximately 500 ships, in the period from 2013 to 2023. In same period the distance sailed by ships in the Arctic Polar Code Area, has increased from 6.1 million to 12.7 million nautical miles.

Risk assessments are useful to provide clues and develop watch lists of non-indigenous species and invasive alien species. This report makes a horizon scanning of the approach used to predict species of concern to the Arctic to date. A relatively limited number of risk assessments have been done for NIS and IAS for the Arctic waters. This report shows that the most common approach used in risk assessments in the Arctic, has been to predict species of concern with a focus on species known to be in potential source regions and pathways. However, experimental information on survival and reproductive thresholds is frequently lacking, especially with respect to lower thresholds at near zero and sub-zero temperatures common to Arctic waters. In addition, species distribution models only indicate the possibility of a species to establish given the current or predicted future conditions and rarely consider pathways and vectors.

To combat the problem of species introductions in ballast water, IMO has adopted the International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 (Ballast Water Management (BWM) Convention) and the Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species (Biofouling Guidelines 2023). This report summarizes these guidelines and the convention in an Arctic context. In February 2025, the BWM Convention had 97 Parties representing; out of the eight Arctic Countries, two are not Parties to the BWM Convention. Recent studies indicate that even if ships are compliant with the ballast water performance standard for indicator microbes and organisms (size class 10-50 µm), some exceed the limit for viable organism's ≥50 µm. Therefore, it is suggested to further study the efficiency of filter mesh sizes and different filtration units associated with ballast water management systems, to improve mechanical removal of larger organisms ≥50 µm. In 2023, IMO developed non-

binding Biofouling Guidelines to encourage the control and management of ships' biofouling to minimize the transfer of non-indigenous species.

Arctic marine ecosystems differ from other ocean environments and are characterized by a great variability in environmental conditions, including seasonal extremes in photoperiod, cold temperatures, river runoff and ice conditions. Factors of importance in relation to the establishment of new marine species are salinity, temperature, light condition and levels of nutrients in the waters. In line with climate change, environmental and ecological conditions in the Arctic marine areas have changed in many places. Studies have documented that in Arctic regions climate-induced changes in ocean and sea ice environments, together with human introduction of non-native species, have expanded the range of some temperate species. The projected climate changes for Arctic waters will push some species out of their ranges, whereas other species may colonize new areas.

This report is Phase 1 of a joint effort between CAFF and PAME to implement actions related to the Arctic Invasive Alien Species Strategy and Action Plan. A phase 2 is planned to build upon results from this report and to include aspects related to risk assessments and on preparing programs for monitoring, detection, and prospective registration of non-indigenous species (NIS) and invasive alien species (IAS) in Arctic waters.

2. Background

In the Arctic Invasive Alien Species Strategy and Action Plan (ARIAS), the Conservation of Arctic Flora and Fauna (CAFF) and Protection of the Arctic Marine Environment (PAME) sets forth the priority actions that the Arctic Council and its partners are encouraged to take to protect the Arctic region from a significant threat: the adverse impacts of invasive alien species (CAFF and PAME 2017).

This report is part of a joined CAFF - PAME project. The project is according to the CAFF and PAME workplans 2021-2023/5 divided into two phases where phase one is this report and phase 2 is planned to build upon results from the report, and include aspects related to risk assessments and on preparing programs for monitoring, detection, registration of nonindigenous species and invasive alien species in Arctic waters. The focus of this report is on implementing actions related to ARIAS action no. 2. to improve the knowledgebase for well informed decision making, with the goal to improve the capacity of the Arctic Council and its partners to make well-informed decisions.

In recent years shipping has increased in the Arctic region, due to changing climate and increased sea ice melt in the region (CAFF 2010, Zhao et al. 2024). According to the Arctic Shipping Status Report (PAME, 2025) the number of unique ships entering the Arctic area has increase by around 37%, to about around 500 ships in the period from 2013 to 2023. This trend is expected to continue in the future.

In relation to Arctic marine species, ships are the most prevalent pathway for the introduction of non-indigenous species in marine systems through organism entrainment in ballast water and biofouling (Molnar et al. 2008; Williams et al., 2013; Cottier-Cook et al., 2024). Studies of shipping operations have demonstrated that the external hull and ballast tanks of ships operating in the Arctic can support a wide variety of non-native marine organisms (Ware et al. 2014 and 2016; Chan et al. 2015; Chan et al., 2022).

Terminology has long been debated in the invasion biology world and continues to this day (Soto et al. 2024). In the Arctic Invasive Alien Species Strategy and Action Plan (ARIAS) “Invasive Alien

Species" (IAS) are defined as species that are not native to a given ecosystem due to an intentional or unintentional escape, release, dissemination, or transport into that ecosystem as a result of human activity and which may cause economic, environmental harm, including harm to subsistence species and activities and/or harm to human health. In contrast Non-Indigenous Species (NIS), is a synonym to alien species that are not harmful.

With warming climate and increasing ship traffic to the Arctic and within arctic ecoregions (Miller and Ruiz 2018, Ricciardi 2018) there has been a growing interest and concern regarding potential for introduction and establishment of NIS in this region (Fernandez et al. 2014, Snook et al. 2018). This has led to an increasing number of surveys and inventories to better understand baseline native and non-indigenous species diversity in high risk areas of the Arctic such as active shipping in areas of the Canadian Arctic (e.g., McKenzie et al. 2021, Dhifallah 2022, Gianasi et al. 2022a, 2022b, Golder/WSP 2020, 2021, 2022, Dispas 2019, ICES 2022), Alaska (Reimer et al. 2017), Iceland (Thorarinsdottir et al. 2014), and Norway (Sandvik 2019; Artsdatabanken 2023).

To assess the possibility for establishment of potentially new species entering the Arctic marine environment, it is important to understand that the processes that influence Arctic marine ecosystems. The marine Arctic is characterized by a large variability in environmental conditions, including seasonal extremes in photoperiod, cold temperatures, river runoff and ice conditions (CAFF 2017). All these factors constitute key forcing to Arctic marine ecosystem functioning and biodiversity.

The Arctic can be divided into different Arctic Large Marine Ecosystems (Arctic LMEs) defined by PAME and adopted by the Arctic Council. Based on the individual ecological and oceanographic characteristics 18 Arctic Large Marine Ecosystems are defined for the Arctic (Figure 2.1) (PAME 2013) and this report use LMEs in the descriptions and assessments. More information on each LME can be found in the PAME LME fact sheet series (link: https://pame.is/ourwork/ecosystem-approach-to-management-ea/large-marine-ecosystems/).

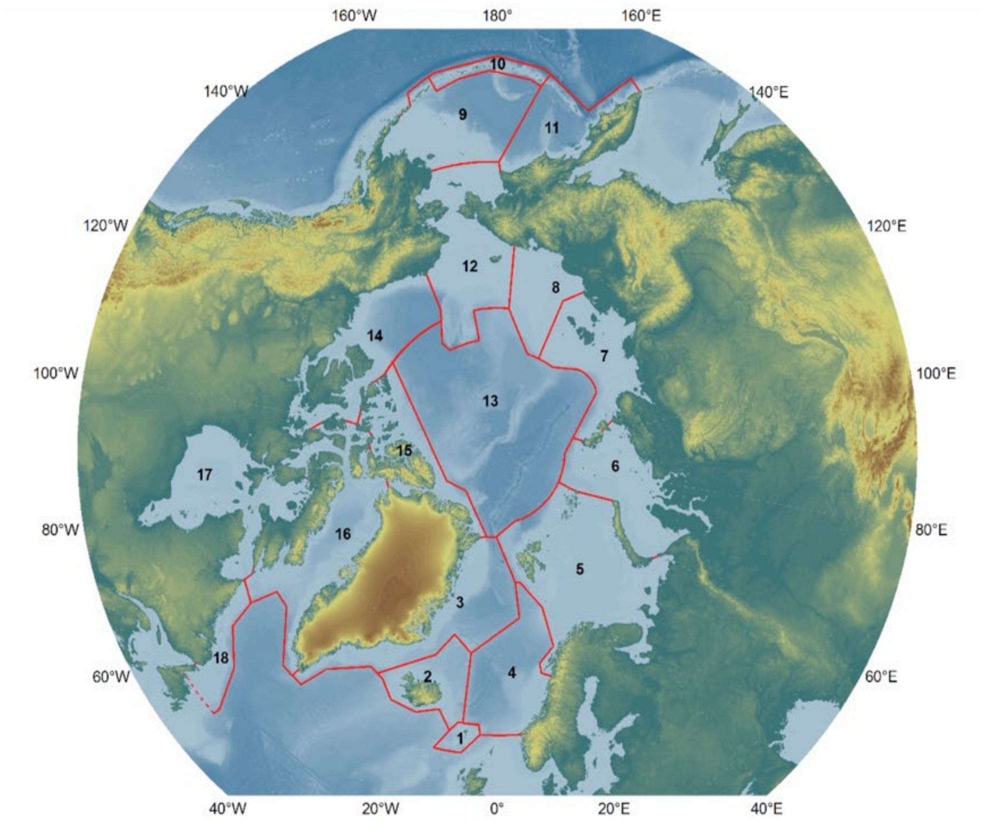


Figure 2-1: Map of 18 Arctic LMEs (version 17 April 2013)

This report builds upon data from existing databases and published information and includes:

- A list of known non-indigenous species, including their current distributions based on a comprehensive review on published information and upon data from existing databases.
- A review of methods and tools used for risk assessment of invasive species, vectors, and pathways with a focus on the Arctic.
- A review of current regulation and updating work related to the IMO regulation reducing the spreading and transport of non-indigenous species by ships, as well present challenges in relation to comply with the IMO Ballast Water Performance Standard.
- A time trend analyses of ship entering the Arctic Polar Code area from 2013 to 2024 in number of ships and distance sailed in the arctic waters.
- A reflection upon and short review of the observed and expected future climate changes and its impacts on arctic marine ecosystem
- Conclusion and recommendation for the continuation of this project (Phase 2)

3. Marine Invasive Alien Species in different Arctic Marine Ecosystems

3.1 Terminology

Terminology has long been debated in the invasion biology world and continues to this day (Soto et al. 2024). While this report does not dwell on the topic, it is important to clarify terminology used in the document and its intended meaning. In the Arctic Invasive Alien Species Strategy and Action Plan (ARIAS), the Conservation of Arctic Flora and Fauna (CAFF) and Protection of the Arctic Marine Environment (PAME) Working Groups provide guidance for Arctic States to address issues for Arctic Invasive Alien Species (CAFF and PAME 2017). Here, "Invasive Alien Species" (IAS) are defined as "… species that are not native to a given ecosystem (that is, when a species is present due to an intentional or unintentional escape, release, dissemination, or placement into that ecosystem as a result of human activity) and which may cause economic, environmental harm, including harm to subsistence species and activities or harm to human health" In this report, we retain this definition and utilize this terminology for consistency with ARIAS. However, we acknowledge that the term "Invasive" is fraught with being interpreted in many ways (e.g. Carlton and Schwindt 2024, Soto et al. 2024, Blackburn et al. 2011, Colautti and MacIsaac 2024). "Invasive" may variably include notions of spread or impact (economic or environmental), although this varies greatly among publications. In contrast, there is little ambiguity about the terms "Non-indigenous" and "Non-native," and "Alien," as pointed out by Carlton and Schwindt (2024). Given that details on impacts and abilities of introduced taxa in the Arctic to establish and spread, are frequently limited, or unknown, we mainly use the more over-arching term non-indigenous species (NIS) throughout Chapter 3; this terminology includes species that are not known to be harmful or where ability to cause harm is unknown.

The term "Cryptogenic" may be defined as "taxa of a known identity (to varying taxonomic levels, as discussed below) whose evolutionary and biogeographic origins are poorly described or not yet known and thus cannot yet be resolved as either non-native or native" (Carlton 1996; Carlton and Schwindt 2024). Although cryptogenic taxa are not the focus in this report, they were frequently present on existing survey lists from Arctic regions that were reviewed as part of this chapter (e.g., Goldsmit et al. 2014, Hines et al. 2000, Hines and Ruiz 2001) and may have been designated as such due to poor baseline information or knowledge of taxonomy in this part of the globe (discussed further below). This lack of knowledge may lead to overlooked introductions, thus we felt it was important to document these species together with existing knowledge (global distributions, evidence of invasiveness or introductions in other parts of the world and potential transport vectors) for future information and use by various Arctic States.

3.2 Introduction

There are a variety of vectors (defined as mechanisms by which species are introduced) for aquatic non-indigenous species (NIS) including aquaculture, aquarium trade, baitfish transfers, water gardens, live seafood industry (Ruiz and Carlton 2003, Hewitt et al. 2007; Weigle et al. 2005). However, shipping, through ballast water and biofouling vectors, is responsible for the majority of marine introductions globally (Hewitt et al. 2009, Bailey et al. 2020). Thematic Assessment Report on Invasive Alien Species and their Control has been published by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2023), in North America (Ruiz et al. 2000) and in Arctic coastal waters (Chan et al. 2019). This pattern is consistent with knowledge that in areas where there is regular monitoring, hot spots for marine NIS tend to be situated primarily around ports (Miralles et al. 2021), followed by aquaculture sites and marine protected areas (Tsiamis et al. 2021).

To date, the number of documented aquatic NIS in Arctic regions has been relatively low, most likely due to relatively limited shipping activity and harsh conditions (Ruiz and Hewitt 2009, Goldsmit et al. 2014, Goldsmit et al. 2018, Chan et al. 2019, Adeniran-Obey and Osagie 2024,). However it is important to note that in cases where baseline surveys have been undertaken (e.g., Alaska, Canada; Hines et al. 2000, Hines and Ruiz 2001, Goldsmit et al. 2014) there are typically high numbers of cryptogenic species and organisms with uncertain taxonomy as these regions are not well surveyed and baseline native species distributions remain poorly understood relative to many other coastal areas (Archambault et al. 2010). This makes it challenging to assess the origins of newly discovered species. The limited knowledge of native species distributions in these areas increases the probability of missing novel NIS due to poor survey efforts and the reluctance to designate new organisms (especially those without a past invasion history) as non-indigenous since their distribution taxonomy is so poorly known (Seebens et al. 2018). When poor knowledge of native baseline biodiversity is combined with increased exposure to novel species through opening of new shipping routes in the Arctic (Miller and Ruiz 2014), new introductions may be overlooked. The Arctic is also a vast geographic area, and it can be challenging to delineate species that are present as being indigenous, cryptic, or introduced. The sheer size of this region makes it difficult to determine whether a given species is indigenous and in some cases criteria for evaluating the status of new taxa are not necessarily designed from the perspective of a large contiguous marine region, but rather from an island/continental perspective (e.g., Campbell et al. 2018). This is further complicated by what Ricciardi et al. (2021) refer to as the taxonomic impediment, i.e., the progressive loss of capacity in taxonomy and systematics, particularly for smaller microscopic organisms, that is necessary to accurately determine identity and origins or various taxa.

There have been a small number of previous attempts to document invasions in the Arctic at local (e.g., de Riviera et al. 2011, Thorarinsdottir et al. 2014) and more broad geographic scales (Chan et al. 2019, EMODnet 2025). A previous PanArctic review of information sources spanning 1960-2015 documented 34 marine NIS introductions in Arctic Large Marine Ecosystems (LMEs), 22 of which were considered established (detected at a minimum of two locations or two years in the same location and known to be reproducing successfully) (Chan et al. 2019). The top 85% of recorded non-indigenous taxa included arthropods, ochrophytes, chordates (many of which were salmonid fish), and mollusca. Chan et al. 2019 found the majority of introductions and establishments were in coastal Europe-west, Asia, an area of the Arctic, which is largely ice-free due to warming by the North Atlantic. This may make this area more hospitable for NIS originating from temperate areas with greater shipping and aquaculture activity. The largest proportion of Arctic introductions were attributed to ship ballast water or biofouling (Chan et al. 2019), which is consistent with global patterns (Bailey et al. 2020).

The European Marine Observation and Data Network overview of marine alien species in the Arctic (EMODnet 2025) also provides a list of introduced Arctic species with locations, temperature thresholds, and vectors, although individual species and associated information are not individually referenced, making it challenging to link listed species with original publications. Further, the list mixes species that are introduced with those that have only been found arriving on ships in the Arctic (e.g., in ballast water or biofouling) and does not distinguish the two. In some cases, the list also includes various species from a given genus as being introduced to the Arctic when in fact only the genus was identified in the original surveys of the environment or vessels arriving in the Arctic. While the list provides a good starting point, it should be used with caution, and one should not assume all species on the list are actually introduced in the Arctic. We recommend that individual species on the list be checked to search for original source information and verification.

With warming climate and increasing ship traffic to the Arctic (Miller and Ruiz 2018, Ricciardi 2018, also see Chapter 6 and Chapter 7) there has been a growing interest and concern regarding potential for introduction and establishment of NIS in this region (Fernandez et al. 2014, Snook et al. 2018). This has led to an increasing number of surveys and inventories to better understand baseline native and non-indigenous species diversity in high risk areas of the Arctic such as active shipping ports and harbours in areas of the Canadian Arctic (e.g., McKenzie et al. 2021, Dhifallah 2022, Gianasi et al. 2022a, 2022b, Golder/WSP 2020, 2021, 2022, Dispas 2019, ICES 2022), Alaska (Reimer et al. 2017), Iceland (Thorarinsdottir et al. 2014), and Norway (Sandvik 2019; Artsdatabanken 2023)

3.3 Approach for generating an updated list of introduced taxa in the Arctic

Here, we provide an updated list and associated information on taxa known to be introduced (IAS and NIS) in Arctic marine regions based on a comprehensive review of available information up to the present. Introduced IAS and NIS in the Arctic included in this chapter were identified as part of a broader search to identify known and potential IAS and NIS to the Arctic for inclusion in a model-based risk assessment (a phase 2 of the project). Initial searches were conducted on over 60 databases, primary publications and reports containing lists of known and potential IAS and NIS from northern and temperate regions; these were further supplemented with searches of publications and databases recommended by an Arctic Council Expert Group of nominated representatives from various Arctic states for this project as well as experts from the International Council for the Exploration of the Sea (ICES), Intergovernmental Oceanographic Commission (IOC) of UNESCO, and International Maritime Organization (IMO) Working Group on Ballast and Other Shipping Vectors (WGBOSV) and ICES Working Group on Introductions and Transfers of Marine Organisms (WGITMO) (see list of searched references with detailed species lists in Appendices). Cold-tolerant taxa were identified based on literature searches for general information or experimental studies on thermal tolerance. This was complemented with searches on general distributions of taxa based on biodiversity and taxonomic databases (OBIS, GBIF, WoRMs and NEMESIS and supplemented with a broader literature search if needed, e.g., for more data poor species) to assess if they were generally cold-tolerant (i.e., if they occurred anywhere below the 17 ^{o}C maximum temperature threshold; Figure 3-1, grey shaded region). This threshold represents the maximum temperature found within the AMAP Arctic boundary (White Sea, LME 5) in recent times (2000-2014) based on BioOracle v2.1 (Assis et al. 2018). Given that there were limited experimental studies to assess lower temperature thresholds for most taxa, we developed these additional criteria as a way of screening for cold-tolerant species.

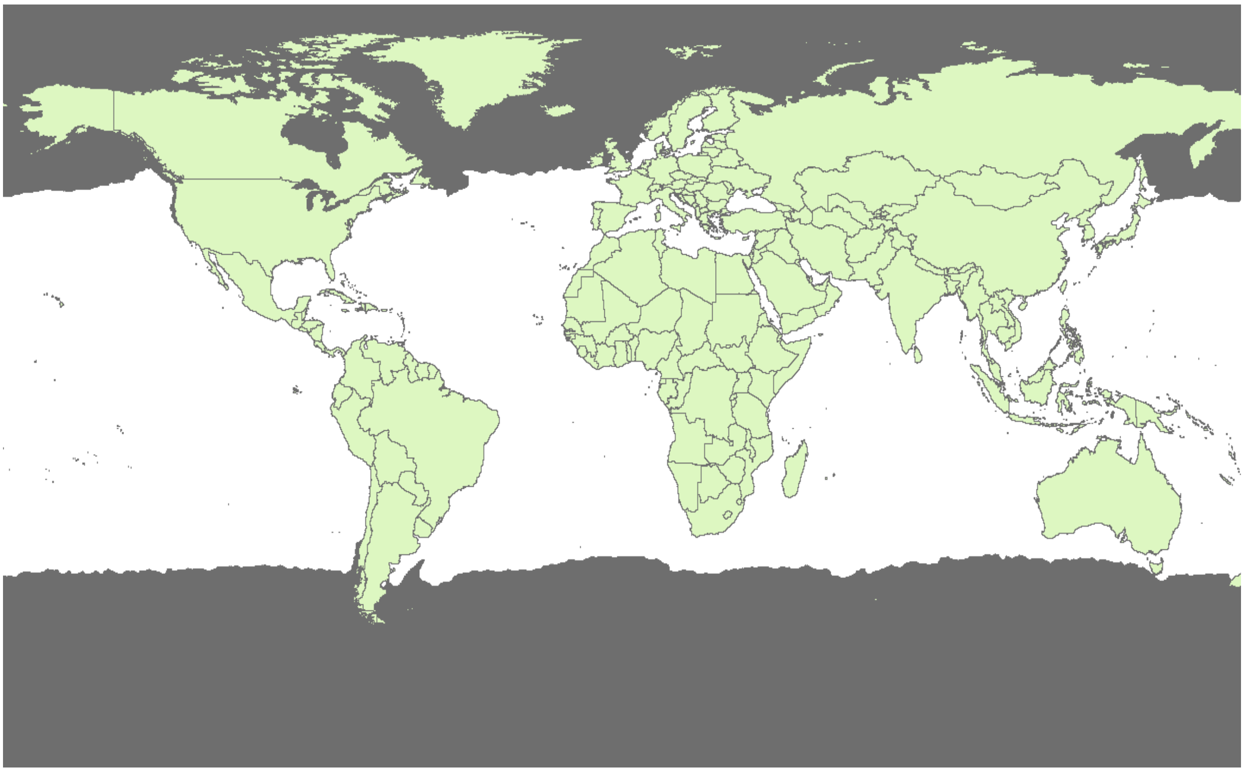


Figure 3-1. Global map showing regions where maximum sea surface temperature does not exceed 17 °C, the maximum temperature recorded within the AMAP Arctic boundary. Data layer obtained from BioOracle version 2.1 present day (2000-2014) maximum sea surface values (Assis et al. 2018).

The Arctic is defined in many ways for the consistency with the rest of this report, we use boundaries of Arctic LMEs (PAME 2013) or the broader Arctic Monitoring and Assessment Program (AMAP) region as delineated by the Arctic Council Protection of the Arctic Marine Environment (PAME) and AMAP working groups, respectively (AMAP 1998). To develop the lists in Chapter 3 we chose to be more comprehensive and reviewed all species that use the marine environment at some stage of their life cycle. Thus, anadromous, catadromous, brackish and marine taxa were considered. Although the focus of this report is on marine IAS transported by shipping, to be more comprehensive, we considered taxa that were moved by any type of pathways (e.g., aquaculture, aquarium trade, bait transfers, deliberate introductions) in the lists developed for this chapter. For purposes of the later model-based risk assessment in a phase 2 of the project, we narrowed known and potential IAS to only include those that do not require freshwater at some stage of their life cycle (i.e., can complete their full life cycle in marine (>20 psu) or brackish (> 5-20 psu) environments (Wolff 1999) and that are known or have potential (based on life history) to be moved by shipping related vectors (ballast, biofouling).

3.4 Updated list of introduced taxa

When considered across all possible vectors, a total of 107 NIS were identified as introduced in at least 1 Arctic LME, with some having been introduced in multiple LMEs (Table 3-1; Figure 3-2; for detailed list see the following Appendices: *Lists of species considered IAS/NIS, cryptogenic or range expanding in at least one Arctic LME with status in each LME together with detailed information on taxonomy, global distribution, invasion history, vectors of transport and supporting references*).

The total number of NIS recorded in Arctic LMEs was substantially higher than in previous studies such as Chan et al. (2019), who recorded a total of 34 species. While total numbers of taxa recorded in the current report are similar to those in the EMODnet (2025) list (101 species), it should be noted that just under half of those were considered introduced based on detailed examination of distribution information and associated literature conducted in the current review (also discussed in **Other Considerations**, below). Three of these species (*Anomalocera patersoni*, *Metridia lucens*, *Neodenticula seminae*) were considered range expansions (Table 3-2, Appendix 3-2) rather than introductions and two (*Heteromastus filiformis*, *Jassa marmorata*) were classified as cryptogenic (Table 3-3, Appendix 3-3). The remaining taxa showed no evidence of occurrence or introduction in Arctic LMEs and to the best of our knowledge appeared to have been placed on the list because they were found in ballast or biofouling assemblages of vessels arriving to Arctic Ports (e.g., Ware et al. 2016, Chan et al. 2015), were detected in southern Alaska outside of Arctic LMEs (e.g., Hines et al. 2000, Hines and Ruiz 2001) but still deemed as Arctic, or were likely native taxa misidentified as NIS due to metabarcoding species mismatch errors (discussed further in **Other Considerations**). A number of these were still retained as potential NIS of concern to the Arctic for the phase 2 of the project risk assessment if they met the required criteria of being cold-tolerant, primarily marine/brackish, had the potential of being transported via shipping, and had sufficient distribution occurrence points to allow for robust use of species distribution modelling.

Geographic patterns

Figure 3-2, below, provides a breakdown of NIS richness across the Arctic LMEs. The Norwegian Sea, Barents Sea, Iceland Shelf and Sea LMEs had, by far, the greatest NIS richness, ranging from 33 to 41 species, with most (70-80%) being well established (i.e., multiple records in more than one location or over more than one year). The Barents Sea had a somewhat lower proportion of established NIS, with a number of detections based solely on metabarcoding or where establishment was uncertain. In many cases, NIS were relatively recent first detections in this region, particularly in the Svalbard area. This may be a combination of increased survey effort and warming climate improved hospitability for more temperate NIS arriving in this region.

The Hudson Bay Complex, Canadian Eastern Arctic-West Greenland, and Labrador-Newfoundland LMEs as well as the East Bering Sea LME had moderate NIS richness ranging from 10-18 taxa, generally had a lower proportion of established NIS (50-70%), with the exception of the Labrador-Newfoundland LME. For the Hudson Bay Complex and Canadian Eastern Arctic-West Greenland, a substantial portion of new detections were based on metabarcoding only and are likely due to increased survey efforts and recent implementation of this new technology in community-based programs in this area of the Arctic (e.g., Lacoursiere et al. 2018; Sevellec et al. 2021, 2024).

The Western Canadian Arctic, Canadian High Arctic, and Eastern Russian Arctic LMEs tended to have much lower NIS richness, ranging from 1-4 NIS/region, with generally greater uncertainty regarding species establishment. Zero NIS were recorded in two LMEs, the Central Arctic Ocean and East Siberian Sea. The lower numbers of NIS in these areas may be attributed to lower survey effort, lower relative levels of shipping (Rodriguez et al. 2024), harsher conditions, or some combination of these.

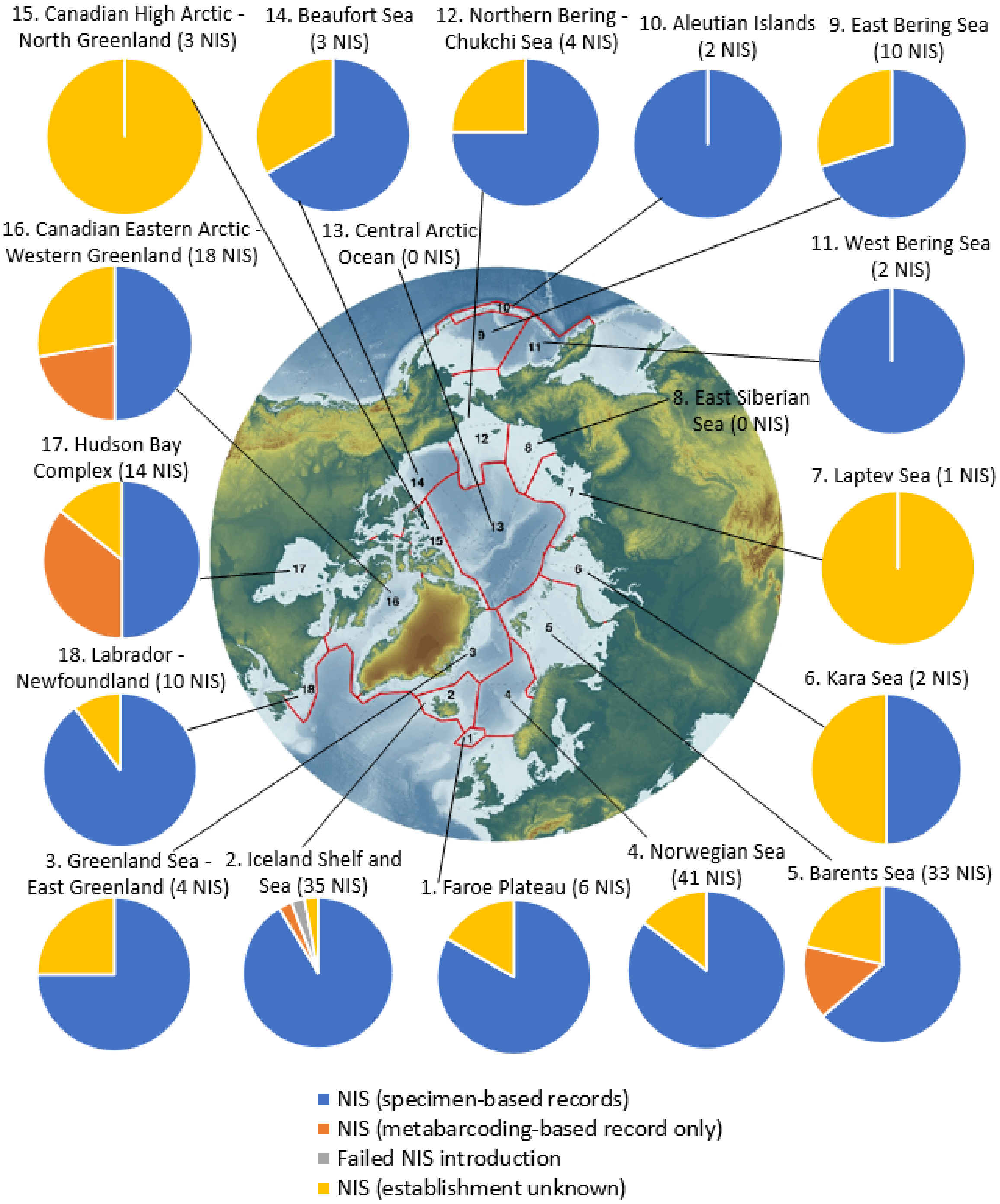


Figure 3-2. Map showing NIS richness by Arctic LME with relative proportion of recorded NIS based on specimen-based records (blue), genetic metabarcoding records only (orange), NIS where establishment is unknown (yellow), and failed NIS introductions (grey). Details on individual species detections and status by LME are provided in Table 3-1 (below) with references and further supporting details in Appendix 3-1

Although overall numbers of introduced NIS were found to be higher than in earlier assessments, the overall geographic patterns were similar to those reported by Chan et al. 2019, with LMEs in the Northeast Atlantic up to the Barents Sea having the greatest NIS richness. These areas remain largely ice-free throughout the year due to warming from the North Atlantic current (Figure 3-3; Weinrich and Lukyanova 2022), creating a hospitable environment for survival and establishment by a greater range of NIS, including those arriving from more temperate regions of the globe. In contrast to the previous assessment, however, there has been a disproportionate increase in NIS richness for LMEs 16 through 18, encompassing the eastern portion of the Canadian Arctic and West Greenland, as well as in the Bering Sea (LME 9), although other areas such as East Greenland (LME 3), the Beaufort Sea (LME 14), Laptev Sea (LME 7), and Faroe Plateau have remained at a low numbers (1-5 NIS, with exception of Faroe Plateau now at 6). While the Central Arctic Ocean and East Siberian Sea continue to show no documented NIS, several LMEs (from the central and eastern Russian coast through to the Beaufort Sea and Canadian High Arctic-North Greenland) that were previously lacking NIS now have low NIS richness (1-4 species). Of particular note is the Bering Sea LME, which has increased from zero to ten documented NIS.

Figure 3-3 Major Ocean currents and sea ice extent over the past 2 decades (Source: Weinrich and Lukyanova 2022)

Taxonomic patterns

Across all NIS, Arthropods were the most dominant phylum, accounting for approximately a quarter of all NIS (Figure 3-4). Within this phylum, Malacostracans (primarily Amphipoda and Decapoda) were dominant (46%), followed by Copepods (38%), Brachiopods (8%), Thecostracan (only Cirrepedia; 8%). Chordates were the next most abundant phylum, accounting for 18% of all NIS, with approximately 58% of taxa in the subphylum Tunicata and the remainder in the subphylum Vertebrata, of which all were bony fishes (Teleostei). Thirteen percent of all NIS were in the phylum

Mollusca, followed by Ochrophyta (9%), Annelida (8%; all Polychaeta), Cnidaria and Rhodophyta (each accounting for 7%), Myzozoa and Bryozoa (each accounting for 5%). Other phyla with lower representation included Chlorophyta (3% of NIS) and Tracheophyta (1% of NIS).

These patterns are similar with previous studies of Arctic NIS (Chan et al. 2019) and NIS in other parts of the world (e.g., Nunes et al. 2014, Bailey et al. 2020) that have shown arthropods are by far the dominant taxa contributing to introductions through shipping. This group also tends to be dominant among high-risk taxa identified through various risk assessments that have been done for the Arctic (Chapter 4). The taxonomic composition of other well represented phyla is generally consistent with earlier work with many of the same groups including Chordata, Mollusca, Ocrophyta, Rhodophyta, Myzozoa, and Chlorophyta. However, interestingly annelids (polychaetes) were found to be relatively dominant in this more recent data set yet were absent from earlier inventories (Chan et al. 2019). Likewise, bryozoans and cnidarians were reasonably well represented in the recent NIS lists but were not found in earlier inventories. Some of these can be difficult to identify morphologically to the species level if specimens are damaged or immature (e.g., Radashevsky et al. 2021) and with use of barcoding methods may be identified to the species level where they might not have been in the past. For example, the bryozoans, *Juxtacribrilina mutabilis* (previously *Cribrilina mutabilis*) and *Schizoporella unicornis* were identified with metabarcoding in the Barents Sea LME (Table 3-1). Likewise, the polychaete *Marenzelleria arctia* was detected with metabarcoding in the Canadian Eastern Arctic-Western Greenland LME, yet morphological identifications from this area have been inconclusive beyond the genus level (Table 4-1). Additional taxa that differed included one playhelminth, the salmon fluke (*Gyrodactylus salaris*) reported in Chan et al. 2019, but not represented on the updated list (this species was excluded as it appears to occur primarily in freshwater), and one Tracheophyte, *Zostera japonica*, identified in the updated list (NIS in Norwegian and Barent's Sea LMEs, Table 4-1), but was not identified in the previous synthesis by Chan et al. 2019.

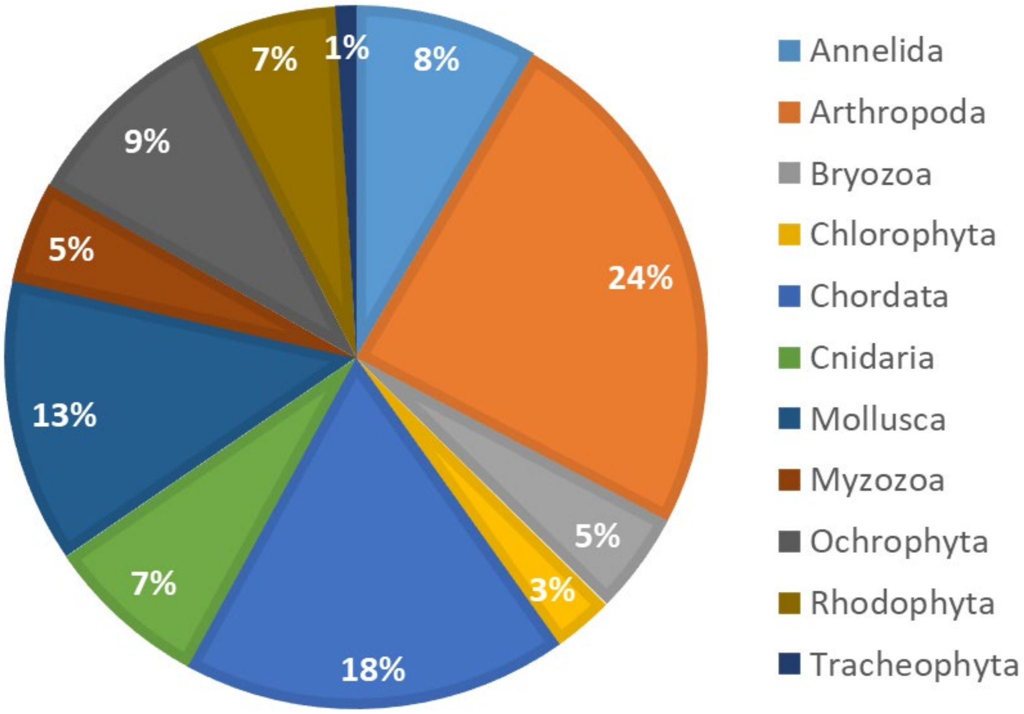


Figure 3-4. Proportion of all recorded NIS taxa in Arctic LMEs by phylum. For details of species and lower taxa within different categories see Appendix 3-1

With respect to broad ecological groupings (Figure 3-5), zoobenthos made up over half of all NIS, followed by phytobenthos and zooplankton which accounted for 19% and 15% respectively, of NIS in Arctic LMEs. Fish and phytoplankton tended to be less dominant making up 7% and 6% of NIS. Although other studies of introduced species in the Arctic have not evaluated ecological groupings, a recent risk assessment of potential vessel-mediated NIS introduction in the Hudson Bay Region of the Canadian Arctic (Goldsmit et al. 2021) found a similar breakdown among the 14 highest relative risk species with 57% made up of zoobenthos, and the remaining 43% of taxa evenly split between zooplankton and phytobenthos. There may be several reasons for these patterns. Many zoobenthos have pelagic larval stages and are also fouling species so may therefore be associated with the two most important vectors, vessel ballast and biofouling (see Figure 3-6 below). Furthermore, a high number of zoobenthos are associated with aquaculture, which is also an important transport vector (e.g. McKindsey et al. 2007). Among NIS to Arctic LMEs almost two thirds (20/33) of those that had ballast and biofouling as associated vectors were zoobenthos, over half (11/20) of which also had aquaculture and translocations as a vector. The vast majority of remaining taxa with these shared vectors were phytobenthos, the next most represented ecological grouping among Arctic NIS. In contrast, nearly all zooplankton and phytoplankton were primarily associated with ballast transport; only one zooplankton species, the cnidarian *Gonionemus vertens*, was noted to also be associated with biofouling and aquaculture transfers (Appendix 3-1). Limited transport vectors together with poorer understanding of plankton distributions, may explain why there are fewer NIS in these groups, especially phytoplankton, many of which had poorly described native distributions, were often referred to as cosmopolitan and/or categorized as cryptogenic (Table 3-3, Appendix 3-1). All but one fish species, *Platichthys flesus* (noted to also be transported in ballast), were associated with either aquaculture, translocations or other less dominant vectors below such fisheries/ wild harvesting and aquarium trade (Figure 3-6). The absence of major vectors including, together with the fact that aquaculture is generally less developed in the Arctic, save for LMEs that remain largely ice-free (Hermanson and Troell 2012), may explain the lower proportions of NIS in the fish grouping.

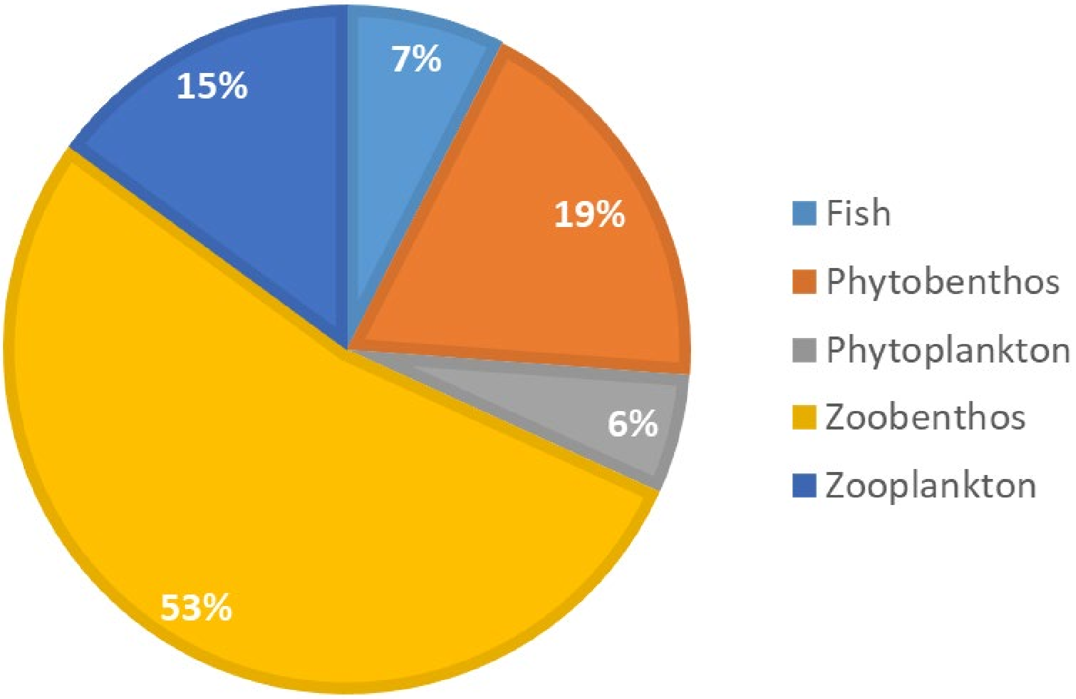


Figure 3-5. Proportion of all recorded NIS taxa in Arctic LMEs by broad ecological groupings. For details of species and lower taxa within different categories see Appendix 3-1

Transport vectors

Similar to other studies, NIS that have been introduced in Arctic LMEs are primarily associated with ship-related transport vectors (Figure 3-6). Ship ballast water was associated with the highest number of NIS (68 species), followed by biofouling (45 species), while 33 NIS had biofouling and ballast water as possible transport vectors. Aquaculture and translocation vectors were next in importance after ship-related vectors and associated with 45 species. Other associated transport vectors included marine debris, live seafood trade, fisheries and wild harvesting practices, canals and the aquarium trade. Although these have relatively low importance these may become a growing threat as northern regions warm and with increases in human populations in the Arctic. For example, as the ice retreats there will be greater connectivity with Arctic marine waters and the potential for increased problems with emerging vectors such as marine debris. Likewise, if more people and materials move north, greater quantities of debris are expected to end up in the ocean and provide floating platforms for species to spread.

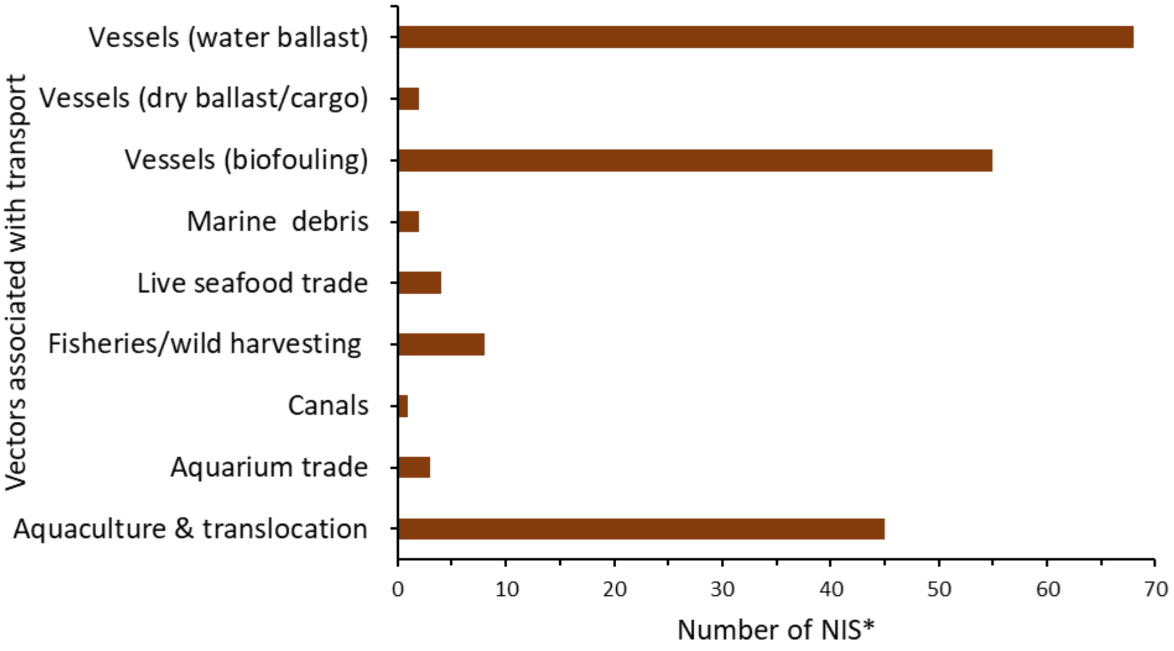


Figure 3-6. Number of introduced NIS in Arctic LMEs associated with various transport vectors. Individual species can be associated with more than one vector. For details of species associated with each transport vector and supporting references see [Appendix 3-1](#)

3.5 Range expansions and occasional records in new areas of the Arctic

There were a number of species (N=17) for which occasional recent records exist in Arctic regions outside of their normal range. However uncertainty exists as to whether they are established, particularly for planktonic species (Table 3-2). These may represent range extensions or be occasionally present due to storm events and currents which bring them north. This pattern was especially prevalent along the coast of Norway in the Norwegian Sea and/or Barents Sea LMEs (16 /17 species) where there are strong currents running from south to north (Mork 1981). This is less apparent in areas including the Canadian Eastern Arctic, where prevailing currents run north to south (Krumhansl et al. 2023). Of the 17 species, *Punctaria latifolia*, was the only one that was noted as a range expansion in an area not including coastal Norway; this species is considered to originate in the Northeast Pacific with a likely range extension to Alaska (Hines et al. 2000) and now occurs as far north as the North Bering - Chukchi LME (Table 3-2, [Appendix 3-2](#)).

3.6 Cryptogenic taxa

In our reviews we found 27 taxa that were cryptogenic within at least 1 Arctic LME and sometimes in several, but had not been identified as introduced in any Arctic LMEs (Table 3-3). Several of these were however listed as introduced in other parts of the globe and may therefore pose a risk or simply be overlooked as potential introductions due to a lack of information on native distributions. This could be particularly problematic in poorly surveyed areas such as more difficult to access regions of the Arctic including northern Alaska and Canada. Indeed the areas with the highest numbers of cryptogenic taxa were Hudson Bay Complex (7 species), Canada Eastern Arctic-West Greenland (5 species) and the North Bering - Chukchi Sea between Alaska and the Kamchatka Peninsula, Russia (6 species); other areas with relatively high numbers of cryptogenic tax included the East Bering Sea and the Barents Sea each with 4 cryptogenic species (Table 3-3). The most common cryptogenic taxa was annelids (8 species, all polychaetes), followed by bryozoans (3 species) and chlorophytes (3 species) (Appendix 3-3). Among the list of NIS within Arctic LMEs there were a number of species that although NIS to some areas of the Arctic were cryptogenic in others. These included *Aurelia limbata*, *Bottrylus schlosseri*, *Diplosoma listerianum*, *Melanothamnus harveyi*, *Mya arenaria*, *Teredo navalis* (Table 3-1).

3.7 Other considerations:

Based on the current review and consideration of detailed distributions for various species, we question the inclusion of several taxa on the earlier Chan et al. 2019 and EMODnet lists and have not included them in our updated lists for various reasons outlined below. These include two zooplankton species, *Temora turbinata* and *Clausocalanus furcatus,* both of which are listed as introduced in the Hudson Bay Complex and Canadian Eastern Arctic-West Greenland Arctic Large Marine Ecosystems (LMEs) based solely on metabarcoding detection. These warm water species are both well represented in global biodiversity/taxonomic databases (e.g., GBIF, OBIS, WoRMS) with clear tropical-temperate distributions and no known records anywhere near the Arctic. The detected sequences of these taxa were most likely from closely related common native Arctic/north Atlantic taxa (e.g., *Temora longicornis*) that were mismatched due to incomplete species sequence reference libraries. This is a common problem in metabarcoding studies, particularly in areas in the Arctic that are more poorly surveyed (Archambault et al. 2010). *Neodenticula seminae*, a diatom, was also listed as introduced in several Arctic LMEs (2 = Iceland Shelf, 3 = Greenland Sea East-Greenland, 4 = Norwegian Sea, 5 = Barents Sea, , 16 = Canadian East Arctic-West Greenland, 18 = Labrador-Newfoundland; Chan et al. 2019). However there has been much debate in the literature over the past decade regarding the origins and status of this species. While recent appearances in Arctic and North Atlantic waters (since the 1990s) could be linked to transarctic movement of ballast water, a recent comprehensive review indicates climate change and increased transport of Pacific waters into subarctic areas of the Labrador Sea and Nordic Seas as the most likely mechanism for its appearance in these areas (Matul and Kazarina 2020). Further, evaluation of surface sediments shows that it has had repeated appearances in the Arctic during past climate warming intervals and can therefore be considered a normal part of the fauna in these regions. Likewise, *Oithina similis*, a zooplankton species was described as an NIS to the Canadian Arctic and sub-Arctic Ports of Iqaluit, Churchill, Deception Bay and Steensby Inlet based on metabarcoding of bulk zooplankton samples (Brown et al. 2016) and listed as an introduced (Chan et al 2019, EMODnet 2025). This is unlikely given the broad distribution and common reports across Arctic regions including in the Canadian Arctic as indicated in biodiversity databases such as OBIS and GBIF where the species is well represented. *Oithina similis* is also reported as common in the Svalbard region and was not considered an NIS when it was detected through metabarcoding of sediment samples in this area of the Arctic (van den Heuvel-Greve et al. 2021)

4.8 Future directions:

An important component in ongoing efforts to improve knowledge of baseline biodiversity and for early detection of NIS is the establishment of programs for regular standardized monitoring, however this is challenging in the Arctic due to its vast size and limited access to many areas. Automated methods such as use of the Continuous Plankton Recorder (CPR) and collection of samples on vessels of opportunity have vastly improved our knowledge of baseline diversity in marine systems, particularly for planktonic taxa (e.g., Batten and Burkill 2010, Rosa et al. 2021). However, there are still limited opportunities for regular surveys in nearshore areas, which are at highest risk of invasions. Given travel costs and logistics of sampling in many Arctic regions, the most cost-effective approach to regular monitoring at high-risk sites needs to involve development of user-friendly, standardized sampling approaches and training/engagement at the local community level (e.g., Komangapik 2024).

The probability of early detection can be further strengthened through citizen-science, which is an ideal complement to standardized monitoring (e.g., Friewald et al. 2018) as suggested for European marine waters (e.g., Kousteni et al., 2022). Many of the NIS in other parts of the globe have been first detected by citizens and research has shown that citizen science can be an effective approach (Delaney et al. 2008; Gallo and Waitt 2011). In Arctic regions citizens, especially Indigenous peoples, typically spend time outdoors and on the water (e.g., hunting and fishing) on a more regular basis, giving them a greater likelihood of observing new and unusual species or changes in their environment. Being aware of these changes has been, and continues to be, essential to well-being and maintaining food security (Inuit Circumpolar Council-Alaska 2015).

Collection of environmental DNA also has great potential as a method that can easily be implemented for collection and that can provide species level information provided sequence reference libraries are reasonably comprehensive. These methods allow for relatively low cost sampling, including the collection of coastal water or sediment samples and have been successfully applied in community-based programs for some areas of the north (e.g., Pond Inlet, Nunavut; Lacoursiere et al 2018; Sevellec et al 2021). Such methods (eDNA, eRNA) may also be utilized to gain a better understanding of movement of organisms by vessels among ports (e.g., Grey et al. 2018.

Table 3-1. List of NIS introduced in at least one Arctic LME with status in each LME. Species are listed according to their status as Non-indigenous (NIS), Native (Nat), Cryptogenic (Cr), Range Expansions (RE), or Present with uncertain status (Pres). Unless otherwise noted species designations are based on morphological observations. Cases where detections have been made with metabarcoding only are noted in parentheses. Other cases that may lead to uncertainty in establishment of taxa such as observations in a single year and location (1 event), or uncertainty in identifications are also noted

Non indigenous species (NIS) Scientific name	1. Faroe Plateau	2. Iceland Shelf and Sea	3. Greenland Sea - East Greenland	4. Norwegian Sea	5. Barents Sea	6. Kara Sea	7. Laptev Sea	8. East Siberian Sea	9. East Bering Sea	10. Aleutian Islands	11. West Bering Sea	12. Northern Bering - Chukchi Sea	13. Central Arctic Ocean	14. Beaufort Sea	15. Canadian High Arctic - North Greenland	16. Canadian Eastern Arctic - Western Greenland	17. Hudson Bay Complex	18. Labrador - Newfoundland	Ballast	Fouling	Other
Acantholeberis curvirostris				NIS?	NIS?															x	
Acartia (Acartiura) clausi	Pres	Pres		Pres	NIS							Pres		Pres					x		
Acartia tonsa				NIS	NIS												NIS (metabarcoding)		x	x	
Alderia modesta					Nat									NIS (1 event)							
Alexandrium ostenfeldii	Nat	Nat	Pres		Pres							NIS			Pres	Pres			x		
Amphibalanus improvisus				NIS															x	x	with oysters
Arcuatula senhousia									NIS		Nat			NIS						x	
Ascidiella aspersa		NIS		Nat	Nat														x	x	aquaculture
Asparagopsis taxiformis					NIS (metabarcoding only)														x	x	aquaculture, aquarium, live seafood trade
Aurelia aurita/coerulea	Pres	Pres		Pres	Pres				Pres	Pres		Pres				Pres	Pres	Pres	x	x	
Aurelia limbata									Cr	Cr	Cr					NIS (metabarcoding only)	NIS		x	x	
Balanus trigonus																		NIS (not evident if established)		x	Floating debris
Bonnemaisonia hamifera	NIS	NIS		NIS															x	x	Shellfish
Botrylloides violaceus				NIS	NIS (metabarcoding only)															x	oysters, aquaculture
Botryllus schlosseri	Cr	NIS		Cr															x	x	oysters, aquaculture
Bougainvillia muscus		Pres		Nat													NIS (metabarcoding only)		x	x	Aquaculture & Fisheries
Calanus helgolandicus	Nat	Nat	Nat	Nat	RE, NIS (Svalbard)													Pres	x		
Cancer irroratus		NIS																Nat	x		
Caprella mutica				NIS	NIS														x	x	with oysters
Carcinus maenas		Nat		Nat														NIS	x	x	Sea chests, aquaculture, bait release, dry ballast.
Centropages hamatus	Nat	Nat		Nat	NIS? RE?	NIS? RE?						NIS? (1 record)						Nat		x	

Non indigenous species (NIS) Scientific name	1. Faroe Plateau	2. Iceland Shelf and Sea	3. Greenland Sea - East Greenland	4. Norwegian Sea	5. Barents Sea	6. Kara Sea	7. Laptev Sea	8. East Siberian Sea	9. East Bering Sea	10. Aleutian Islands	11. West Bering Sea	12. Northern Bering - Chukchi Sea	13. Central Arctic Ocean	14. Beaufort Sea	15. Canadian High Arctic - North Greenland	16. Canadian Eastern Arctic - Western Greenland	17. Hudson Bay Complex	18. Labrador - Newfound land	Ballast	Fouling	Other
Centropages typicus	Pres	Pres	Pres	Pres	RE											NIS (2 recent records in 2 separate years)		Pres	X	X	
Cerastoderma edule		NIS		Nat	Nat														X		
Chionoecetes opilio					NIS								Nat	Nat		Nat			X		live aquarium and restaurant trades
Ciona intestinalis		NIS		Nat												Pres	Pres			X	
Ciona robusta		NIS																		X	
Cladophora sericea				Pres	Pres				NIS			NIS		NIS				Pres	X	X	
Codium fragile subsp. fragile		NIS		NIS															X	X	Fishing gear, boat decks, fouled shellfish, aquaculture
Colpomenia peregrina				NIS					NIS										X	X	Shellfish (mainly oysters)
Coregonus peled				NIS?	NIS?																Translocation
Coscinodiscus wailesii				NIS															X		Possibly Crassostrea gigas
Crangon crangon		NIS		Nat	Nat														X		
Crassicorophium bonellii				Nat	Nat											NIS			X	X	
Craterolophus convolvulus					NIS (1 event)														X	X	
Crepidula fornicata				NIS (1 event)											NIS? (1 event)				X	X	Oysters
Dasysiphonia japonica				NIS															X	X	Oyster stocking
Desmarestia ligulata		NIS																			Aquaculture related
Didemnum vexillum				NIS																X	with oysters
Diplosoma listerianum		NIS		Cr																X	aquaculture
Dumontia contorta		Nat		Nat	Nat				NIS	NIS	NIS						NIS	NIS		X	
Ensis terranovensis		NIS																	X		
Esox lucius				NIS																	Translocation
Euphysa aurata					RE				NIS (1 event)								NIS (metabarcoding only)	Pres (1 event)	X	X	
Eurytemora affinis affinis																	NIS		X		Oyster transplants, fish stocking
Eurytemora americana		NIS			NIS							Pres		Pres			Pres		X		
Euterpina acutifrons					NIS (metabarcoding only)											NIS (metabarcoding only)	NIS (metabarcoding only)		X		

Non indigenous species (NIS) Scientific name	1. Faroe Plateau	2. Iceland Shelf and Sea	3. Greenland Sea - East Greenland	4. Norwegian Sea	5. Barents Sea	6. Kara Sea	7. Laptev Sea	8. East Siberian Sea	9. East Bering Sea	10. Aleutian Islands	11. West Bering Sea	12. Northern Bering-Chukchi Sea	13. Central Arctic Ocean	14. Beaufort Sea	15. Canadian High Arctic-North Greenland	16. Canadian Eastern Arctic-Western Greenland	17. Hudson Bay Complex	18. Labrador-Newfoundland	Ballast	Fouling	Other
Monocorophium insidiosum																NIS? (identity uncertain)			X	X	with oysters
Mya arenaria	NIS	NIS		NIS	NIS				Cr								NIS (metabarcoding only)		X		
Mytilus galloprovincialis		NIS		NIS	NIS											NIS (metabarcoding only)			X	X	
Oncorhynchus gorbuscha	NIS	NIS	NIS	NIS	NIS			RE	Nat	Nat	Nat	RE		RE		NIS	NIS	NIS			Fish stocking
Oncorhynchus mykiss	NIS	NIS		NIS	NIS					NIS	NIS										Fish stocking
Orchestia gammarellus		NIS		Nat	Nat																Dry ballast/cargo
Osmerus mordax									Pres			Pres		Pres		Pres (identity uncertain)	NIS				Fish translocations (deliberate and accidental)
Paralithodes camtschacticus				NIS	NIS				Nat	Nat	Nat	Nat									Aquaculture
Penilia avirostris				NIS															X		
Petricolaria pholadiformis				NIS														Nat			oysters, aquaculture
Platichthys flesus		NIS		RE?	NIS														X		
Polycarpa fibrosa					Nat											NIS			X		
Polydora websteri									NIS (1 event)							NIS	NIS (1 event)				shellfish aquaculture
Potamopyrgus antipodarum				NIS	NIS														X	X	
Praunus flexuosus		NIS		Nat															X		
Proboscidactyla flavicirrata									NIS										X	X	
Prorocentrum cordatum		NIS	NIS		NIS														X		
Pseudocalanus newmani		NIS (metabarcoding only)			NIS (metabarcoding only)				Nat?			Nat?		Nat?		NIS (1 event, metabarcoding)	NIS (1 event)		X		
Pyropia leucosticta	NIS	NIS																		X	Possibly with oysters
Pyropia njordii	Pres	NIS														Pres	Pres		X	X	aquaculture, aquarium, live seafood trade
Rhizogeton nudus		NIS	Pres (1 event)														Pres (1 event)		X	X	
Salmo salar						NIS			NIS												Aquaculture, Fisheries, Angling
Sargassum muticum				NIS															X	X	On Pacific Oysters
Schizoporella japonica				NIS																X	oysters, marine debris

Table 3-1 (cont'd)

Non indigenous species (NIS) Scientific name	1. Faroe Plateau	2. Iceland Shelf and Sea	3. Greenland Sea - East Greenland	4. Norwegian Sea	5. Barents Sea	6. Kara Sea	7. Laptev Sea	8. East Siberian Sea	9. East Bering Sea	10. Aleutian Islands	11. West Bering Sea	12. Northern Bering - Chukchi Sea	13. Central Arctic Ocean	14. Beaufort Sea	15. Canadian High Arctic - North Greenland	16. Canadian Eastern Arctic - Western Greenland	17. Hudson Bay Complex	18. Labrador - Newfoundland	Ballast	Fouling	Other
Schizoporella unicornis	Nat			Nat	NIS (metabarcoding only)															X	oysters
Scolelepis (Scolelepis) foliosa		Pres		NIS?	NIS?														X		
Scolelepis korsuni				Nat	Nat or RE; NIS? (possibly in Svalbard)														X		
Scolelepis tridentata				NIS	NIS														X		
Sosane wireni		Nat		Nat	Nat		Nat									NIS					
Spiophanes kroyeri			NIS?	NIS?	NIS?	Pres (NIS?)	Pres (NIS?)		Pres (NIS?)							NIS?			X		
Stephanopyxis turris		NIS																	X		
Styela clava				NIS					Nat	Nat										X	sea chests, oysters
Taurulus bubalis		NIS?																			
Teredo navalis	Cr	Cr	Cr	Cr					NIS							Cr		NIS	X	X	
Tricellaria inopinata				NIS																X	Oyster aquaculture
Tripos furca																NIS		NIS	X		
Tripos muelleri		Pres		Pres	Nat	Nat										NIS	NIS	NIS	X		
Ulonema rhizophorum			NIS																X	X	aquaculture, aquarium, live seafood trade
Ulva rigida		NIS																	X		
Urosalpinx cinerea				NIS												NIS				X	Oyster
Zostera japonica				NIS	NIS						Nat										oysters

Table 3-2 List of species noted to be expanding their range due to climate warming/ ocean currents and natural dispersal into Arctic LMEs with status in each LME. Species are listed according to their status as Native (Nat), Range Expansions (RE), or Present with uncertain status (Pres). Unless otherwise noted species designations are based on morphological observations.

Scientific name	1. Faroe Plateau	2. Iceland Shelf and Sea	3. Greenland Sea - East Greenland	4. Norwegian Sea	5. Barents Sea	6. Kara Sea	7. Laptev Sea	8. East Siberian Sea	9. East Bering Sea	10. Aleutian Islands	11. West Bering Sea	12. Northern Bering - Chukchi Sea	13. Central Arctic Ocean	14. Beaufort Sea	15. Canadian High Arctic - North Greenland	16. Canadian Eastern Arctic - Western Greenland	17. Hudson Bay Complex	18. Labrador - Newfoundland
Anomalocera patersonii		Nat		Nat	RE?											Pres		Pres
Metridia lucens		Pres	Pres	Pres	RE	Pres			Pres			Pres		Pres		Pres		
Neodenticula seminae		RE	RE	RE	RE				Nat	Nat	Nat					RE		RE
Punctaria latifolia		Pres		Pres	Pres							RE						
Spio decorata				RE (1 record)	RE (1 record)													
Spio symphyta				RE	RE													
Symphodus melops				RE														
Capulus ungaricus					RE													
Gammarus oceanicus		Nat		Nat	RE									Nat	Nat	Nat	Nat	Nat
Pleurotomella packardii				Nat	RE													
Porania pulvillus					RE													
Trivia arctica					RE													
Centropages hamatus	Nat	Nat		Nat	NIS? RE?	NIS? RE?						NIS? (1 record)						Nat
Calanus helgolandicus	Nat	Nat	Nat	Nat	RE, NIS (Svalbard)													Pres
Scolelepis korsuni				Nat	Nat or RE; NIS? (possibly in Svalbard)													

Table 3-3 List of species that are cryptogenic in at least one Arctic LME with status in each LME. Species are listed according to their status as Native (Nat), Cryptogenic (Cr), or Present with uncertain status (Pres). Unless otherwise noted species designations are based on morphological observations. Cases where detections have been made with metabarcoding only are noted in parentheses.

Scientific name	**1. Faroe Plateau**	**2. Iceland Shelf and Sea**	**3. Greenland Sea - East Greenland**	**4. Norwegian Sea**	**5. Barents Sea**	**6. Kara Sea**	**7. Laptev Sea**	**8. East Siberian Sea**	**9. East Bering Sea**	**10. Aleutian Islands**	**11. West Bering Sea**	**12. Northern Bering - Chukchi Sea**	**13. Central Arctic Ocean**	**14. Beaufort Sea**	**15. Canadian High Arctic - North Greenland**	**16. Canadian Eastern Arctic - Western Greenland**	**17. Hudson Bay Complex**	**18. Labrador - Newfoundland**
Aricidea hartmanii																		
Blidingia marginata		Pres								Cr				Pres				Pres
Bugula stolonifera																		Cr
Callopora craticula		Pres		Pres	Pres							Cr						
Capsosiphon fulvescens		Pres															Pres	Nat
Crassicorophium clarencense														Cr		Cr	Cr	
Cuspidella grandis (Mitrocomella polydiademata)				Nat	Pres	Pres						Cr				Pres		
Delamarea attenuata (Kjellman) Rosenvinge, 1893				Pres	Pres							Cr				Pres		
Dipolydora socialis				Cr	Cr											Cr	Cr	
Encentrum astridae				Cr													Cr (metabarcoding only)	
Heteromastus filiformis					Nat				Cr		Cr							
Heterostigma sp																	Cr	
Hymeniacidon perlevis		Cr	Cr			Pres	Pres										Pres (metabarcoding only)	
Jassa marmorata					Cr													
Kornmannia leptoderma non zostericola	Pres								Cr	Cr	Cr							
Lumbrineris zatsepini					Nat												Cr	
Obelia longissima					Pres	Pres	Pres		Cr?			Cr?		Cr?			Pres	
Onisimus sextoni																	Cr	
Owenia borealis				Nat	Nat											Cr		
Paraonides nordica					Pres	Pres	Pres							Pres	Pres	Cr	Cr	
Parasmittina trispinosa				Nat	Nat	Pres						Cr				Pres		
Pileolaria berkeleyana		Cr (NIS?)	Cr (NIS?)													Cr(NIS?)		
Polydora cornuta					Cr													
Protoperidinium saltans					Cr (possibly Nat)													
Pseudo-nitzchia obtusa				Cr														
Punctaria plantaginea	Pres	Pres		Pres	Pres							Cr						
Wildemania miniata (synonym: *Porphyra miniata*)	Pres	Pres		Pres	Pres				Cr							Pres	Pres	

4. Summary from previous and ongoing risk assessments

Literature review including an evaluation of existing and potential methods and tools that could be used for risk assessment in temperate and arctic waters.

Non-indigenous species (NIS) are of increasing concern around the world as global temperatures rise, and this is nowhere more true than in Arctic regions (Anisimov & Fitzharris 2007, Niemi et al. 2019, Rantanen et al. 2022). Thus, many organisms may be able to expand their ranges given this warming (Kortsch et al. 2012, Alcaraz et al. 2013, Jueterbock et al. 2013, Park et al. 2015, Oliver et al. 2018), suggesting that the functioning of the Arctic ecosystem may change in the near future (Alcaraz et al. 2013, Kortsch et al. 2015, Park et al. 2015, Goldsmit et al. 2024). There are many causes of range shifts, including shipping (Fuglestvedt et al. 2014, Cottier-Cook et al. 2024), making this an important pathway for the introduction of non-indigenous species (Ruiz et al. 2000, Carlton & Ruiz 2015, Ghosh & Rubly 2015, Saebi et al. 2020, Stirpe 2024).

4.1 Summary of the methodologies used in the assessments

A number of pathways have been involved in the arrival of non-indigenous species throughout the world, including shipping ballast water (Carlton et al. 2011, Bailey 2015), hull fouling (Sylvester et al. 2011, Lacoursière-Roussel et al. 2012), ballast sediments (Bailey et al. 2005, Simard et al. 2024), aquaculture (McKindsey et al. 2007, Padilla et al. 2011), the aquarium trade (Padilla & Williams 2004, Micael et al. 2023), and many others. In general, the largest groups of non-indigenous species are benthic – both phyto- and zoobenthos (Streftaris et al. 2005), although there are also many reports of many planktonic organisms as well, including zooplankton (Vidjak et al. 2019, Roohi et al. 2024), phytoplankton (Katsanevakis et al. 2014, Silkin et al. 2016), bacteria (Acosta et al. 2015, Aires et al. 2016), and viruses (Wommack & Colwell 2000, Lawrence 2008). There are also plans for monitoring non-indigenous species, including in Canada (Simard et al. 2013) and Norway (Husa et al. 2024).

There have been a limited number of risk assessments done for non-indigenous species for the Arctic (discussed further below) and the Antarctic (Lewis et al. 2003, Lewis et al. 2004, Lee & Chown 2009, Byrne et al. 2016, Hughes et al. 2020, Holland et al. 2021, Tittensor et al. 2021, Holland 2022). This involves In dealing with a large area where there are limited invasions predictive risk assessment tools that are important under conditions of changing climate and shipping activityRecently, the risk of marine invasive alien species has been assessed for various Arctic marine areas. Potential invasive species have recently been listed for the Barents Sea, Bering Sea, Canadian Arctic Seas, Iceland Shelf, West Greenland Shelf and East Greenland Shelf (Chan et al 2019; Droghini et al. 2020, Fernandez et al 2014, Goldsmit et al 2019, Goldsmit et al 2020, Gustavson et al 2020, Norwegian Biodiversity Information Center 2018; Reimer et al 2017; Skjoldal et al. 2009, Thorarinsdottir et al 2014; Verna et al. 2016) using a variety of risk assessment tools.

Species-specific:

Horizon scanning: The is the most common approach used to predict species of concern to the poles to date (Table 4.1), with most studies focused on species known to be in potential source regions and pathways. As pointed out by Thyrring et al. (2025), this type of work requires international collaborations as no country has the resources or capacity to undertake this task alone.

Types of questions asked/approaches for calculating risk:

Sandvik et al. (2020) used a question-based Risk Assessment (3 questions for invasion potential, 6 for ecological effects) and (Sandvik et al. 2019) thus evaluated the risk of 104 marine NIS to Norway. It was not possible to distinguish between Arctic and non-Arctic areas.

Goldsmit et al. (2021) used the Canadian Marine Invasive Screening Tool (CMIST) (8 questions on arrival and spread; 6 questions on impacts) (Drolet et al. 2015) to evaluate the risk of 31 NIS that were not already present in the Canadian Arctic. (A further 61 species were also evaluated but rejected from subsequent analyses as they were unable to tolerate cold or brackish/marine conditions; 8 others were not analyzed further as essential information needed for screening questions was missing.)

Goldsmit et al. (2019) modelled predicted areas in which 23 high risk non-indigenous species could survive today and in 2050 and 2100 under future global change scenarios. Globally, both benthic and planktonic organisms showed a future poleward shift in suitable habitat.

Reimer et al. (2017) used 33 questions related to a species' ability to arrive and establish in the area of interest, reliance on anthropogenic means for introduction, biology, and impacts and management considerations (the latter was not used in ranking). Their ranking system included methods to account for data limitations. They prioritized species for ranking based on their geographic proximity to the area of interest, the Bering Sea. They evaluated the risk of 46 species to the Bering Sea, although the species names are not provided, a list of the taxa is provided (annelids, bryozoans, cnidarians, arthropods, chordates, and mollusks).

Cottier-Cook et al. (2024) evaluated 114 species for Svalbard, Norway. Seven species were presented a high invasion risk and to potentially cause a significant negative impact on biodiversity and five species had the potential to have economic impacts. Decapods, Ascidians, and barnacles dominated the taxa identified.

4.2 Summary of previously completed risk assessments

All horizon scans identified at least a portion of species are likely to pose a risk currently (key taxa: Arthropods (all risk assessments (RAs), followed by mollusks, Chordates, and others.

Caveats of horizon scans

Horizon scans are useful to provide clues and develop watch lists. However, experimental information on survival and reproductive thresholds is frequently lacking, especially with respect to lower thresholds as near zero and sub-zero temperatures are difficult to maintain in experimental settings.

It can also be more challenging to apply at broad scales, e.g. in a region like the Arctic that has vastly different receiving habitats that must be treated independently (cannot all be painted with the same brush) when considering questions to address risk.

These tools also have limited utility to predict which species will pose a greater risk under future climate scenarios as they do not generally include information on potential vectors (but see Goldsmit et al. 2019).

Location (Reference)	# spp. Ranked*	High-risk spp.	High risk taxa
Svalbard, Norway (Thomassen et al. 2017)	25	3	**Arthropoda** (100%; decapods, amphipod)
Greenland (Gustavson et al. 2020)	8	3	**Arthropoda** (100%; decapods)
Hudson Bay, Canada (Goldsmit et al. 2021)	31	14	**Arthropoda** (35%; decapoda, other), **Macroalgae** (21%; multiple phyla) **Cnidaria** (14%), **Mollusca** (14%); **Bryozoa** (7%), **Annelida** (7%)
Canadian Arctic (Goldsmit et al. 2021; 2023)	23	23 (only high-relative risk species modeled using SDM - see table 4-2 below)	**Arthropoda** (17%; decapoda, other), **Macroalgae** (17%; multiple phyla) **Cnidaria** (4%), **Mollusca** (9%); **Bryozoa** (4%), **Ctenophora** (4%), **Tunicata** (21%), **Phytoplankton** (22%)
Bering Sea, Alaska (Reimer et al. 2017)	46	"Top 10"	**Arthropoda** (multiple), **Mollusca** (bivalves), **Bryozoa**, and **Chordata** (tunicate)
Norway, including Svalbard and Jan Mayen (Marine species; Sandvik et al. 2020)	104	17 severe Impact; 16 High Impact	**Macroalgae (41%), Arthropoda (29%),** Mollusca (12%), Cnidaria (6%), Annelida (6%), Tunicata (6%) **Arthropoda (38%),** Tunicata (13%), Mollusca (13%), Annelida (13%), Bryozoa (13%), Vertebrata (6%), Porifera (6%)
Norway (Artsdatabanken 2023)	?	?	?
NORION Consult (2024)	?	?	?
Vilizzi et al. 2021	Subset of 15 species of concern to Arctic using ASISK		Subset of those identified by Goldsmit et al. (2021)

Table 4-1. List of published species (from above RAs) identified as potential invasive alien species in Arctic marine waters.

Species Distribution Models (SDMs):

Although correlative Ecological Niche Models, ENM (species distribution models) come with their own set of caveats and challenges, they can also allow for more detailed projection of suitable habitats for species establishment across broad geographic areas and can be used in conjunction with global change models to consider future climate scenarios. The greatest caveat is perhaps that the outputs indicate where a given species would be able to establish if it were introduced in an area but in no way includes any vectors (but see Goldsmit et al. 2019), which may be many. In addition, a given species may only become established following multiple introduction events (Dlugosch &

Parker 2008, Britton & Gozlan 2013), making it difficult to predict the number of introduction events required for a given introduction event to be successful.

Arctic studies have focused on species of localized concern to Svalbard, Norway; Hudson Bay, Canada and the Bering Sea, Alaska, USA (Table X). These focused on species either found by sampling arriving vessels (Norway, Canada) or known to be in vessel source regions and deemed to be higher risk (based on previous horizon scans or known impacts elsewhere where they have been introduced).

Findings of all studies showed that at least some Arctic areas are already suitable for the establishment of a portion of high-risk AIS, suggesting that climatic barriers to invasion may already be absent in key areas of the Arctic. Under future scenarios, most assessed species were projected to encounter suitable habitat in the Arctic with an overall increase in areas suitable for establishment.

Location, Ecological Niche Model (ENM) projection (reference)	# Species assessed	# Species with Suitable polar habitat (present)	# Species with Suitable polar habitat in the future (2050 or 2100)
Svalbard, Norway, **Panarctic** (Ware et al. 2015)	8	1 in Svalbard, 3 in Panarctic	6 in Svalbard, 8 in Panarctic
Hudson Bay, Canada, **Panarctic** (Goldsmit et al. 2020)	23	16-20 in Pan Arctic	16-20 in Pan Arctic (but with increased suitable area)
Bering Sea, Alaska, **Local** (Reimer et al. 2017)	42	33-35	33-36 (increase suitable area, excluding North Bering Sea)

Table 4-2. List of published species (from above RAs) identified as potential invasive alien species in Arctic marine waters.

Shipping-Pathway based risk assessments

In addition to species-specific risk assessments, some countries have attempted to characterize risks of different ports and pathways in the Arctic based on ship traffic and ballast water release. For example in Canada, Canadian shipping risk assessments led by Sarah Bailey (Chan et al. 2012, Casas-Monroy et al. 2015; (Bailey et al. 2003, Bailey et al. 2005a, Bailey et al. 2005b, Wonham et al. 2005, Duggan et al. 2006, Briski et al. 2010, Chan et al. 2011, Bailey et al. 2012, Briski et al. 2012a, Briski et al. 2012b, Briski et al. 2013, Adams et al. 2014, Chan et al. 2014, Bailey 2015, Casas-Monroy et al. 2015, Chan et al. 2015, Chan et al. 2016, Chan et al. 2019, Chan et al. 2022, Fisheries and Oceans Canada 2022) have identified both ballast water and sediments (as did Simard et al. 2024) and hull fouling; assessment of Arctic Ballast Exchange zones close to Arctic ports in the event that ships are not able to exchange waters where they normally do or if a ship is forced to return and exchange ballast water due to too low of a salinity, for example) led by Kim Howland (Stewart et al. 2015, Goldsmit et al. 2019) and domestic Arctic pathways (Laget 2017, Tremblay 2017), Svalbard (Ware et al. 2014, 2016, Alsos et al. 2015).

Risk Assessments linking shipping and species-specific information:

Few risk assessments, with exception of Goldsmit et al. 2019, link shipping patterns to potential introductions of non-indigenous species. A new pan Arctic study will include modelling of 132 potential NIS of concern across all Arctic states in phase 2 of the project.

4.3 Summary

Although much work has concentrated on pathways world-wide, little has focused on Arctic regions, with some notable exceptions (e.g. Chan et al., 2011, 2012, 2013, 2014, 2015, 2016, 2019, 2022, Laget 2017, Tremblay 2017, Ware et al. 2016). In addition, little work has considered vectors in any of the analyses and, as such, there is little known of the importance of shipping in the potential introduction of non-indigenous species to this area. Moreover, the importance of shipping as a vector for the introduction of non-indigenous species is well known (e.g. Stirpe, 2024; Qi et al 2024). This is of particular importance as species distribution models only indicate the possibility of a species establishing given the current or predicted future conditions and do not consider vectors. In addition, little effort has focused on species that have been intentionally introduced (e.g. red king crab (*Paralithodes camtschaticus*), although its impact on the environment is quite well known (Falk-Petersen et al. 2011, Oug et al. 2011, Fuhrmann et al. 2017, Pedersen et al. 2018, Aune et al. 2022)

Given this, it is clear that the risk of the Arctic to non-indigenous species remains poorly understood. It is hoped that assembling the information pertaining to this subject in a single place will provide the impetus to expand on the ideas presented here.

5. Current regulation, including from IMO, on reducing the spreading and transport of non-indigenous species by ships

5.1 Introduction

Because of the changing climate and increased sea ice melt, some types of shipping have increased in recent years in the Arctic regions. This trend is expected to continue in the future (CAFF 2010). Several extractive industries (such as oil, gas, and mineral industries) are well-established and show a growing interest in the region as melting ice makes access to natural resources more feasible for extraction (CAFF 2010). While there are currently few known invasive non-indigenous species (NIS) in the Arctic, more are expected with climate change and increased human activity (CAFF 2013; Ware et al. 2014 and 2016; Bellard et al. 2016, Nordic Council of Ministers 2014, Kaiser & Kourantidou 2021).

In relation to Arctic marine species, ships are the dominant pathway for the arrival of NIS in marine systems through organism entrainment in ballast water and biofouling (Molnar, Gamboa, Revenga, & Spalding, 2008; Williams et al., 2013; Bailey et al., 2020). Studies of polar shipping operations have demonstrated that the external hull and ballast tanks of ships operating in ice-covered waters can support a wide variety of NIS organisms (Ware et al. 2014 and 2016, Chan et al. 2015 and 2019).

An analysis of the current trend and future invasion risk in large marine ecosystems of the Arctic shows that ships transferred the greatest number of aquatic non-native marine organisms (39%) to the Arctic, followed by natural spread (30%) and aquaculture activities (25%) (Chan et al. 2019 Ware et al. 2016).

According to the Convention on Biological Diversity, non-indigenous species are those species introduced outside their natural past or present distribution. Once introduced in a new area they can become 'invasive' and have impacts on local ecosystems. Such species may arrive in new areas through natural migration, but they are often introduced by human activities, such as maritime transport, aquaculture and canals.

Maritime transport accounts for the largest proportion — up to 49 % — of NIS (including invasive species) introductions in the seas around the EU since records began in 1949. Organisms are transported mainly through ballast water (up to 25.5 %) and hull fouling (up to 21.2 %), with other sources, such as dredging, angling and fishing equipment, accounting for a minor percentage (EEA 2019)

To combat the problem IMO has adopted the International Convention for the Control and Management of Ships’ Ballast Water and Sediments, 2004 (Ballast Water Management (BWM) Convention) and the Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species (Biofouling Guidelines 2023).

Concerns about invasive species introductions through ballast water were first brought to the attention of IMO's Marine Environment Protection Committee (MEPC) in the late 1980s (by Canada and Australia). In 1991 the MEPC adopted the International Guidelines for Preventing the Introduction of Unwanted Aquatic Organisms and Pathogens from Ships' Ballast Water and Sediment Discharges, while the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992, recognized the issue as a major international concern.

In November 1993, the IMO Assembly requested the MEPC and the Maritime Safety Committee (MSC) to keep the Guidelines under review with a view to developing internationally applicable, legally binding provisions. While continuing its work towards the development of an international treaty, the Organization adopted, in November 1997, the Guidelines for the Control and Management of Ships' Ballast Water to Minimize the Transfer of Harmful Aquatic Organisms and Pathogens. After more than 14 years of complex negotiations between IMO Member States, the BWM Convention was adopted by consensus at a Diplomatic Conference held at IMO Headquarters in London on 13 February 2004, and the Convention entered into force on 8 September 2017.

As of February 2025, the BWM Convention has 97 Parties representing 93.73% of the world's gross tonnage; out of the eight Arctic Countries, Iceland and the United States are not Parties to the BWM Convention. However, in line with IMO's fundamental 'no more favourable treatment' principle, Article 3 of the BWM Convention provides that "Ships of non-Parties to the Convention making international voyages can be inspected by port States which are Parties to the Convention and are expected to apply the requirements of the Convention as may be necessary to ensure that no more favourable treatment is given to these ships". In other words, in practice the provisions of the Convention apply equally to all ships, including those of non-Party flags, when they operate in the waters of Parties.

Regarding biofouling, the Biofouling Guidelines are intended to provide a globally consistent approach to the management of biofouling. The Biofouling Guidelines were originally adopted by the MEPC in July 2011 and were the result of three years of consultation between IMO Member States. Following a thorough review that also took three years, the revised Guidelines were adopted by the MEPC in July 2023.

5.2 IMO –Ballast Water Management Convention

Ballast water is pumped into, between, and out of ship ballast tanks to maintain safe draught, trim and stability during voyages and cargo operations. Ballast water may contain marine organisms and life cycle stages that can pass through the ship's ballast water intake and piping systems (i.e., viruses to vertebrates). Globally hundreds of invasions have already taken place often due to ballast water, sometimes with devastating consequences for the local ecosystem, the economy, and infrastructure.

To prevent the spread of harmful aquatic organisms from one region to another, the IMO has adopted the Ballast Water Management Convention (BWMC). The BWMC entered into force in September 2017 and establishes standards and procedures for the management and control of ships' ballast water and sediments.

The BWMC requires ships to manage their ballast water for minimizing the risk of introducing invasive aquatic species into coastal areas, including exchanging their ballast water or treating it using an approved ballast water management system. Initially, IMO introduced two standards (D-1 and D-2 standards). The D-1 standard required ships to exchange their ballast water in open seas, away from coastal waters, at least 50 nautical miles from land and in waters of at least 200 metres depth if 200 nautical miles and 200 metres depth are not practicable. D-1 is phased out and no longer an acceptable form of compliance with the Convention.

The D-2 standard is a performance standard that specifies the maximum concentration of viable organisms allowed to be discharged in the ballast water. Since the BWMC's entry into force, new ships must meet the D-2 standard upon entering service, while existing ships had to meet the D-1 standard as a transitional measure until a ship-specific compliance date, after which they are subject to the D-2 standard or can use other methods, such as discharging to port reception facilities. The latest possible date during this transition period was 8 September 2024, which means that as of this date all ships must meet the D-2 standard or any other accepted equivalent method. Currently, for most ships, this involves installing special equipment for treatment of the ballast water (ballast water management systems, BWMS).

Under the BWMC ships are required to be surveyed and certified by flag States and inspected by port State control officers. This includes, among many things, inspection of valid certificates, Ballast Water Record Books and the ship’s equipment and procedures. In case of clear grounds, a detailed inspection may be carried out, which may also entail sampling of the ballast water, and, if necessary, further corrective actions can be requested and stronger enforcement actions can follow.

All ships registered or flagged under a signatory state or operating in the jurisdiction of a signatory state presently, must comply with the D-2 standard as the D-1 standard is not longer a regulatory option .

In accordance with the D-2 Ballast Water Performance Standard, ships conducting ballast water management shall discharge:

i. less than 10 viable organisms per cubic metre greater than or equal to 50 micrometres in minimum dimension; and
ii. less than 10 viable organisms per millilitre less than 50 micrometres in minimum dimension and greater than or equal to 10 micrometres in minimum dimension; and
iii. discharge of the indicator microbes shall not exceed the specified concentrations:
    - Toxicogenic Vibrio cholerae with less than 1 colony forming unit (cfu) per 100 millilitres or less than 1 cfu per 1 gram (wet weight) zooplankton samples;
    - Escherichia coli less than 250 cfu per 100 millilitres;
    - Intestinal Enterococci less than 100 cfu per 100 millilitres.

Ballast water management systems (BWMS) must be approved by the Administration (flag state) in accordance with the BWMS Code. As of February 2025, almost 60 systems have been communicated to IMO by Member States as type-approved for treatment of ballast water under the BWMC’s current approval requirements that entered in effect in October 2019, namely the BWMS Code.

Resolution MEPC.300(72) includes the Code for Approval of Ballast Water Management Systems (BWMS Code). The Code is aimed to assess whether ballast water management systems meet the standard set out in regulation D-2 of the Convention. In addition, the Code is intended for manufacturers and ship-owners as a reference on the evaluation procedure that equipment will undergo, and the requirements placed on BWMS. The Code includes general requirements concerning the design, installation, performance, testing, environmental acceptability, technical procedures for evaluation and procedures for issuance of Type Approval Certificates of BWMS and reporting to the Organization.

5.3 National regulations for ballast water

The individual countries have the prerogative to enforce additional or stricter requirements for ships that operate in their waters.

In the case of Canada, the 2021 Ballast Water Regulations give effect to the BWM Convention in Canada, and based on science evidence, apply not only to ships on international service, but also those operating domestically within Canada. Furthermore, science shows that requiring ships to both exchange and treat ballast water provides additional protection for freshwater recipient ecosystems. Accordingly, Canada’s rules require that ships planning to release ballast water into Canadian freshwater areas first exchange the ballast water in addition to treating it through a

BWMS. Finally, Canada also requires that ships arriving in Canada provide a ballast water reporting form at least 96 hours in advance of entering waters under Canadian jurisdiction.

As a further example outside the BWMC, the United States has adopted the same discharge standards as that of regulation D-2 (though the counting method to validate organism count is different, such that in the US, any organisms found to be alive but unable to reproduce count as living, whereas in the IMO regime they count as non-viable), but its regulations also include additional requirements regarding a ship's operational procedures that go beyond the IMO's requirements:

- Clean ballast tanks regularly to remove sediments.
- Rinse anchors and chains when the anchor is retrieved.
- Remove fouling from the hull, piping, and tanks on a regular basis.
- Submit a report form 24 hours before calling at a US port.
- The EPA and VGP (Vessel General Permit) has additional requirements for periodical sampling as specified below:
    - Calibration of sensors
    - Sampling of biological indicators
    - Sampling of residual biocides

5.4 Updating of the Ballast Water Management Convention

IMO´s Marine Environment Protection Committee (MEPC) continuously reviews the BWMC. New guidelines, revisions of existing guidelines and amendments to regulations are approved or adopted at virtually every MEPC session.

In addition, in 2017 the MEPC established the experience-building phase (EBP) associated with the BWM Convention with the aim of monitoring and improving the Convention following its entry into force, including the development of a package of amendments to the Convention and/or its associated instruments in a holistic, evidence-based and systematic approach based on experience gained from its implementation. Following extensive data gathering and analysis, since 2022 the MEPC has initiated the convention review stage of the EBP, based on which a package of amendments to the Convention and its supporting instruments is expected to be approved and adopted over the course of the next few years. The endorsed list of provisions and instruments to be amended currently includes seven regulations and one appendix in the Annex to the Convention, several parts of the BWMS Code, three Guidelines, and six guidance documents, as well as four new guidance documents to be developed.

5.5 Compliance testing of ballast water management systems

Ships' ballast water and sediments are vectors that contribute to the unintentional spread of aquatic non-native species globally. Resolution MECP. 300(72), published in 2018, includes the Code for Approval of Ballast Water Management Systems (BWMS Code). The code is aimed to assess whether ballast water management systems meet the standard set out in regulation D-2 of the BWM Convention. Requirements of the BWM Convention include commissioning testing of ballast water management systems and compliance monitoring.

A recent study compiled treated ballast water samples collected and analysed from 228 ships during 2017–2023 (Outinen et al., 2024). Number of living organisms is counted and held up against the D-2 Ballast Water Performance Standard. The samples of ballast water were collected from the ballast discharge line or directly from the ballast tank. The main finding of the study is that nearly all ships were compliant with the ballast water performance standard for indicator microbes and organisms in the size class 10-50 µm. However, nearly half of all samples exceeded the limit for viable organisms ≥50 µm. The study suggests further research on the efficiency of filter mesh sizes and different filtration units associated with ballast water management systems, to improve mechanical removal of larger organisms ≥50 µm.

Challenging water quality refers to the ambient uptake of water, having, for example, high total suspended solids or turbidity or dissolved organic carbon originating from, for example, biological population fluctuations and chemical pollutants input from stormwater. Challenging water quality conditions may result in the ballast water management systems to be temporarily inoperable due to, for example, filter clogging or causing the system to operate outside its system design limitations. Ships operating in ports with challenging water quality may be unable to operate the ballast water management systems to maintain ballasting rates required for optimum cargo operations. Management of challenging water quality may include require the ship to bypass the BWMS while water quality is poor, exchanging then the ballast water before treating it on the way the next port of call (IMO, 2021; IMO, 2022b, 2022c).

5.6 Regulation for biofouling

Sea life such as algae, molluscs and other sessile organisms can travel from one place to another by attaching themselves to a ship's hull, hereafter referred to as hull fouling, slowing down the ship, increasing fuel consumption and, most importantly for this report, facilitating the movement and dissemination of NIS.

There have been very few assessments. Biofouling develops slowly on vessels, and its speed of growth is affected by type, and condition of the vessel’s anti-hull fouling coating, and the frequency of hull cleaning. Areas of a ship other than and hull, such as the anchor chain locker, seawater piping and other niche areas, may be more likely to be fouled due to prolonged contact with still water. fouling (GloFouling, 2019).

Biofouling on ship-submerged surfaces is considered to be a significant vector for transfer of invasive alien species between different regions (Briski et al 2012, Davidson et al. 2018, Ulman et al. 2019, Lacarella et al 2020). Some nations impose biosecurity measures such as biofouling compliance regulations for incoming ships (there are mandatory biofouling regulations in Australia, New Zealand and the US state of California (Davidson et al., 2018; Ministry for Primary Industries, 2018, GloFouling 2022).

In 2023, IMO developed non-binding Biofouling Guidelines to encourage the control and management of ships' biofouling to minimize the transfer of invasive aquatic species.

IMO’s 2023 Biofouling Guidelines represent a decisive step towards reducing the transfer of invasive aquatic species by ships and include recommendations in relation to the selection of anti-fouling systems, inspection of biofouling, cleaning and maintenance, record keeping, etc.

IMO’s Biofouling Guidelines are further supplemented by the IMO’s Guidance for minimizing the transfer of invasive aquatic species as biofouling (hull fouling) for recreational craft (MEPC.1/Circ.792). This Guidance is for use by all owners and operators of recreational craft less than 24 metres in length, which may constitute an important vector for the transfer of invasive aquatic species due to their large numbers and their operating profile that may make them particularly susceptible to biofouling as well as more likely to access remote areas.

In addition, IMO has implemented the GloFouling Partnerships project since 2018 with project completion anticipated in mid-2025. This project aims to build capacity in developing countries to implement the Biofouling Guidelines and protect marine ecosystems, and is complemented by the TESTTEST-Biofouling project which focuses on showcasing effective approaches to biofouling management by means of demonstration activities.

IMO forward-looking regulation

Following the finalization of the review of the 2011 Biofouling Guidelines and adoption of the 2023 Biofouling Guidelines, there is increasing expectation for the development of mandatory requirements for biofouling management. A formal proposal to that end was submitted to MEPC 83, which is being held in early April 2025. If this proposal gets approvedapprovedapproved2025, the pertinent process for the development of the new treaty or other instrument would be initiated, leading towards a possible Diplomatic Conference; such a process would normally take several years. (the timeframe in the submitted proposal indicates a possible Diplomatic Conference in 2030)

GEF-UNDP-IMO GloFouling Partnerships Project and GIA for Marine Biosafety, 2022, Compilation and Comparative Analysis of Existing and Emerging Regulations, Standards and Practices Related to Ships' Biofouling Management.

6. Invasive Species and Shipping

As PAME has shown there has been an increase in the number of ships in the Arctic and in the distance they navigate. PAME’s database on Arctic Shipping, ASTD, has resulted in PAME producing a report on this increase which was updated in January 2025. The increase is due to several factors, including increased resource extraction, growing popularity of cruise tourism in the Arctic and diminishing sea ice.

An increase in shipping can result in increased danger of invasive species entering the Arctic. A detailed analysis of worldwide shipping to the Arctic is needed to identify from which regions, countries and ports ships enter the Arctic from. This could help shed light on where ships come from and were existing or potential invasive species origin.

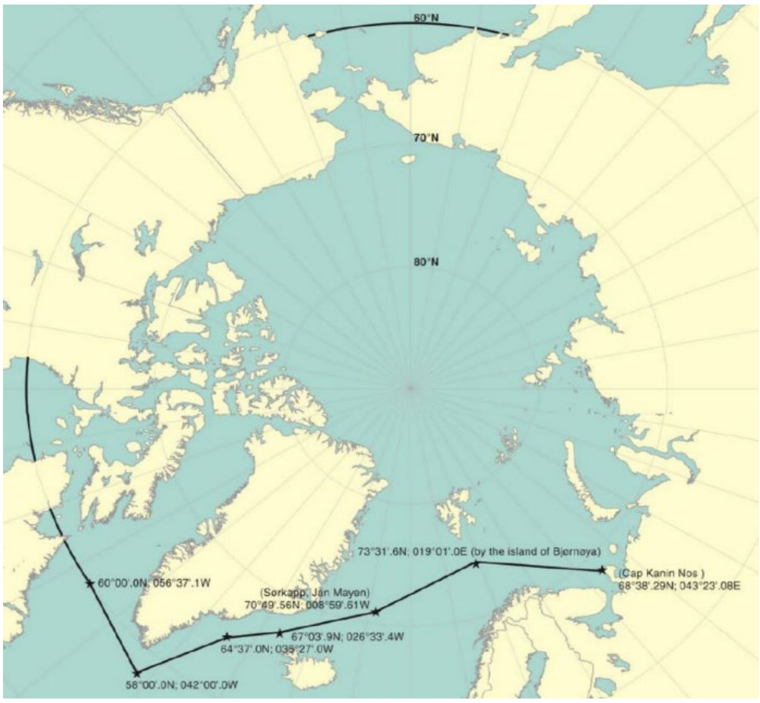
PAME’s report uses the geographic definition of the Arctic contained in the IMO’s International Code for Ships Operating in Polar Waters (Polar Code). The Polar Code defines Arctic waters as the area in figure 6-1

Most larger ships that operate in this area must comply with the Polar Code. The Polar Code covers the full range of design, construction, equipment, operational, training, search and rescue and environmental protection matters relevant to ships operating in the inhospitable waters of the Arctic.

INVASIVE SPECIES AND SHIPPING

Ships can transport invasive species in **a few key ways:**

- Ballast water: Ships often take on ballast water to stabilize them when they are empty or partially loaded. This water can contain a variety of organisms, including plankton, larvae, and even small fish. When the ship reaches its destination, the ballast water is discharged, potentially introducing these organisms to a new environment.
- Hull fouling: Organisms like barnacles, mussels, and algae can attach themselves to the hull of a ship. These organisms can then be transported long distances and introduced to new areas where they can establish themselves and become invasive.
- Cargo: Some invasive species can be transported in or on cargo.

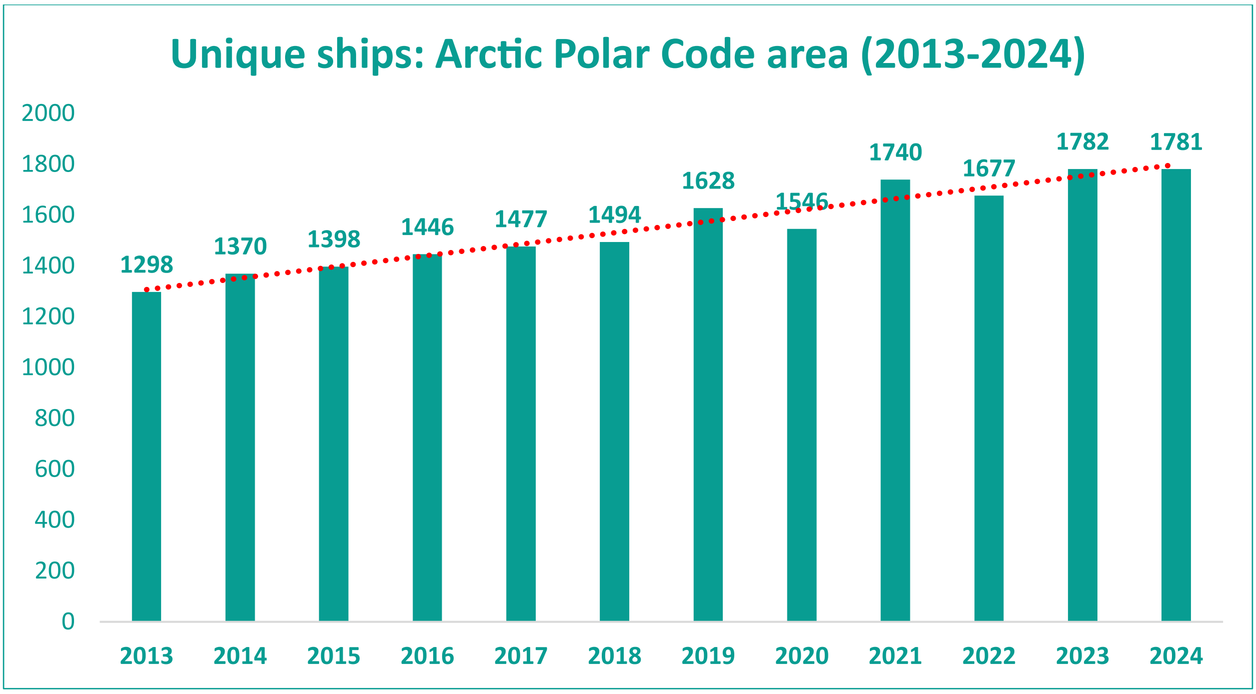


Figurer 6-1 The Polar Code defines area of Arctic waters

6.1 Increase in ships in the Arctic and distance sailed

The number of unique ships entering the Arctic Polar Code area from 2013 to 2024 increased by 37%, around 500 ships (Figure 6-2). Unique ships refer to each ship only counted once, although it might enter the area multiple times over each year. The number of unique ships entering the Arctic Polar Code area is generally highest in the month of September, when Arctic sea ice is typically at its lowest extent. For example, in September 2024, 1064 ships entered the Polar Code area, out of the total 1781 ships that entered the entire year showing that many of these ships entered the area in more than one month of the year.

As the graph below shows (Figure 6-2), there has been a steady increase in the number of ships entering the Polar Code Area, rising from almost 1300 ships in 2013 to almost 1800 in 2024. The increase is of around 37% in these 11 years.



Figurer 6.2 Number of ships entering the Polar Code Area 2013-2024.

The same story can be seen when it comes to sailed distance (Figure 6-3). Comparing 2013 to 2024, the distance sailed by ships in the Arctic Polar Code Area increased from 6.1 million to 12.7 million nautical miles. The distance sailed represents the aggregate sailed for each ship in nautical miles.

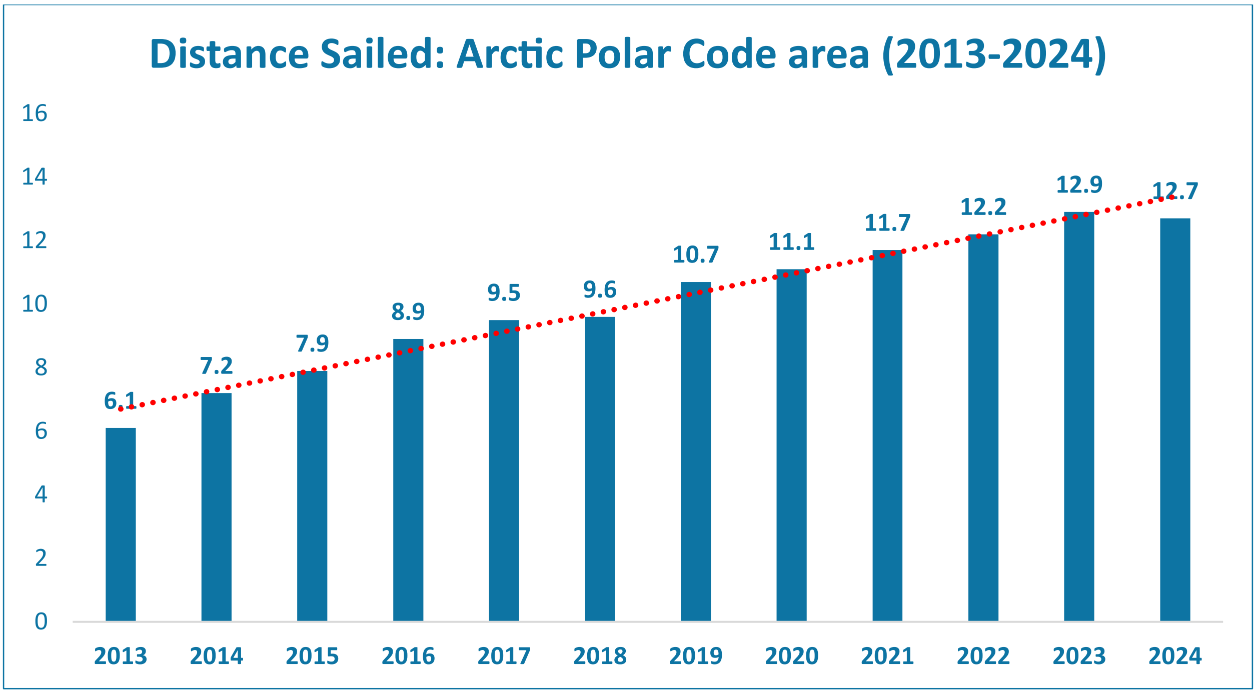


Figure 6-3. Distance sailed by ships in the Arctic Polar Code Area 2013-2024

Fishing vessels are the most common type of ship in the Arctic Polar Code Area, representing over one-third of all ships (Table 6-1). The second most common ship type is general cargo ships. Between 2013 and 2024, there was an increase in the number of ships of each ship type in the Arctic Polar Code Area apart from oil tankers and research vessels.

Table 6-1. Type of ship in the Arctic Polar Code Area2013-2024.

Unique Ships in the Arctic Polar Code area – By type

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Ro-Ro cargo ships	6	8	12	6	7	6	6	6	9	9	8	8
Dredging vessels	11	14	12	12	4	3	7	19	16	6	9	11
Other service offshore vessels	10	16	12	8	13	10	10	12	13	8	11	11
Container ships	12	6	8	8	12	9	6	11	7	8	13	15
Yachts	7	9	9	12	8	9	14	5	10	21	19	26
Passenger ships	10	14	12	17	14	17	17	9	13	15	20	18
Crude oil tankers	12	10	9	14	17	19	26	24	18	16	31	46
Gas tankers	1	0	1	0	4	13	24	26	26	26	31	43
Offshore supply ships	25	52	41	25	36	45	45	51	52	31	44	38
Chemical tankers	42	45	54	50	50	60	60	53	47	55	53	58
Oil product tankers	62	70	58	47	58	53	55	55	58	54	53	54

Research vessels	62	70	59	58	60	53	48	47	50	51	54	56
Refrigerated cargo ships	71	68	77	76	92	81	81	89	83	81	90	89
Cruise ships	58	58	55	63	63	65	73	7	12	78	96	87
Other activities	55	65	60	72	67	67	67	69	85	81	104	98
Bulk carriers	71	66	78	78	75	86	106	98	96	114	119	111
Towing / Pushing vessels	76	71	87	79	79	80	93	97	119	104	121	133
General cargo ships	141	160	164	199	182	155	174	187	219	183	181	187
Fishing vessels	566	568	590	622	636	663	716	681	807	736	725	692

6.2 Shipping in the Arctic Large Marine Ecosystems (LMEs)

The ship traffic in the Large Marine Ecosystems in the Arctic has increased in recent years, following the trend from the Polar Code Area. As the table below shows (Table 6-2, Figure 6-4 and Figure 6-5) the number of ships in each of the 18 LME's increased, apart from the Hudson Bay where it was the same in 2013 and 2024. The increase ranges from a minimal 8% to a huge increase of 314% in the Labrador Sea LME. There is also a large increase in the East Bering Sea LME, the reason for the increase is the Mary River Many as highlighted in PAME's Report on the increase of Arctic shipping.

The analysis shows that the Norwegian Sea LME has the most ships and the only one with over 3000 unique ships in 2024. Three LME's had over 2000 unique ships and four below 100. This shows how vastly different ship traffic is between the LME's.

The same can be said of the sailed distance. There is a huge gap between the over 16.700.000 nautical miles in the Barents Sea LME and the below 10.000 in the Northern Canadian Archipelago LME. The Barents Sea is followed by the Norwegian Sea LME with over 14.500.000nm.

Table 6-2. The number of ships and distance sailed in each of the 18 LME's 2013 and 2024.

Large Marine Ecosystem in the Arctic: Ship traffic trend from 2013 to 2024							
LME		***Number of ships***			***Distance Sailed (nm)***		
Nr.	**Name**	**2013**	**2024**	***Change***	**2013**	**2024**	***Change***
1	Fareo Plateau LME	736	1,105	*50%*	1,029,575	1,557,606	*51%*
2	Iceland Shelf and Sea LME	674	849	*26%*	2,546,783	3,812,832	*50%*
3	Greenland Sea LME	144	238	*65%*	238,959	482,935	*102%*
4	Norwegian Sea LME	3,017	3,246	*8%*	12,780,427	14,547,644	*14%*
5	Barents Sea LME	2,243	2,565	*14%*	11,982,304	16,724,419	*40%*
6	Kara Sea LME	196	373	*90%*	528,738	1,861,256	*252%*
7	Laptev Sea LME	104	203	*95%*	193,290	391,008	*102%*
8	East Siberian Sea LME	94	194	*106%*	97,997	210,052	*114%*
9	East Bering Sea LME	632	2,169	*243%*	1,151,716	3,853,213	*235%*
10	Aleutian Islands LME	301	545	*81%*	199.329	269.081	*35%*
11	West Bering Sea LME	1,972	2,826	*43%*	3,338,891	5,614,587	*68%*
12	Chukchi Sea LME	265	509	*92%*	455,589	1,001,760	*120%*

13	Central Arctic LME	10	27	*170%*	10,381	42,522	*310%*
14	Beaufort Sea LME	47	72	*53%*	69,601	106,886	*54%*
15	Northern Canadian Archipelago LME	4	11	*175%*	1,200	9,637	*703%*
16	Baffin Bay LME	149	299	*101%*	896,317	1,788,509	*100%*
17	Hudson Bay LME	64	64	*0%*	154,560	185,344	*20%*
18	Labrador Sea LME	100	414	*314%*	298,306	531,886	*78%*

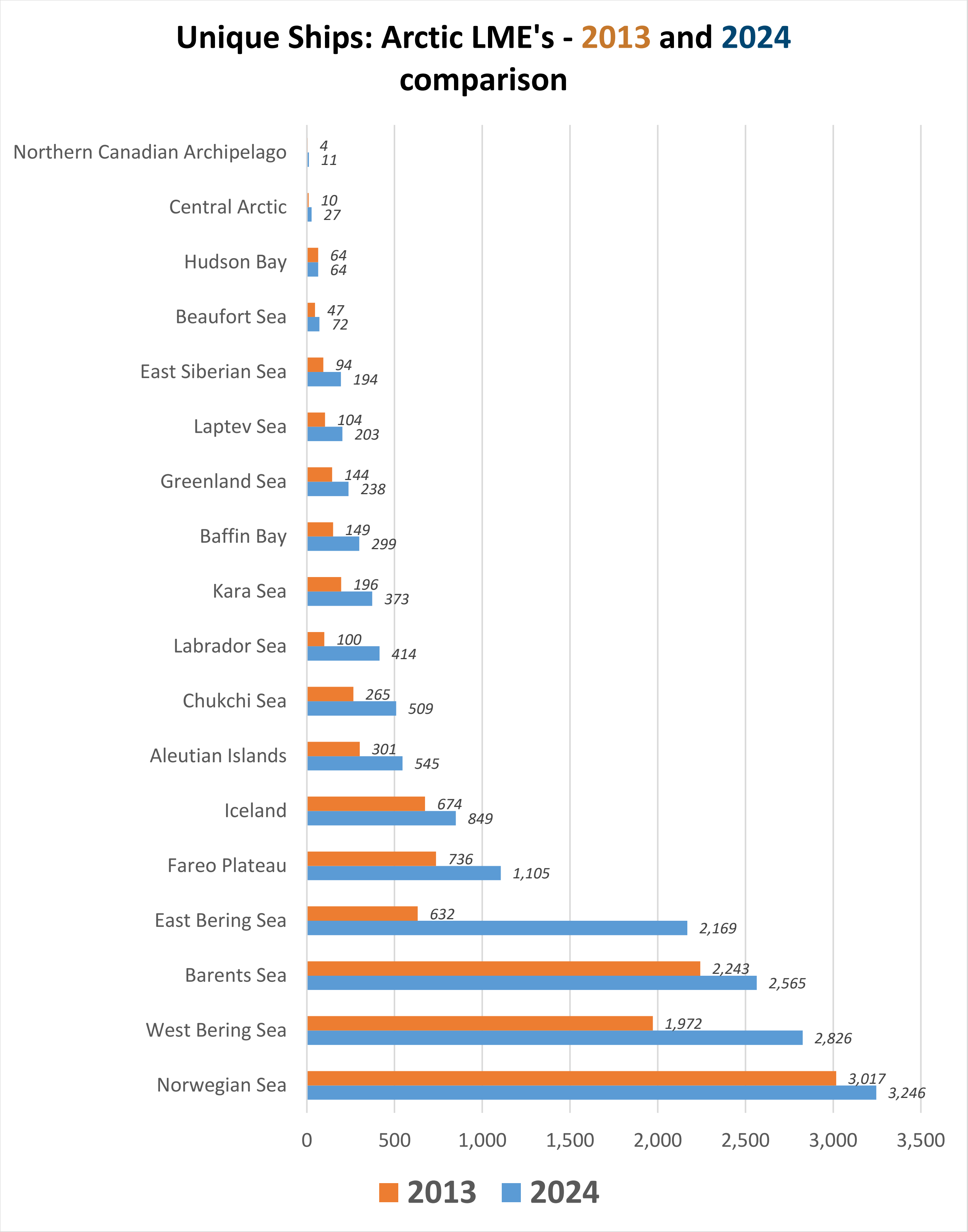


Figure 6-4 The number of ships and distance sailed in each of the 18 LME's in 2013 and 2024

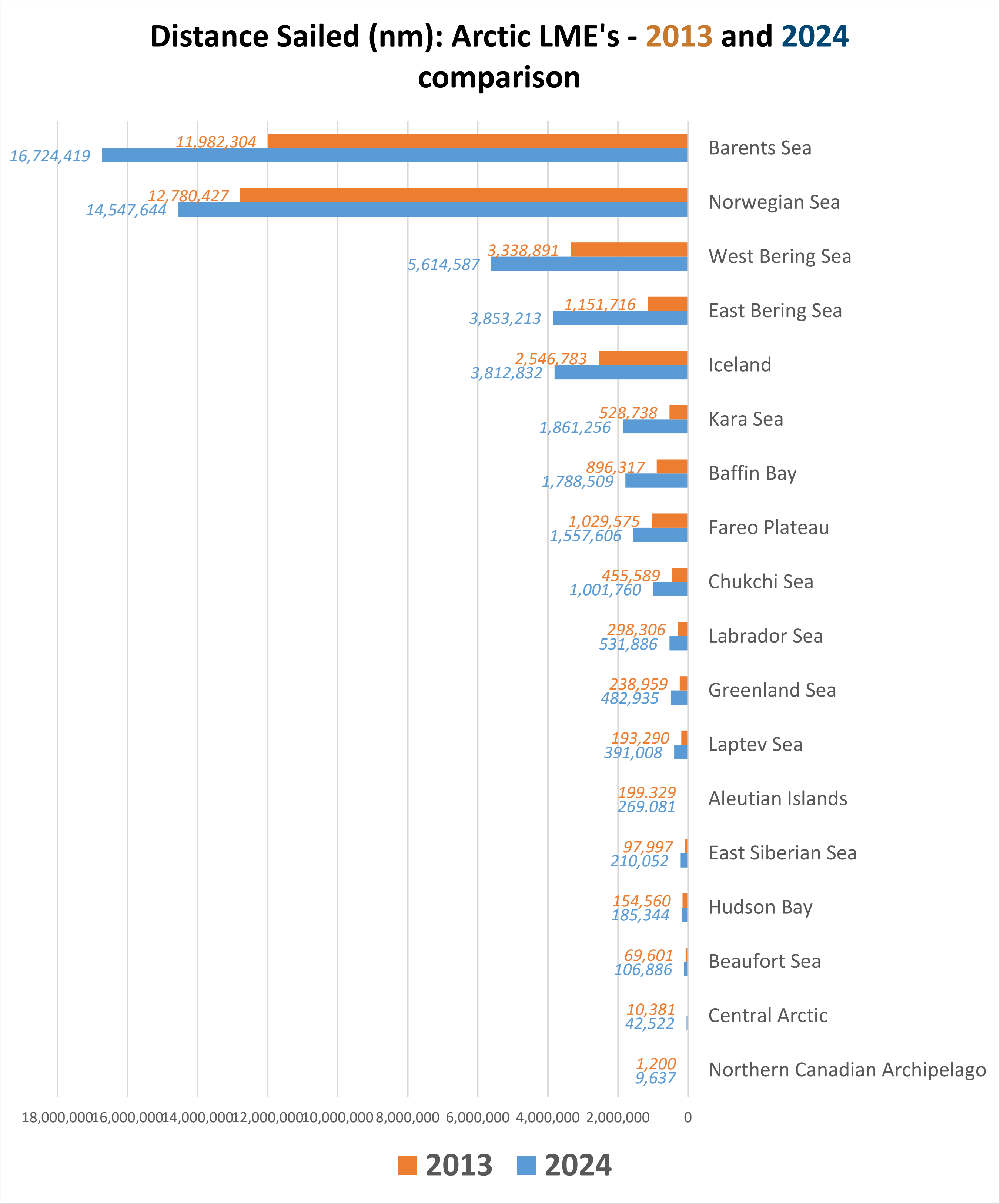


Figure 6-5. *Distance sailed in each of the 18 LME's in 2013 and 2024.*

6.3 AIS-satellite data and origins of Arctic ships

Data from PAME's Arctic Ship Traffic Data (ASTD) contains satellite data provided by the United States and Norway. The data collected is from a specific geographic region, designed to incorporate areas such as the Large Marine Ecosystems in the Arctic, the Exclusive Economic Zones of the Arctic States and the Arctic Polar Code area.

Through the analysis of satellite AIS data, the Norwegian Coastal Administration has established connections or voyages in- and between different Large Marine Ecosystems (LMEs). A key component of this analysis involves identifying the last LME where each ship made port calls. It is important to note that multiple ships on different voyages may traverse LMEs without making port calls; these instances are not included in the voyage count.

In total, 112,019 voyages were recorded in 2022 and 2023 by the 1,092 ships over 1,000 GT observed in the Polar Code area in 2023. The dataset reveals that the most frequent voyages occur within single LMEs with 78,032 voyages. 12,348 voyages are between Arctic LMEs and 11,296 voyages are between LMEs outside the Arctic and Arctic LMEs. In addition, the appr. 1,000 ships observed in the Polar Code Area in 2023 also produce 10,343 voyages between Non-Arctic LMEs in the two-year period.

A closer examination of the 112,000 voyages also highlights the asymmetrical distribution of voyages among individual ships. Ships observed in the Polar Code area in 2023 completed up to 1,084 voyages over the two years of 2022 and 2023. Notably, the single or individual ship with the highest number of voyages was a passenger ship operating on the West Coast of Greenland. The other ships in the top five for the number of voyages included a chemical/oil product tanker (Greenland), a passenger/cruise ship (Norway), a research vessel (Norway), and a container ship (Greenland).

Since voyages covering short distances within each Arctic LME do not serve the same analytical purpose for risk assessment concerning alien species, we will now focus on voyages between different Arctic LMEs and those between LMEs outside the Arctic and Arctic LMEs.

6.4 Voyages between Arctic LMEs and non-Arctic LMEs

In the context of voyages to Arctic Large Marine Ecosystems (LMEs) from non-Arctic LMEs, the West Bering Sea LME stands out as the most frequented, recording 1,590 voyages that made port calls within this region. Most of these voyages began in the Sea of Okhotsk LME (665) and the Oyashio Current LME (440) while 406 voyages came from the Sea of Japan LME.

The Kara Sea ranks as the second-largest Arctic LME concerning voyages from non-Arctic LMEs. In 2022 and 2023, there were 849 voyages originating from non-Arctic LMEs, with notable starting locations being the North Sea LME (523) and Celtic-Biscay Shelf LME (260).

The Barents Sea LME holds the third position for voyages from non-Arctic LMEs, where 785 ships arrived at various ports in 2022 and 2023. Of these, 449 voyages originated from ports in the North Sea LME, 151 voyages began in ports in the Baltic Sea LME.

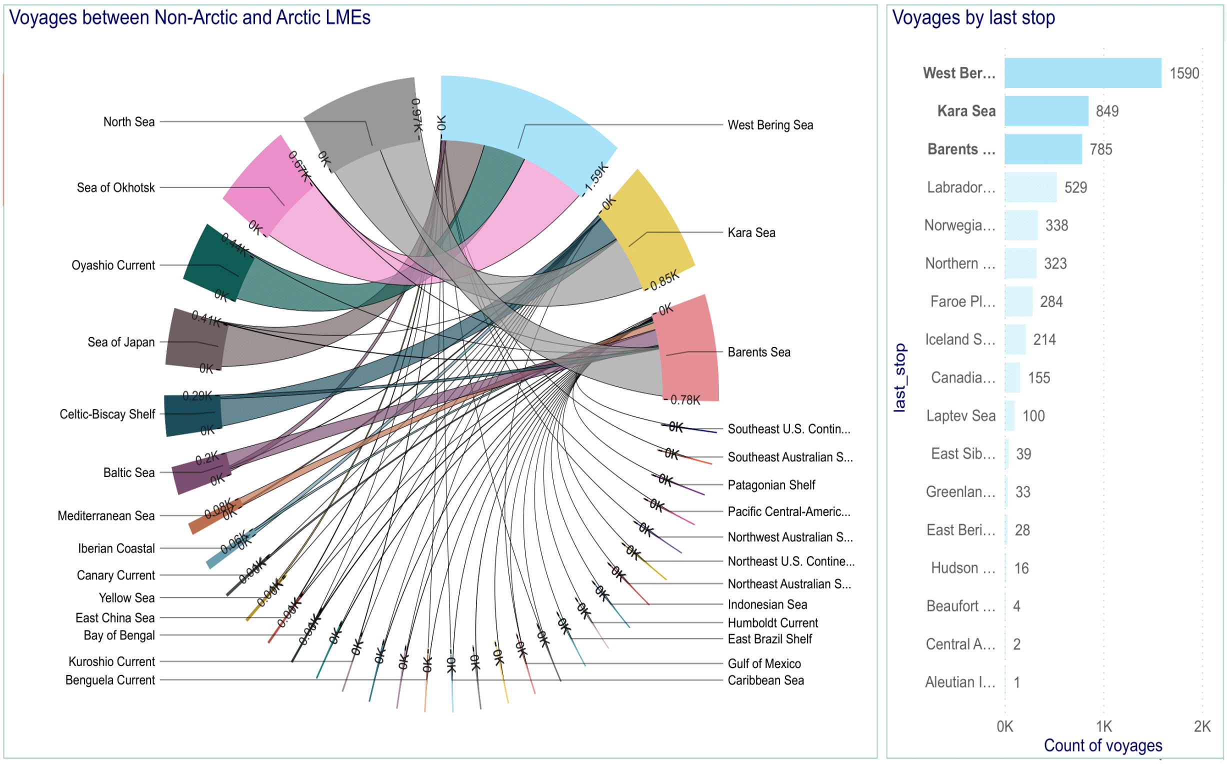


Figure 6-6. Chord diagram voyages between Non-Arctic and Arctic LMEs (left) and Bar chart for last stop/destination (right)

6.5 Intra-Arctic voyages across different LMEs

In terms of intra-Arctic voyages, those occurring between Arctic LMEs, the Barents Sea LME received the highest number of voyages in 2022 and 2023, totalling 3,461. The chord diagram illustrates that a significant portion of these voyages originated from the Kara Sea LME (2,376), followed by the Norwegian Sea LME (766).

The Kara Sea LME ranks second in terms of the number of voyages from other Arctic LMEs, with 2,552 recorded between 2022 and 2023. Most of these voyages originated from ports in the Barents Sea LME, particularly Russian ports, highlighting the significant traffic flow towards Russian destinations in the region.

The Norwegian Sea LME occupies the third position in terms of intra-Arctic voyages, reporting 1,517 recorded journeys. A large proportion of destinations within the Norwegian Sea LME are linked to voyages originating from the Barents Sea LME (1,159 voyages).

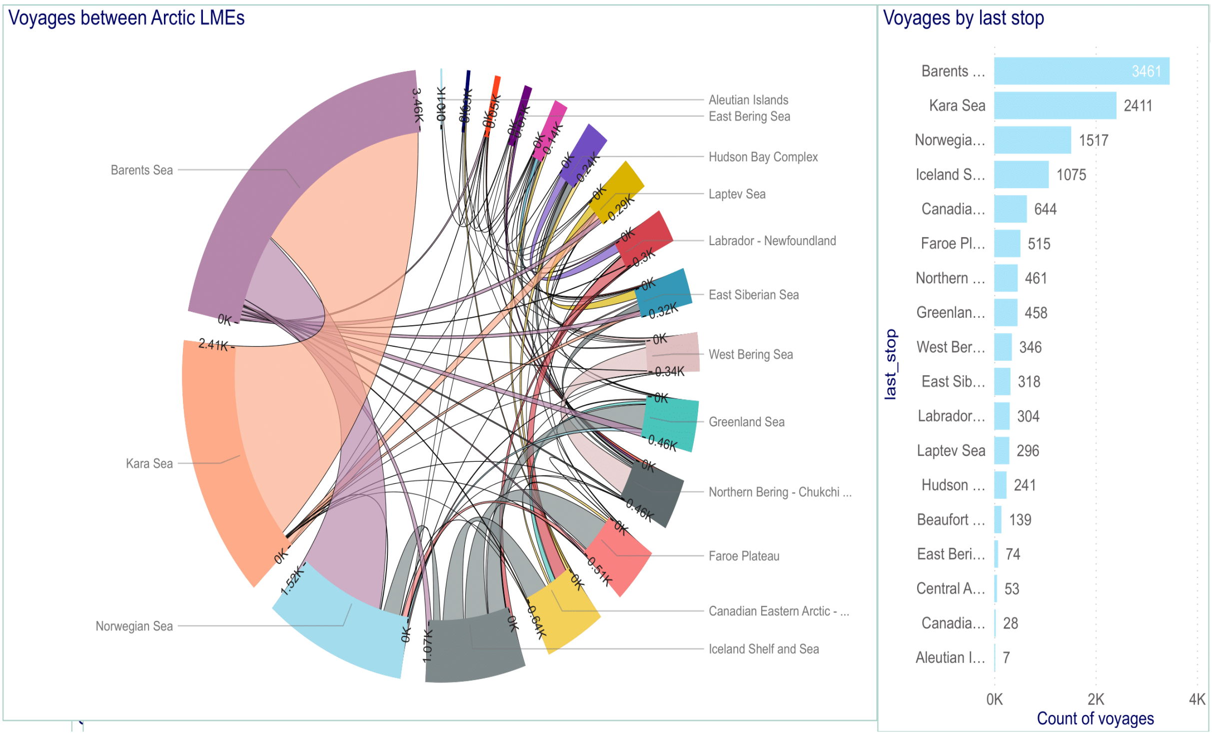


Figure 6-7: Chord diagram showing voyages between Arctic LMEs (left) and Bar chart for last stop/destinanations (right)

Summary

In summary, the dynamics of intra-Arctic and inter-Arctic connections with the rest of the world underscore the complexity of maritime interactions, as illustrated by the approximately 1,000 ships identified in the Polar Code Area in 2023. These voyages exemplify significant maritime connectivity across Large Marine Ecosystems (LMEs) globally and present a potential risk for the introduction of invasive species into the Arctic ecosystem.

7. Arctic Marine Ecosystems and impact of climate changes in the different Arctic regions today and in a future scenario for year 2100

Despite extreme environmental conditions, Arctic marine ecosystems support a great diversity of life, including species found nowhere else on Earth. The Arctic marine environment supports over 5,000 animal species and over 2,000 species of algae and tens of thousands of microbes (Meltofte 2013). The unique characteristics of Arctic marine ecosystems are critical to global diversity, providing unique habitat for arctic species such as polar bear, narwal, many marine mammal species and bird colonies. Feeding grounds in the Arctic support both non-migratory and migratory species, and are therefore necessary for the survival of species endemic to the Arctic, as well as species migrating to the Arctic (during summer) from far away subtropical and tropical ecosystems. A vast array of commercial interests also depends on the Arctic, which hosts harvested species, such as fish, shrimp, mussels and crabs that constitute a vital source of protein for people around the world.

This chapter is, with a few exemptions, based on literature developed as part of other Arctic Council work, including within the Arctic Monitoring and Assessment Programme (AMAP), Conservation of Arctic Flora and Fauna (CAFF) as well as in Protection of Arctic Marine Environment (PAME), with the main purpose to link this report to other Arctic Council initiatives.

7.1 The Arctic marine ecosystems and features of importance to new species

To assess the possibility for establishment of potentially new species entering the Arctic marine environment, it is important to understand that the processes that influence Arctic marine ecosystems differ from other ocean environments. The marine Arctic is characterized by a large variability in environmental conditions, including seasonal extremes in photoperiod, cold temperatures, river runoff and ice conditions (CAFF 2017). All these factors constitute key forcing to Arctic marine ecosystem functioning and biodiversity.

The reduced light during winter months limits primary production, which then changes dramatically when the spring sun returns. Large areas of sea ice also characterize Arctic marine areas and appear seasonally over extensive shelves and more permanently as a large central area of multi-year pack ice. However, as described in 8.3, there has been a substantial decrease in sea-ice extent and area during the last three decades (Skjoldal 2022). Marine areas in the Arctic are often highly stratified because freshwater flows from rivers and melting sea ice make the upper layer of the ocean less salty compared with other oceans (CAFF 2017).

Arctic marine biodiversity and ecosystem processes are fundamentally linked to the main hydrographic features of the Arctic Ocean with the exchange of water and associated physical, chemical and biological properties. This includes the connections to the Pacific and Atlantic Ocean, strong stratification and critical influence of the large continental shelves and riverine input. Relatively warm and salty Atlantic water enters the Arctic through the eastern part of Fram Strait and less salty Pacific water enters through the Bering Strait, while the western Fram Strait acts as the major outflow from the Arctic Ocean. Arctic marine biodiversity is reliant on these dynamic patterns of ocean conditions creating an inherent biodiversity associated with the presence and circulation of Pacific and Atlantic water masses (Eamer et al.2013, Meltofte 2013; CAFF 2017). Other related physical features, including polynyas, leads, marginal ice zones and upwelling zones, also have major impacts on Arctic marine ecosystems (CAFF 2017). Polynyas and leads play an important role in the productivity and biodiversity of Arctic marine ecosystems. Polynyas are areas of recurrent open water amidst ice-cover and are distinguished from leads by being broad openings reoccurring at the same locations rather than long, narrow fractures of much more variable appearance (Figure 7-1).

Most Arctic marine species are highly seasonal and specialized when it comes to feeding, reproduction and migration patterns, so the timing and duration of sea ice retreat and ice-free ocean determine when, where and for how long species can accomplish activities that are vital to survival (CAFF 2017).

Figure 7.1 Polynyas, landfast and mobile ice (After CAFF 2017)

Zooplankton represent key links between primary producers and middle trophic levels (e.g., fish and seabirds), with *Calanus* copepods and pelagic or ice-associated amphipods as the most important groups in the Arctic for lipid production and transfer of energy to higher trophic levels as well as to the benthos though vertical transport (CAFF 2017).

Large ocean currents play a major role in global weather patterns and are also affecting ocean life. The Arctic plays a key role in the global climate system through the production of North Atlantic Deep Water, which helps drive the circulation of the world's oceans (Meltofte 2013). The currents in the Arctic marine areas also influence the distribution of marine organisms. Simplified Arctic Ocean currents and water mass distribution are illustrated in figure 4-3.

Other factors of importance in relation to establishment of new marine species are salinity, temperature, light condition and levels of nutrients in the waters. In this regard it should be mentioned that nutrient-rich areas can be of special importance as they stimulate growth of algae and serve as an important feeding basis of invertebrates, fish, seabirds, marine mammals. Nutrient-rich waters can be found in areas of sea-ice melt, ice edges, upwelling zones and throughout nutrient-rich currents. (Meltofte et al 2013). Finally, it should be mentioned that sea ice cover plays a major role in Arctic marine ecosystems, affecting seasonal cycles of light availability, water temperature, levels of nutrients and the flow of energy and nutrients through the food web, as well as serving as a habitat for several organisms.

7.2 The Arctic Large Marine Ecosystems (LME)

Large Marine Ecosystems (LMEs) are regions of marine waters of 200,000 km² or greater, that encompass coastal areas from river basins and estuaries to the outer margins of a continental shelf or the seaward extent of a predominant coastal current. LMEs are defined by ecological criteria, including bathymetry, hydrography, productivity, and tropically linked populations (GEF, 2017).

PAME developed a map delineating 18 Arctic Large Marine Ecosystems (Arctic LMEs) in the Arctic oceans and adjacent seas in 2006. The Arctic LMEs were subsequently adopted by the Arctic Council. The adoption of the Arctic LMEs acknowledged related work in other forums, in which place-based assessments of the changing states of Arctic LMEs served as the framework for ecosystem-based management practices in the Arctic. A revision was made in 2013 and resulted in 18 LMEs for the Arctic (Fig. 3) (PAME 2013). The LMEs are used in the descriptions and risk assessments in this report, based on the individual ecological and oceanographic characteristics. More information on each LME can be found in the PAME LME fact sheet series (link: https://pame.is/ourwork/ecosystem-approach-to-management-ea/large-marine-ecosystems/).

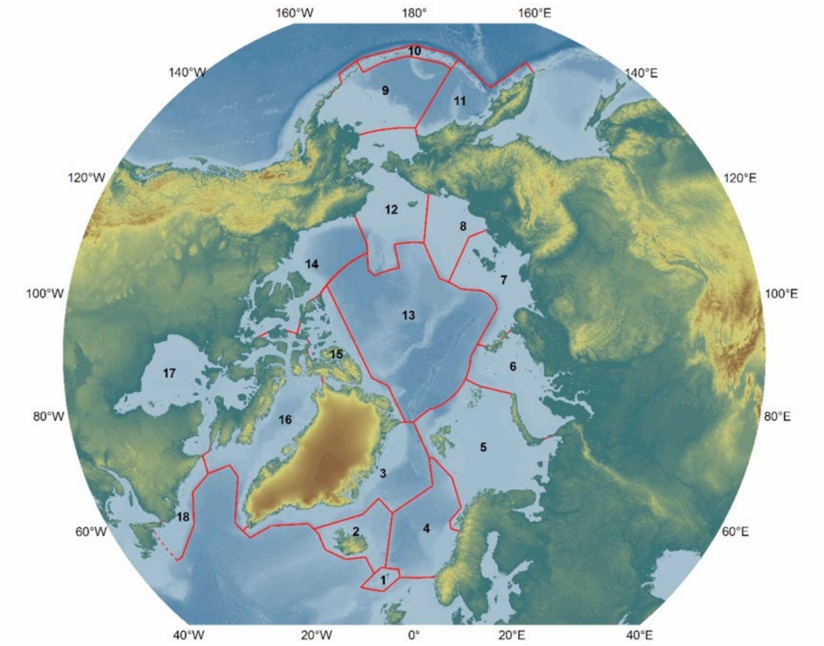


Figure 7-2: Map of 18 Arctic LMEs (version 17 April 2013)

7.3 Observed climates changes and impacts

In recent years, extensive work has been done on assessing climate change and ecological effects in the Arctic, including work made by The Intergovernmental Panel on Climate Change (IPCC) and The Arctic Council working groups Arctic Monitoring and Assessment Programme (AMAP), Conservation of Arctic Flora and Fauna (CAFF) and Protection of The Arctic Marine Environment (PAME).

In line with climate change, environmental and ecological conditions in the Arctic marine areas have many places changed.

In some Arctic areas, climate change has already had a major impact on habitat suitability for different organisms (CAFF 2017, CAFF 2019, CAFF 2021, Kovacs et al. 2021, AMAP 2021, Merideth et al. 2019, Michel & Christensen 2021).

The Arctic was warmer from 2011 to 2015 than at any time since instrumental records began in around 1900 and has been warming more than twice as rapidly as the world as a whole for the past 50 years (AMAP 2017, ICPP 2023). The air temperature is presently 5°C warmer than the 1981–2010 average and sea temperatures are distinctly increased in seawater, both near the sea surface and in deeper water (AMAP 2017).

Sea ice extent has varied widely in recent years but continues a long-term downward trend. Sea ice thickness in the central Arctic Ocean has declined by 65% over the period 1975–2012 and a record low minimum sea ice extent occurred in 2012 and a record low maximum sea ice extent occurred in 2016 (AMAP 2017). Human influence is very likely the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic sea ice area between 1979–1988 and 2010–2019 IPCC 2023). In addition, multi-year sea ice is rapidly disappearing and most sea ice in the Arctic is now 'first year' ice that grows in the autumn and winter but melts during the spring and summer. More open water occurs in all months of the year compared to 2011 (AMAP 2017, Skjoldal 2022).

Ecosystems across the Arctic are undergoing fundamental changes in the productivity, seasonality, distribution and interactions of species in coastal, and marine ecosystems has been observed and the primary productivity in the arctic water still increases (CAFF 2017, AMAP 2021). The combination of loss of sea ice, increased runoff of freshwater to the coastal waters, and regional stratification of the water columns, has affected the timing, distribution and production of primary producers in Arctic waters (IPCC 2019). IPCC (2019) refers to satellite data showing that the decline in ice cover has resulted in a >30% increase in annual net primary production in ice-free Arctic waters since 1998. Ice loss has also resulted in earlier phytoplankton blooms dominated by larger-celled phytoplankton. The longer open water season in the Arctic has also increased the incidence of autumn blooms, a phenomenon previously very rarely observed in Arctic waters (IPCC 2019). In addition, different studies shows that warm conditions may affect the production of large copepods in Arctic waters. Large copepods play a central role in arctic food webs as energy source for many species at higher trophic levels including fish, seabirds and baleen whales.

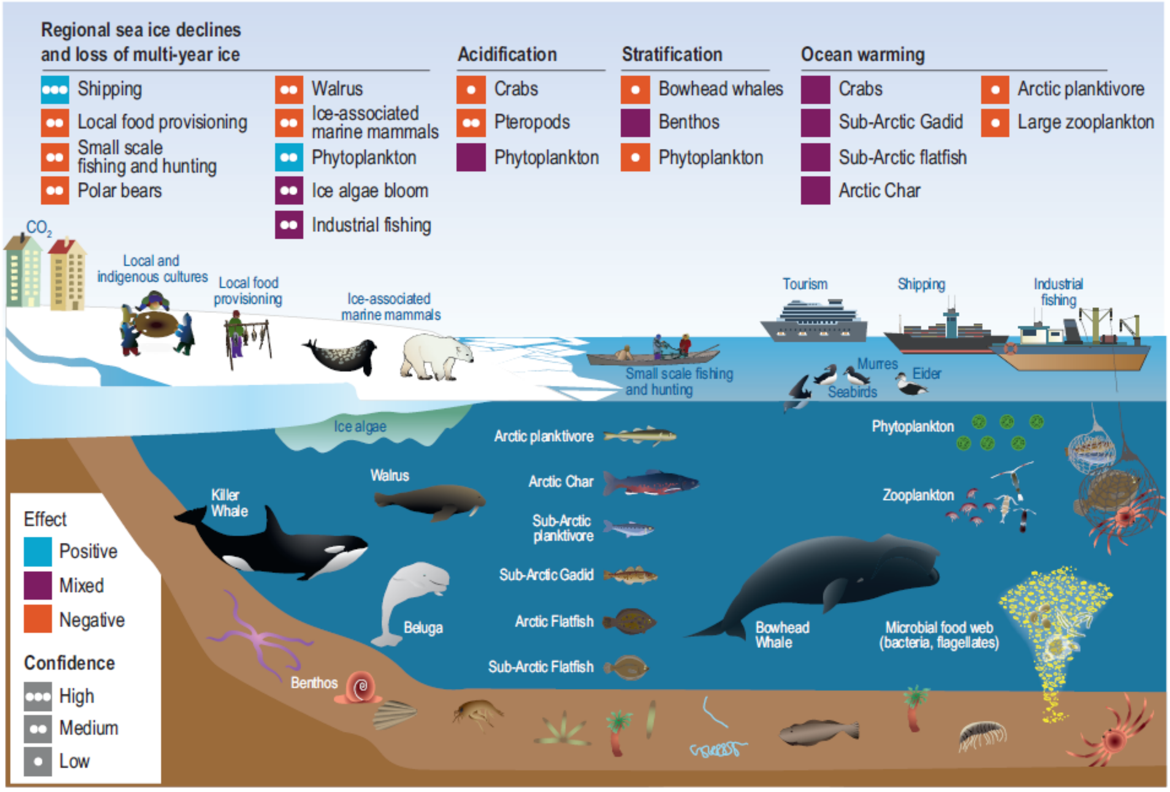


Figure 4 Adapted from IPCC 2019 show key drivers that are causing, or are projected to cause, direct effects on Arctic marine ecosystems with associated confidence levels. Projected effects are conceptual representations based on high emission climate scenarios. The cross-sectional view of the Arctic ecosystem shows the association of key functional groups (marine mammals, birds, fish, zooplankton, phytoplankton and benthic assemblages) with Arctic marine habitats.

In Polar Regions climate-induced changes ocean and sea ice environments, together with human introduction of non-native species, have expanded the range of some temperate species (IPCC 2019). Summary of IPCC assessment for effect on Arctic marine ecosystems is illustrated in the figure 4.

7.4 Future climate changes and impacts

Models project that autumn and winter air temperatures in the Arctic will increase to 4–5°C above late 20th century values before mid-century (AMAP 2017). Climate models predict that water temperature will rise, the distribution and thickness of sea ice will decrease, and freshwater runoff from land will increase, among other changes (AMAP 2017 & 2021). AMAP (2017) refers to recent observed data suggesting a largely ice-free summer ocean by the late 2030s, which is earlier than projected by most climate models. Furthermore, the prediction indicates that there will be significant regional differences.

Sea ice has a major impact on the rate of warming since sea ice reflects a high proportion of incoming solar radiation back to space, providing thermal insulation between the ocean and atmosphere, and influences thermohaline circulation (IPCC 2019). Projected future reductions in summer sea ice, increased stratification in summer, shifting currents and fronts and increased ocean temperatures and ocean acidification are all expected to impact the future production and distribution of several marine species (IPCC 2019).

The near-future Arctic will be a substantially different environment from that of today, and by the end of this century, Arctic warming may exceed thresholds for the stability of sea ice and the Greenland ice sheet (IPCC 2019, AMAP 2021).

Assessments made by AMAP and CAFF conclude that the decline in sea ice thickness and extent, along with changes in the timing of ice melt, are affecting marine ecosystems and biodiversity, changing the ranges of Arctic species, increasing the occurrence of algal blooms, leading to changes in diet among marine mammals; and altering predator-prey relationships, habitat uses, and migration patterns. Changes in sea ice are expected to affect populations of polar bears, ice-dependent species of seals and, in some areas, walrus, which rely on sea ice for survival and reproduction. There will also be losses of ice-associated algae and associated species (Meltofte 2013, AMAP 2017, CAFF 2017, AMAP 2021).

The projected changes for Arctic waters will push some species out of their ranges, while other species may colonize new areas. Species that depend on sea ice for survival and reproduction may decline with changes in sea ice thickness and extent while phytoplankton and populations of non-native species may increase due more available light for a longer periods of the year due to loss of sea ice (AMAP 2017, CAFF 2017).

Warming can affect organisms that are well adapted to low temperatures that may be replaced by other species that are better adapted to warmer temperate conditions (Meltofte, 2013). Many Arctic species are adapted to low temperatures with presumably limited capacity to adapt to temperatures exceeding optimal conditions for growth and reproduction, making them vulnerable to temperature increases. Phytoplankton, which form the base of marine food webs, and bacteria involved in the cycling of nutrients in marine biogeochemical cycles are harbingers of change as they respond rapidly to environmental changes. A comparison of thermal thresholds for Arctic phytoplankton species suggests that sub-optimal temperature conditions affect phytoplankton dynamics and community structure (AMAP 2021). Increased runoff can also lead to the formation of a stratification of low-saline water in the surface water, which can result in reduced production in the surface water due to nutrient limitation.

Projected climate driven changes in ocean properties and hydrography and the abundance of pelagic grazers could alter the export of organic matter to benthos (organisms inhabiting the seafloor) at the sea floor (IPCC 2019).

Climate change is affecting marine ecosystems throughout the circumpolar Arctic, altering seasonal habitats and the food bases for fishes, seabirds, and marine mammals. Arctic and Subarctic regions provide resources for resident species and for species that migrate to the north from more southerly regions Changes in northerly latitudes thus impact endemic as well as non-endemic animals (cf. Kuletz et al. 2024).

Climate change is rapidly modifying biodiversity across the Arctic, driving a shift from Arctic to more boreal ecosystem characteristics. A large body of literature reports evidence of such northward shifts into the Arctic by boreal species of many functional groups, driven by local habitat modifications and advection of warm water and associated species from lower latitudes (Polyakov et al., 2020a; Brandt et al., 2023), a phenomenon called “borealization” (Fossheim et al., 2015). Borealization is driven by long-term strengthened inflow of increasingly warm waters from the south and punctuated by advection and low sea ice extreme events (Husson et al. 2024). We expect current borders of Arctic and boreal ecosystems to progress further northward and ultimately reach an equilibrium state with seasonal borealization. Risks to the system are difficult to estimate, as adaptive capacities of species are poorly understood. However, ice-associated species are clearly most at risk, although some might find temporary refuge in areas with a slower rate of change (Husson et al 2024).

8. Conclusion and recommendations

This project is part of a joint effort between The Conservation of Arctic Flora and Fauna (CAFF) and the Protection off Arctic Marine Environment (PAME) Working Groups to implement actions related to the Arctic Invasive Alien Species Strategy and Action Plan.

With warming climate and increasing ship traffic there has been a growing interest and concern regarding the potential for introduction and establishment of Invasive Alien Species (IAS) and Non-Indigenous Species (NIS) in arctic waters. For Arctic marine species the report assessed that ships are the most common source for the introduction of Invasive Alien Species (IAS) and Non-Indigenous Species (NIS) in marine systems through organism entrainment in ballast water and biofouling of outer surfaces.

Based on a comprehensive review of available information in over 60 databases, primary publications and reports this report includes a list and associated information of species /taxa known to be NIS and/ or IAS. The report present details on individual species/taxa detections in 18 different Arctic Large Marine Ecosystems (Arctic LMEs). The list includes higher total number than in other previous studies of the Arctic marine areas while numbers of species/taxa recorded in the current report are like those found in The European Marine Observation and Data Network list.

The assessment in the report indicates that ship traffic to and within the Arctic waters has significant increase in period year 2013 to 2024. The number of unique ships entering the Arctic area has increase by around 37%, corresponding to approximately 500 ships. In same period distance sailed by ships in the Arctic Polar Code Area has increased from 6.1 million to 12.7 million nautical miles. An increased shipping can result in increased risk of invasive species entering the Arctic. A detailed analysis of worldwide shipping to the Arctic is needed to identify from which regions, countries and ports ships enter the Arctic. This could help identify where ships come from and were existing or potential non-indigenous species and invasive alien species invasive species come from.

Risk assessments are useful to provide clues and develop watch lists of NIS and AIS. However, only a relatively limited number of risk assessments have been done for NIS and AIS for the Arctic waters and there is little known of the importance of shipping for the possibly introduction of non-indigenous species and invasive alien species to and into Arctic waters. The most common approach used in risk assessment is to predict species of concern with a focus on species known to be in potential source regions and pathways. However, experimental information on survival and reproductive thresholds is frequently lacking, especially with respect to lower thresholds at near zero and sub-zero temperatures common to Arctic waters over much of the year. In addition, species distribution models only indicate the possibility of a species establishing given the current or predicted future conditions and rarely consider pathways and vectors. The risk to the the Arctic to non-indigenous species introductions, particularly with respect to shipping, remains largely unknown.

To combat the problem of species introductions in ballast water, IMO has adopted the International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 (Ballast Water Management (BWM) Convention) and the Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species (Biofouling Guidelines 2023). As of February 2025, the BWM Convention had 97 Parties representing; out of the eight Arctic Countries, two are not Parties to the BWM Convention. Recent studies indicate that even if ships are compliant with the ballast water performance standard for indicator microbes and organisms (size class 10-50 µm), some exceed the limit for viable organism's ≥50 µm. Therefore, it is suggested to further study the efficiency of filter mesh sizes and different filtration units associated with ballast water management systems, to improve mechanical removal of larger organisms ≥50 µm. In 2023, IMO developed non-binding Biofouling Guidelines to encourage the control and management of ships' biofouling to minimize the transfer of non-indigenous species.

Arctic marine ecosystems differ from other ocean environments and are characterized by a great variability in environmental conditions, including seasonal extremes in photoperiod, cold temperatures, river runoff and ice conditions. Factors of importance in relation to the establishment of new marine species are salinity, temperature, light condition and levels of nutrients in the waters. In line with climate change, environmental and ecological conditions in the Arctic marine areas have changed in many places. Studies have documented that in Arctic regions climate-induced changes in ocean and sea ice environments, together with human introduction of non-native species, have expanded the range of some temperate species. The projected climate changes for Arctic waters will push some species out of their ranges, whereas other species may colonize new areas.

This report is Phase 1 of a joint effort between CAFF and PAME to implement actions related to the Arctic Invasive Alien Species Strategy and Action Plan. A phase 2 is planned to build upon results from this report and to include aspects related to risk assessments and recommendations for monitoring, detection, and prospective registration of NIS and IAS in Arctic waters.

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