Ecosystem assessment of the Central Arctic Ocean: Description of human activities, its pressures, and vulnerability of the ecosystem

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Part II of CRR Vol. 355

ICES INTERNATIONAL COUNCIL FOR THE EXPLORATION OF THE SEA
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Editor

Lis Lindal Jørgensen

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Contents

I Summary

Pressures occur in the Central Arctic Ocean (CAO) as a result of both local human activities, such as research and ship traffic from tourism and the military, and distant global sources that arrive via means such as air, rivers, and ocean currents.

Contaminants, non-indigenous species, marine litter (including microplastics), artificial noise pollution, nutrient and organic enrichment, extraction of species, extraction of non-living resources, physical seabed and sea ice disturbance, artificial light pollution, unintended injury and mortality in open water, and human presence on ice are the 11 local, direct human-induced pressures recognized as relevant for the CAO. Pressures from global sources include contaminants, litter, and non-indigenous species that enter the ocean from global sources. Both categories of pressure are included in this report. The impact of climate change originating from human activity (the pressure "heating") is included as climate-related effects on the ecosystem.

Ice prokaryotes and viruses, water column and seabed prokaryotes and viruses, ice algae, phytoplankton, ice invertebrates, zooplankton, pelagic squid, soft-bottom and hard-bottom benthos, sympagic-, mesopelagic-, and demersal/bentho-pelagic fishes, polar bear, ringed seal, bowhead whale, narwhal, beluga whale, transient-, seasonal resident- and ice obligate-sea birds were identified as groups or species that represent relevant ecosystem components of the CAO. Most of these taxonomic groups have populations that are widely distributed across the entire CAO, while a few groups have limited distributions on the seabed (hard-bottom benthos), in the water column (whales), or along the ice edge (ice-obligate seabirds and ringed seal). While most ecosystem components are present inside the CAO year-round, some few components (whales and migratory and seasonally resident seabirds) are only present for a few months each year.

Some of the relevant pressures introduced by local sources in the CAO are anticipated to have impacts on all (e.g. contaminants), some (e.g. artificial noise pollution), or only a few (e.g. nutrient and organic enrichment) ecosystem components in the CAO.

II Foreword

Integrated ecosystem assessments (IEAs) incorporate all available information about environmental conditions, species, and stressors (e.g. local human activities and climate change) to take an ecosystem view to understand the current state of and trends within a target ecosystem, and to develop indicators of ecosystem health and undertake risk assessments to support ecosystem-based management.

The ICES–PICES–PAME Working Group on Integrated Ecosystem Assessment of the Central Arctic Ocean (WGICA) conducts integrated ecosystem assessments of the CAO. The assessment was carried out as a three-step process:

1. All relevant information on the biology, human activities and sources, pressures and vulnerability of the ecosystem was compiled using definitions, methods, and glossaries already in use in ICES (2023a) and adapted to the CAO (see the CAO Ecosystem Overview [ICES, 2021a], Skjoldal *et al.*, 2022, and this report).
2. A scoring process [online workshops, Jørgensen *et al*. (submitted)] was carried out, with multidisciplinary groups of scientists evaluating and scoring the spatial and temporal overlap of the pressures from each of the sources with the ecosystem component population, the degree of vulnerability of each of the ecosystem components, the longevity of the longest living species within the ecosystem component, and the persistence of the pressures when released in the environment.
3. A final assessment was run, drawing on the results of the ranking and evaluation of the risk scoring (see Ecosystem Overview of the CAO, Jørgensen *et al.*, submitted, and future regularly produced assessments in the WGICA).

This report builds on the description of the CAO ecosystem in Skjoldal *et al.* (2022) and details the human activities and global sources, the pressures they create, and how these pressures impact ecosystem components in the CAO. Besides the global sources bringing in pressures via air, rivers, and ocean currents (Section 2), the relevant human activity for the CAO includes science-, tourist-, and military ship traffic and a limited number of people on the icecap arriving by air or ships. A set of 11 pressures derived from these sources are identified and described (sections 3–8). Furthermore, the entire CAO ecosystem, from the smallest bacteria to the largest sea mammal, is divided into 19 components and described according to their spatial distribution and temporal occurrences. Each component is also described in terms of its vulnerability to both categories of pressure (chapters 10–17). This information is the foundation for ongoing and future assessments of the CAO that have evaluated (Ecosystem Overview, Jørgensen *et al.*, submitted) or will evaluate the risk of human activities on the ecosystem components.

Conducting an IEA for the CAO is an important step for implementing the ecosystem approach to management [EA, or its synonymous term ecosystem-based management (EBM)]. An expert group in the Arctic Council has established a framework with six elements (IEA being one of them) and a first set of guidelines based on the framework for implementing EA to management of Arctic large marine ecosystems (LMEs). ICES views IEA as an important mechanism for promoting the development of EA and has established regional working groups to perform IEAs, e.g. for the Barents Sea, Norwegian Sea, and North Sea LMEs.

1 Introduction

The CAO (Figure 1.1) mostly comprises high seas areas remote from any landmasses, including deep basins and slopes up to depths of approximately 500 m, as well as some shallower shelf areas of the bordering Beaufort, Chukchi, East Siberian, and Laptev seas. The boundary of the ecoregion follows the outer slopes on the Eurasian side, from the Chukchi Sea to the Barents Sea, the shelf edge of north Greenland and the Canadian High Arctic, and runs along the 76°N in the Beaufort/Chukchi seas. The seabed in the ecoregion consists of two large deep basins (between 3 000 and 4 500 m), the Eurasian and the Amerasian basins, separated by the Lomonosov Ridge. This ~1 300 m deep ridge consists of steep slopes rising about 3 000 m above the seabed.

The main human pressures affecting the ecoregion are the introduction of contaminating compounds, marine litter, the introduction of non-indigenous species, and underwater noise. Some of the activities causing these are scientific icebreakers, tourism, and military shipping (ICES, 2022).

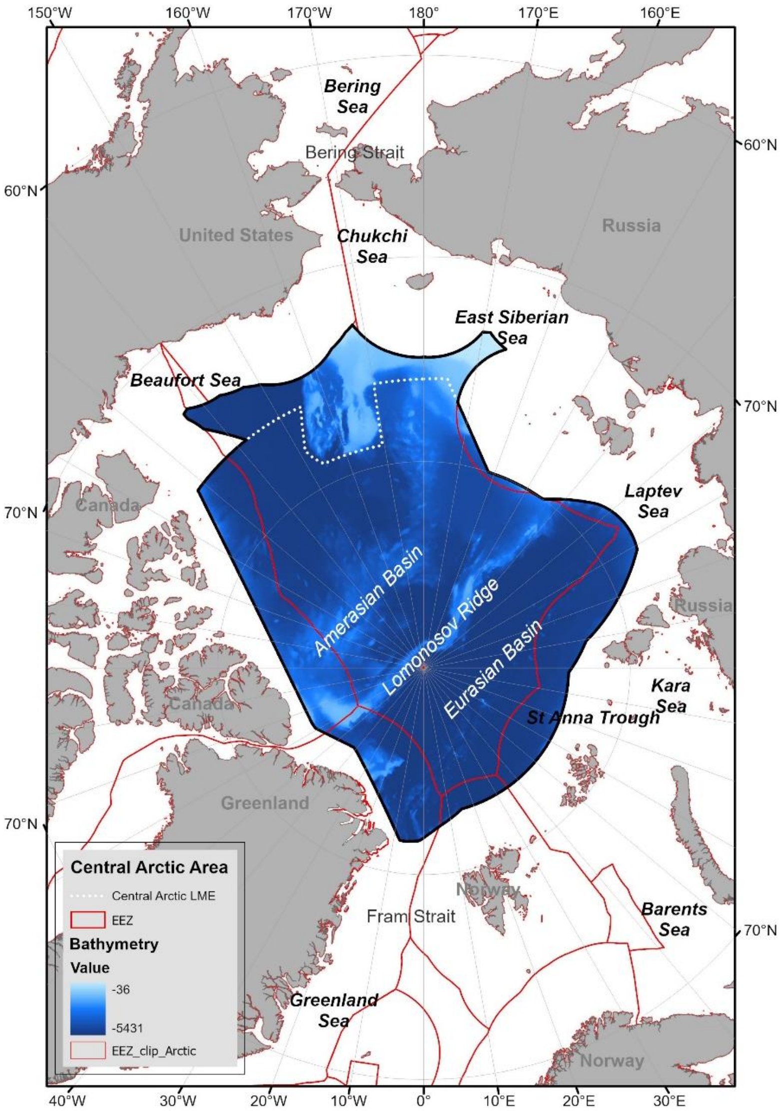

Figure 1.1. The Central Arctic Ocean (CAO; shaded blue, with depth gradient), adjacent seas, and exclusive economic zones (EEZs). Reproduced from ICES (2022).

The presence of sea ice, the absence of ports and transportation infrastructure over large areas, frigid temperatures, frequent storms, and seasonal darkness, mean that human activities within the CAO are currently limited. Impacts from these activities are dwarfed by pressures resulting from human activities outside the ecoregion, including climate change and the introduction of contaminants, plastics, invasive species, and noise pollution. The Northern Sea Route is anticipated to become a major Arctic shipping lane, with the Russian government intending to increase annual transit volumes on the route from 1.3 million tonnes in 2020 to 30 million tonnes in 2030 (Staalesen, 2021). This shipping activity will give rise to a range of different pressures on the environment related both to potential accidents (collisions, groundings, and sinking of ships) and normal ship operations (emissions, noise, and discharges; Hannah *et al.*, [2020]; Jalkanen *et al.*, [2018, 2021], Moldanová *et al.*, [2022]). While the frequency of accidental oil spills has steadily decreased since the 1970s (ITOPF, 2024), the size of the global fleet has grown extensively (UNCTAD, 2021), meaning that the total environmental pressure from the shipping industry has increased. Ships can be considered floating industrial sites or, in the case of cruise ships, floating towns, giving rise to a range of waste streams to the marine environment.

Ship accidents have happened in the past (discussed in Stewart and Dawson [2011]; Stewart and Draper [2008]). The question is therefore not if they will occur again, but when. There is a large body of evidence indicating that all stresses caused by ship traffic and human activity are already impacting the Arctic ecosystem (e.g. Nahrgang *et al.*, 2016; Kühn *et al.*, 2018; Peeken *et al.*, 2018). Disturbances in addition to ship traffic are in connection with landing operations with small boats and air operations, e.g. helicopter tours (Hagen *et al.*, 2012).

Finally, there is the prospect of modern military activities, including conflict, which would cause dramatic habitat alteration, environmental pollution, and disturbance, contributing to population declines and biodiversity losses arising from both acute and chronic effects in terrestrial and aquatic systems (Lawrence *et al.*, 2015). The extent to which warfare affects an ecosystem and its constituent populations depends on the nature of the disturbance, the sensitivity and resilience of the biological system, and the duration of the impacts (Westing, 1971; Demarais *et al.*, 1999; Dudley *et al.*, 2002; Warren and Büttner, 2006; Warren *et al.*, 2007).

As Arctic sea ice continues to diminish, the CAO is expected to serve as an increasingly critical refuge for high-Arctic species reliant on summer ice. Since the 1990s, the region has experienced significant sea ice loss during the so-called "Great Melt," marked by a dramatic shift from thicker, multiyear pack ice to thinner, annual ice.

Further stress to the already climate-stressed CAO ecosystem components can result from local human activities on the seabed, in the pelagic zone, or on/within the area of the shrinking ice habitat, and also from global sources such as contaminants, litter, and non-indigenous species (NIS). This report attempts to identify the most vulnerable ecosystem components facing pressures from the variety of relevant sources of the CAO. The intention is, along with the first part of the report (Skjoldal, 2022), to provide all the background necessary for assessing the risks these pressures pose to the ecosystem components.

The Options for Delivering Ecosystem-Based Marine Management (ODEMM) is a risk assessment approach to a risk scoping tool to improve operationality in ICES IEA working groups (Pedreschi *et al.*, 2023). While the ODEMM approach and key terminology used (Roux and Pedreschi, 2024) have been applied within WGICA, the description of the ODEMM method, the definitions, and the understanding of risk and how the method was used, are outside the scope of this report (for more information see Roux and Pedreschi [2024]).

2 Global sources of pressures

2.1 Introduction routes into the CAO

Randi Ingvaldsen, Bjørn Einar Grøsvik, Lis Lindal Jørgensen, and Martine van den Heuvel-Greve

Some pressures occurring in the CAO can be the result of human activities that take place outside the ecoregion, sometimes even far away. This is partly the case for NIS, contaminants, and marine litter, which reach the ecoregion via ocean currents, rivers, and atmospheric deposition (Figure 2.1). These three pressures will be described in detail in respective subsections of this section. Several processes exist that influence the inflow and distribution of these pressures within the CAO.

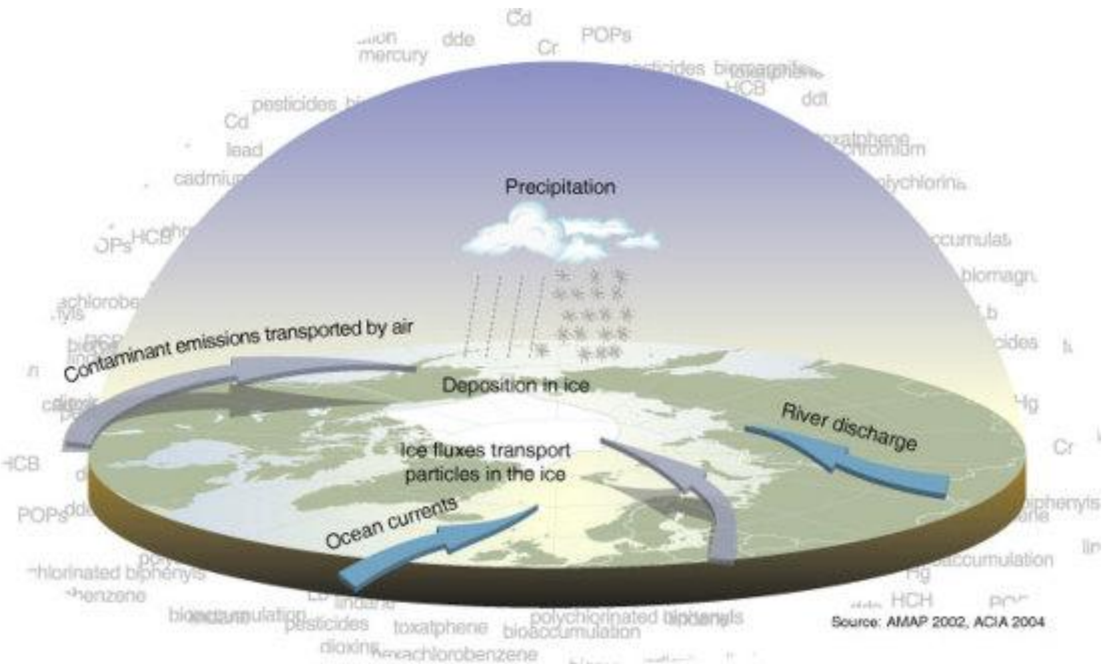

Figure 2.1. Global sources may lead to the introduction of several pressures into the Central Arctic Ocean by ocean currents, rivers, or atmospheric deposition. Cartographer: Hugo Ahlenius. Reproduced with permission from UNEP/GRID-ArendalFrom AMAP collection (https://www.grida.no/resources/7021).

The Arctic Ocean is an enclosed ocean that connects with the North Atlantic through the Fram Strait (depth of 2 600 m) and the Barents Sea, and with the Pacific Ocean through the shallow (50 m) and narrow (85 km) Bering Strait (Figure 1.1). The Fram Strait is the only gateway allowing for a two-way deep exchange (Rudels, 2015). The CAO is tightly connected to the northern Pacific and Atlantic oceans through this advection (Hunt *et al.*, 2016), forming lengthy contiguous domains that connect the subarctic with the Arctic (Wassmann *et al.*, 2015). The Atlantic Ocean has been estimated to contribute 79% of the water in the Arctic Ocean, while the inflow through the Bering Strait is estimated to contribute 19% (Murray *et al.*, 1998). In addition to heat and salt, the Atlantic current imports nutrients (Randelhoff *et al.*, 2015), organisms (Wassmann *et al.*, 2015), contaminants (Kohler *et al.*, 2022), and microplastics (Kim *et al.*, 2021; Ross *et al.*, 2021) into the Arctic.

The inflow from Atlantic water runs northwards at the surface, but cools gradually along the way and sinks to intermediate levels when reaching the northeastern Barents Sea and the Arctic

Basin downstream of the Fram Strait. It continues to flow cyclonically around the Arctic Ocean as a subsurface layer (Rudels, 2015). The inflow from the Pacific is also modified en route and enters the convergent Beaufort Gyre, where Ekman downwelling brings surface and Pacific waters downwards in the upper water column (Timmermans and Marshall, 2020). In addition, cooling, ice freezing, and mixing in localized regions can produce dense waters reaching the intermediate and deep (> 1 000 m) Arctic Ocean (Rudels *et al.*, 2004, 2015; Schauer *et al.*, 1997). With this, contaminants and marine litter brought into the Arctic can be transferred to great depths, where they stay for a considerable amount of time, with only a little able to escape out of the system through the Fram Strait.

The Arctic is under the influence of the Beaufort High, centred over the Canadian Basin and introducing anticyclonic circulation in the Beaufort Gyre, and the Icelandic Low, inducing cyclonic tendencies in the Atlantic inflow region (Proshutinsky and Johnson, 1997). The Transpolar Drift Stream flows between these two circulation cells, transporting sea ice and freshwater from the north of Siberia into the CAO and further towards the Fram Strait.

Many rivers flow from the massive, surrounding continents into the CAO (Rudels and Carmack, 2022), meaning the ocean receives some 11% of the globe's freshwater (Yakushev *et al.*, 2021). The flow of freshwater between the land, the atmosphere, and the ocean is increasing. Besides freshwater, Arctic rivers are pouring enormous quantities of sediment, nutrients, and organic carbon into the Arctic Ocean every year (AMAP, 2017a). An intensification of shelf-derived material inputs to the central basin may be a source of recorded elevated concentrations of dissolved organic carbon, nutrients, and microplastics (Kipp *et al.*, 2018; Yakushev *et al.*, 2021).

Atmospheric transport into the Arctic is also of high importance, with observations of (i) light-absorbing airborne pollutants (black carbon aerosols) in quantities that well exceed the background levels (Backman *et al.*, 2021); (ii) microplastics in ice floes from the Fram Strait and Svalbard (Bergmann *et al.*, 2019) and in snow samples from Baffin Bay (Huntington *et al.*, 2020); and (iii) microplastic particles produced by road traffic (tire wear particles and brake wear particles), modelled to be of similar magnitude as the total estimated direct and riverine transport of such particles to the ocean (Evangeliou *et al.*, 2020).

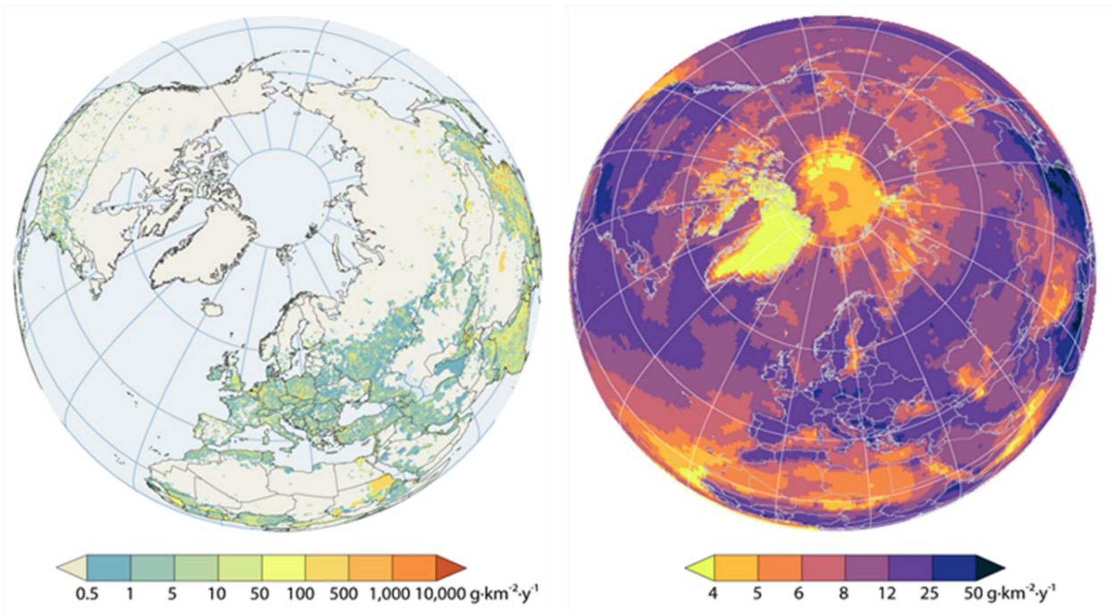

Figure 2.2. Mercury emissions (total Hg), 2015 (left panel), and model-ensemble -simulated total mercury deposition (right panel). Reproduced with permission from Steenhuisen (2023).

Air pollution resulting from agricultural waste burning in eastern Europe (mostly Russia, the Baltic countries, Belarus, and the Ukraine) took three to four days to be transported by air to the European Arctic, while forest burned in North America emitted a pollution plume which reached the Arctic after three to four weeks (Stohl *et al.*, 2007). It is predicted that mercury emissions from lower latitudes are deposited in high Arctic regions such as the CAO (Figure 2.2). Unusually high concentrations of polychlorinated biphenyls (PCBs), far away from the sources, were also proposed to be caused by such biomass burning emissions (Eckhardt *et al.*, 2007), further showing the occurrence of long-distance atmospheric transport of contaminants towards the Arctic region.

2.2 Non-indigenous species

Haakon Hop, Martine van den Heuvel-Greve, and Tom Christensen

2.2.1 Definition of a non-indigenous species

A non-indigenous species (NIS) can be defined as "a species that through human interference has been moved from its native dispersal range to a new area" (Olenin *et al.*, 2017).

2.2.2 Where non-indigenous species occur in the CAO

There are currently no records of NIS in the CAO. In cases where such species are brought into the ecoregion, ships are considered the most prevalent vector through organism entrainment in ballast water and biofouling (Ware *et al.*, 2014; Chan *et al.*, 2015). So far, the CAO has not been much subjected to these distribution vectors. The number of ships operating in the ecoregion is currently limited to a few research vessels, tourist icebreakers, and military vessels; ice stations have also been used for both research and tourist purposes. Because of the ongoing decline in sea ice extent and volume and the opening of northern sea routes, shipping will be further increasing in subsequent decades (Rosenhaim *et al.*, 2019), thereby increasing the risks for biological introductions (Ware *et al.*, 2016).

Studies of polar shipping operations have demonstrated that the external hull and ballast tanks of vessels operating in ice-covered waters can support a wide variety of NIS (Ware *et al.*, 2014, 2016). The International Maritime Organization (IMO) regulation (see Section 5) allows ballast water to be exchanged in open sea (hence the CAO) but encourages ships to install special equipment for treatment of ballast water (IMO, 2004). There are also national ballast water regulations in countries such as Norway (Norwegian Ministry of the Environment, 2009). Biofouling, which includes the undesirable accumulation of marine organisms on submerged structures such as ship hulls, may also be a vector for spreading NIS to the CAO, although the hulls of ships that sail through sea ice are typically cleaned by abrasion of most of the attached organisms. Non-binding IMO Biofouling Guidelines have been developed to encourage the control and management of ship biofouling to minimize the transfer of NIS.

Floating microplastic-like litter can also transport (boreal) species to the Arctic, for example gooseneck barnacles (*Lepas* sp.), blue mussels (*Mytilus edulis*), and bryozoans (Węsławski and Kotwicki, 2018). However, these are typically hard-structure residents of relatively shallow waters, so even if their larvae drift into the CAO, they probably are unable to establish populations in the deep basin of the ecoregion. In the coastal areas surrounding the CAO, so far, only species related to hard substrate have been recorded. Located in the Svalbard archipelago, these coastal marine invaders include the barnacles *Amphibalanus improvisus* and *Austrominius modestus*, the blue mussel, the crab species *Carcinus maenas*, *Paralithodes camtschaticus*, and *Chionoecetes opilio*, and potentially the tunicates *Botrylloides violaceus* and

Molgula manhattensis (Leopold *et al.*, 2019; Nilssen and Sundet, 2006; van den Heuvel-Greve *et al.*, 2021; Ware *et al.*, 2016; Zakharov *et al.*, 2021).

2.2.3 When non-indigenous species occur in the CAO

There are currently no records of NIS in the CAO.

2.3 Contaminants

Martine van den Heuvel-Greve, Bjørn Einar Grøsvik, and Hilde Elise Heldal

2.3.1 Definition of contaminants

Contaminants are chemical elements or compounds that may be naturally occurring or man-made.

This report focuses on the available information on levels of mercury (Hg), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and per- and polyfluoroalkyl substances (PFAS) in sea water, sediment, and biota in the CAO. It also focuses on the occurrence of radioactive compounds, discussed in Section 2.3.2.6.

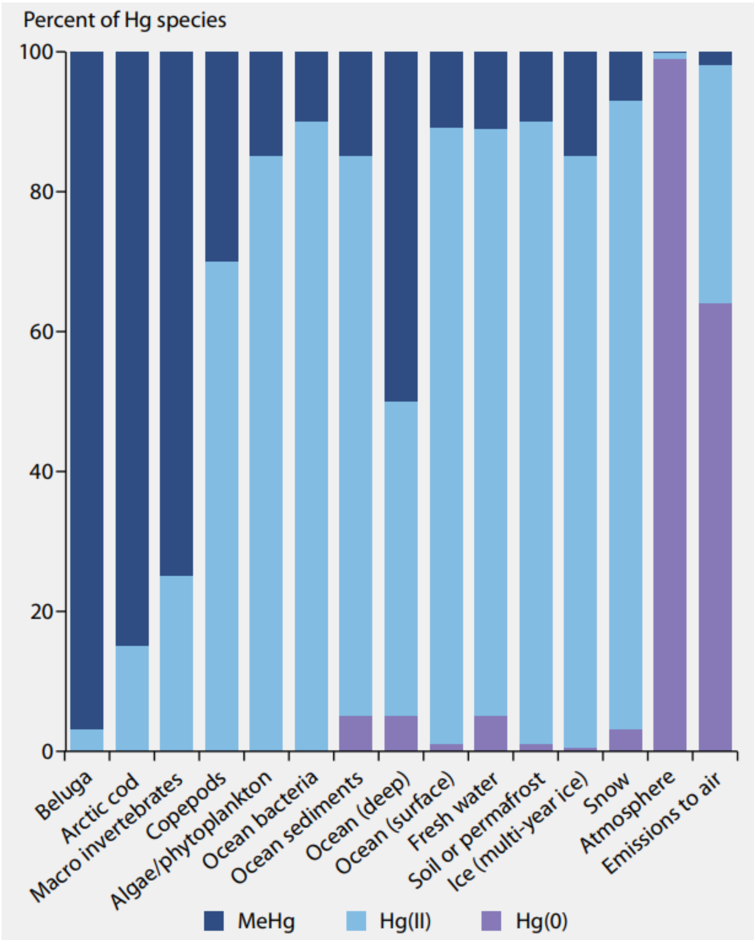

Figure 2.3. Partition of different Mercury (Hg) species (Hg[0], Hg[II] and MeHg) in emissions and in various Arctic environmental compartments and biota, expressed as percentages of total Hg (THg;). Reproduced from AMAP (2011).

Hg can originate from both natural and industrial sources and is transported via air and water to the CAO (figures 2.1 and 2.2). Emission and atmospheric transport occur predominantly in the elemental form of mercury (Hg[0]), whereas occurrence in water and sediment is mainly in the inorganic form (Hg[II]; Figure 2.3). Inorganic mercury can be further transformed into the organic form, methylmercury (MeHg), which accumulates in the foodweb and has the highest potential to exert effects.

PCBs, PBDEs, and PFAS are man-made or industrial-made chemicals that are emitted predominantly outside the Arctic region through the production, processing, use, and waste handling of materials containing these chemicals. They reach the CAO via ocean and atmospheric currents, and river run-off (see Section 1.1). Radioactive compounds can also originate from both natural and industrial sources and are transported via air and water to the ecoregion.

For all contaminants listed in this section, existing data are compiled in tables per compartment (water, sediment, and biota). Additional contaminant types are compiled in a separate table in Annex 3.

2.3.1.1 Bioaccumulation of contaminants

Contaminant concentrations in biota are influenced by physicochemical and biological processes (Borgå *et al.*, 2004; Selck *et al.*, 2012). Physicochemical processes consist of, for example, the chemical characteristics of the specific compound (water solubility, ability to bind to organic matter, and trophic transfer potential), water temperature, and salinity. Biological processes are, for example, diet preference, place in the foodweb, longevity, and fat content. All these parameters determine the bioavailability, uptake, and bioaccumulation potential of a chemical compound. The higher the bioaccumulation potential of a contaminant, the higher the contaminant concentration at the top of the foodweb. Some of these biological parameters happen to be key characteristics for the Arctic (Borgå *et al.*, 2004). Species living here grow larger and older than related species at lower latitudes. The strong seasonality in the Arctic leads to large differences in lipid content throughout the year and a high capacity of the organisms to store fat. Arctic marine foodwebs are long compared to other latitudes (Borgå *et al.*, 2004), running from phytoplankton and ice algae, to zooplankton, fish, seals, all the way to predatory fish (Greenland shark), scavenging birds (ivory gulls), polar bears, and humans. The highest contaminant concentrations of such bioaccumulative contaminants are, therefore, found in top predators of the Arctic foodweb.

2.3.2 Where contaminants occur in the CAO

Contaminants can be transported to the Arctic region via air currents, rivers, and ocean currents (Figure 2.1; AMAP, 1998). While the Northeast Atlantic Current transports water masses northwards together with nutrients, plankton, and other marine organisms, it also moves contaminants and radioactive compounds. Studies of levels of contaminants such as Hg, PCBs, PBDEs, and pesticides in fish have shown a gradient with decreasing levels from south (the Skagerrak and the North Sea) to north (the Barents Sea; Karl *et al.*, 2016; Ho *et al.*, 2021). The same applies to radioactive compounds (Skjerdal *et al.*, 2020).

Fragmented data show that contaminants can be found throughout the CAO and can, therefore, be considered widespread depending on their chemical characteristics, persistence, and bioaccumulation potential. There are only a few reports of actual contaminant concentrations in sea water, snow, sea ice, sediment, and biota in the ecoregion, and these data are not recent (tables 2.1, 2.2, and 2.3). Samples have been analysed from the Oden SWEDARCTIC expedition in 2001, the Oden SWEDARCTIC expedition in 2005, the 4th CHINARE expedition in 2010, and the Polarstern ARK-XXII/3 expedition in 2012. Additionally, chemical data exist based on old, archived biota samples (1983–1998; Table 2.3).

2.3.2.1 Contaminant concentrations in seawater

Mercury (Hg)

The latest assessment of status and trends of Hg in the Arctic was performed in 2021 (AMAP, 2021a; Table 2.1). Rivers and coastal erosion were identified to be dominant transport pathways for the delivery of MeHg to the CAO, while MeHg production in the ocean water column and sediments (coastal and deep-water) were identified as important *in situ* sources of Hg for the ecoregion. MeHg that accumulates in Arctic foodwebs is, therefore, converted within the Arctic (AMAP, 2021a). In Arctic seawater, MeHg concentrations are often highest at subsurface depths of ~100–300 m, where phytoplankton uptake may be an important entry route into pelagic foodwebs (AMAP, 2021a).

Polychlorinated biphenyls (PCBs)

The major pathways of PCBs into the CAO appear to be river discharge, atmospheric deposition, and ocean currents. The highest concentrations were found in the shelf seas, while lower concentrations were found in the central Arctic Basin (Figure 2.4, Table 2.1; Carrizo and Gustafsson, 2011a). Trichlorinated PCBs formed about half of the total PCB concentrations in the eastern Arctic (Beaufort, Chukchi, East Siberian, and Laptev seas) and in the central Arctic Basin, indicating a predominant atmospheric source, whereas hexachlorinated PCBs were more abundant in the western Arctic, pointing at a larger contribution from waterborne transport from North America and Europe (Figure 2.4, Carrizo and Gustafsson, 2011a). PCB concentrations increased with depth in the water column of the Nansen, Amundsen, and Makarov basins (Figure 2.5; Sobek and Gustafsson, 2014). The highest concentrations were observed in the deep water and the lowest concentrations in the upper polar mixed layer (PML; figures 2.5 and 2.6). Smaller chlorinated PCBs (tri-, tetra-, and pentachlorinated PCBs) dominated in water, whereas larger chlorinated PCBs (penta- and hexachlorinated PCBs) dominated in sediments (Sobek and Gustafsson, 2014). A decrease in concentration from the Nansen Basin via the Amundsen Basin to the Makarov Basin in intermediate and deep-water masses was suggested to be a result of decreasing concentrations northwards, with increasing distance from the shelves (Figure 2.5; Sobek and Gustafsson, 2014).

Polybrominated diphenyl ethers (PBDEs)

PBDEs were observed in seawater samples from the CAO (Salvadó *et al.*, 2016) with Σ14PBDE concentrations ranging from 0.3 to 11.2 pg l^{-1} in the upper PML (Salvadó *et al.*, 2016). Lower levels were observed in the interior basin compared with the surrounding shelf seas (Figure 2.7). Σ14PBDE concentrations in the deeper-water masses were more than one order of magnitude higher than those in the surface water (Figure 2.6). Lower brominated congeners, particularly BDE-47 and BDE-99, increased with depth, as did the concentration of BDE-71. As BDE-71 is not found in any PBDE commercial mixture, its presence in the water was thought to be the result of debromination of the BDE-209.

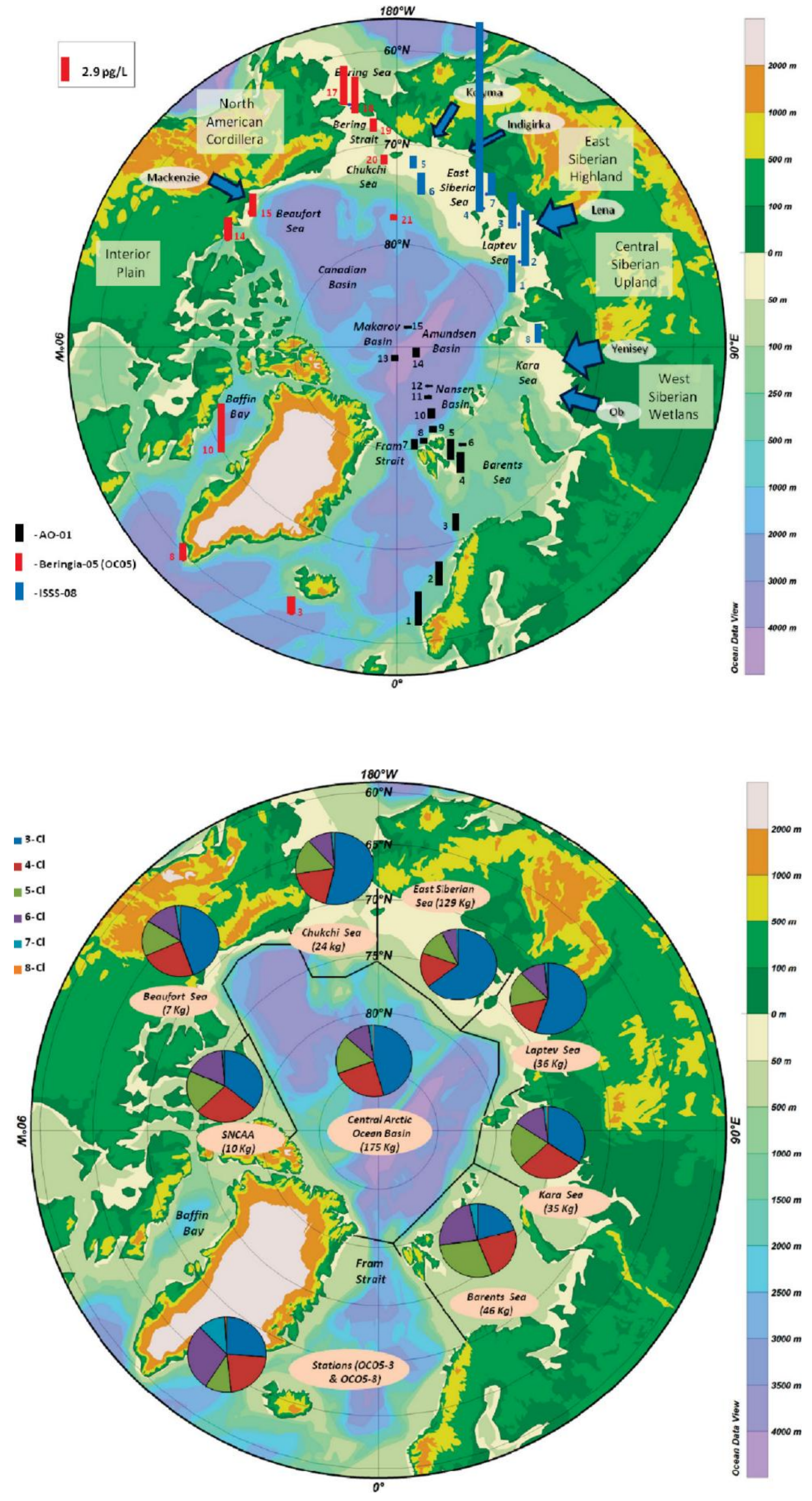

Figure 2.4. Upper panel: Total concentration of Σ13PCBs in surface seawater samples of the seven pan-Arctic shelf seas and the interior basin (pg l^{-1}), based on data from three expeditions in 2001 (AO-01), 2005 (Beringia-05), and 2008 (ISSS-08). Lower panel: Σ13PCBs mass balance inventories (kgs) and relative congener distribution based on the degree of chlorination for each of the seven Arctic shelf seas and for the central interior basin, as calculated from the data of all three basin-wide expeditions collectively. Reproduced with permission from Carrizo and Gustafsson (2011a).

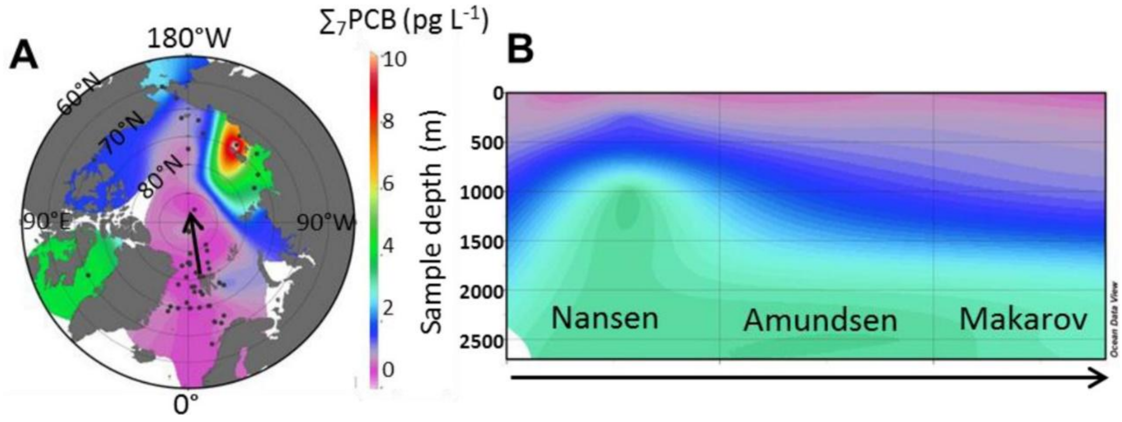

Figure 2.5. Extrapolated Σ7PCB concentration in the Arctic Ocean (pg l−1) in surface water (panel A) and depth profile (panel B) along a section in the Central Arctic Ocean (CAO; see black arrow in the left figure. Reproduced with permission from Sobek and Gustafsson (2014).

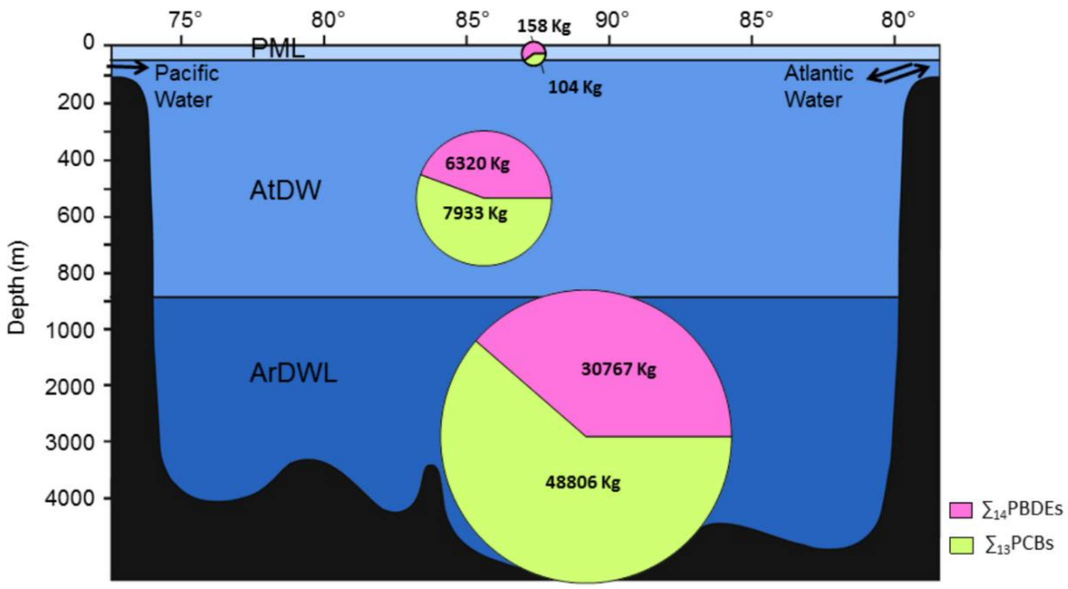

Figure 2.6. Comparison of calculated ∑14PBDE and ∑13PCB inventories (kg) in the water masses of the Central Arctic Ocean basin. Inventories were calculated from data on polybrominated diphenyl ether (PBDE) and polychlorinated biphenyl (PCB) concentrations in water from three expeditions in 2001 (AO-01), 2005 (Beringia-05), and 2008 (ISSS-08). PML: Polar Mixed Layer; AtWL: intermediate Atlantic water layer; ArDWL: Arctic deep water layer. Pie charts are drawn to scale representing the kg of PBDEs in each water mass of the Arctic Ocean. ∑14PBDE: Sum of BDE-17, 28, 71, 47, 66, 100, 99, 85, 154, 153, 138, 183, 190, 209). ∑13PCB: Sum of 13 CB-18, 28, 52, 70, 101, 110, 118, 105, 149, 153, 138, 180, 199. Reproduced with permission from Salvadó *et al.* (2016).

Polyfluoroalkyl substances (PFAS)

PFAS were observed in seawater samples collected from the Eurasian Basin (Yeung *et al.*, 2017), in concentrations of 11–174 pg l^{-1} Σ13PFAS (Table 2.1). They were mainly limited to the PML and halocline (150 m below the surface). The main PFAS compounds observed were PFOA, PFOS, PFBS, PFNA, PFHxA, PFHpA, PFDS, PFHxS, and PFUnDA. The profiles of the PFAS varied with location and depth, which may point to different sources (atmosphere, ocean currents, and rivers) and ocean circulation patterns. Higher concentrations of PFAS than PCBs were observed in the PML because PFAS dissolve better in water. Despite the observed low concentrations in the deep water, it is expected that this part of the CAO contains most of the

PFOS mass in the Arctic, a trend that is predicted to continue to increase until 2038 (Yeung *et al.*, 2017). This was also found in modelling studies in which it was estimated that 30% of the PFOS discharges from North America and Europe had reached the CAO in 2015, with the deep ocean being the ultimate PFOS sink (Zhang *et al.*, 2017). While PFOS concentrations at the surface appeared to have decreased since 2000, concentrations in the waters below 1000 m were thought to have increased (Zhang *et al.*, 2017).

In snow and melt ponds of first-year sea ice, higher PFAS concentrations and more PFAS compounds were observed than in the underlying sea water. Average ΣPFAS concentrations in snow and melt ponds were 403 ± 405 pg l^{-1}. Atmospheric deposition is thought to be an important source for PFAS in the Eurasian part of the CAO, especially because of the proximity to atmospheric emissions from the Eurasian continent (Yeung *et al.*, 2017).

2.3.2.2 Contaminant concentrations in sediment

Contaminant data in sediments from the CAO are severely lacking, with only some data reported for Hg and PFAS. No data were found for PCBs or PBDEs in sediments from the ecoregion.

Marine sediments from eight locations in the Arctic Ocean basin showed Hg concentrations varying from < 5 ng g^{-1} up to 170 ng g^{-1} (Gleason *et al.*, 2017; Table 2.2). The samples included information for stratigraphic ages spanning 56 Ma to the present. Based on this long time frame, a terrestrially dominated Hg source input for Arctic Ocean sediment was observed; other sources, however, as well as the influence of sea ice, atmospheric Hg depletion events, and anthropogenic Hg (in core top samples) on Hg isotopic signatures must also be considered (Gleason *et al.*, 2017).

Atmospheric deposition is currently thought to be a major source of Hg in the Arctic Ocean, resulting in approximately 100 metric tonnes being added annually, approximately half of its total modern Hg input (Douglas *et al.*, 2012). Inorganic Hg(II) is the dominant Hg species found in marine sediments and has been demonstrated to be the form of Hg dominating the total Hg pool for Arctic marine sediments (e.g. Soerensen *et al.*, 2016).

Polyfluoroalkyl substances (PFAS)

PFAS concentrations in surface sediments were 1.3 ± 0.5 ng g^{-1} Σ14PFAS, based on dry weight, at the border of the Amerasian Basin in 2010 (Kahkashan *et al.*, 2019; Table 2.2). The main PFAS components consisted of perfluorobutanoic acid (PFBS) and perfluorooctanoic acid (PFOA). Increasing trends of PFAS in surface sediments from the Bering Sea to the Arctic Ocean were observed, indicating oceanic transport. The concentrations of PFAS in surface sediments from the Bering Sea to the Chukchi Sea and adjacent Arctic Ocean were found to be at low–moderate levels when compared with other coastal and marine sediments worldwide.

2.3.2.3 Contaminant concentrations in biota

Contaminant data in biota in the CAO are severely lacking. Information in one publication (Bidleman *et al.*, 2013; Table 2.3) reported that Hg, PCB, and PBDE levels in archived samples (1983–1998) of the scavenging amphipod (*Eurythenes gryllus*) from the deep sea were 55–1 023 ng g^{-1} ww ∑Hg, 1020–74100 ng g^{-1} lw ∑104PCBs, and 27–1140 ng g^{-1} lw ∑7PBDEs.

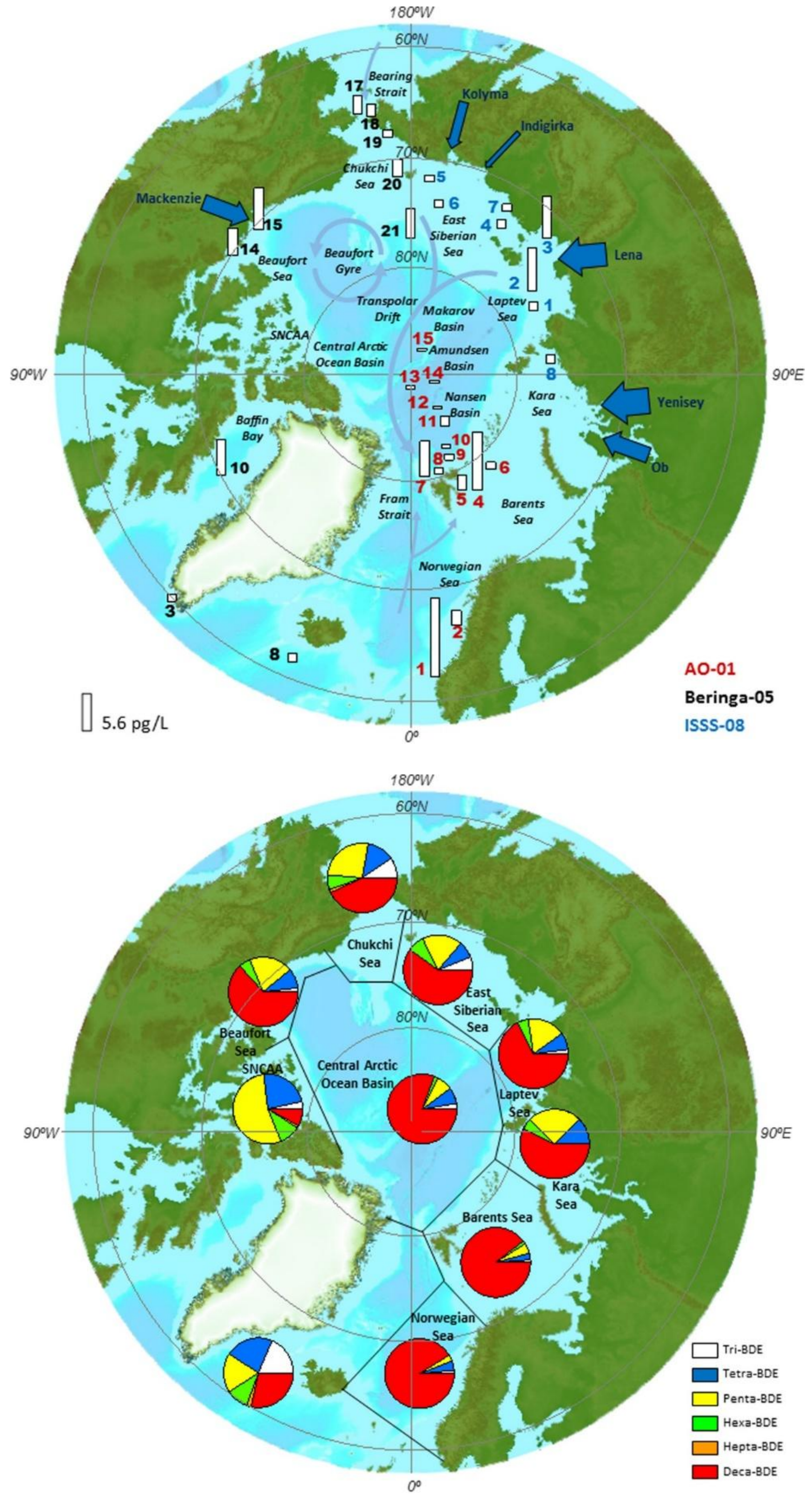

Figure 2.7. Upper panel: spatial distribution of Σ14PBDE concentrations (pg l^{-1}) in the Arctic Polar Mixed Layer, based on data from three expeditions in 2001 (AO-01), 2005 (Beringia-05), and 2008 (ISSS-08; Salvadó *et al.*, 2016). Lower panel: relative abundance of the tri- to deca-BDE congeners in the Polar Mixed Layer of the different pan-Arctic shelf seas and the Central Arctic Ocean (CAO), calculated from the data of all three basin-wide expeditions collectively. Reproduced with permission from Salvadó *et al.* (2016).

Table 2.1. Reported contaminant concentrations in seawater of the Central Arctic Ocean (CAO).

Compound	Sample type	Location	Sampling year	Reported concentrations	Reference
Mercury (Hg)	Seawater	CAO and wider Arctic	Review of studies	Highest Hg concentrations in surface waters (0–20 m; 1.21 ± 0.60 pM, n = 159) Slightly lower Hg concentrations in halocline waters (20–200 m; 0.94 ± 0.46 pM, n = 465) Low Hg concentrations in Arctic deep waters (>500 m; 0.67 ± 0.30 pM, n = 369) Estimated amount of Hg in the water column of the Arctic Ocean (based on all available Hg measurements): ~ 1 871 mg. Depth distribution: 44 mg at 0–20 m, 228 mg at 20–200 m, 224 mg at 200–500 m, and 1 375 mg below 500 m The deep waters have a long residence time (50–100 years), suggesting that Hg concentrations will change slowly in response to anthropogenic emissions and climate change No difference in Hg concentrations between the Nansen, Amundsen, Makarov, and Canadian basins	AMAP, 2021a
PCBs	Seawater	CAO	2001 (Oden, SWEDARCTIC 2001 expedition)	Σ7PCB concentrations in the Nansen Basin increased from 0.7 pg l^{-1} in the surface Polar Mixed Layer, to 3.6 pg l^{-1} in the Atlantic water layer, and 4.5 pg l^{-1} in the Arctic deep-water layer POC concentrations decreased by a factor of 10–30 from the surface Polar Mixed Layer to the Arctic deep-water layer, supporting a strong particle dissolution/mineralization-influence on the vertical distribution of PCBs	Sobek and Gustafsson, 2014
	Seawater	CAO and surrounding shelf seas	2001, 2005, 2008	Σ13PCB concentrations of 0.13–21 pg l^{-1}, with higher concentrations in the shelf seas and lower concentrations in the CAO basin	Carrizo and Gustafsson, 2011a
PBDEs	Seawater	CAO	2001 (Oden, SWEDARCTIC 2001 expedition), 2005 (Oden SWEDARCTIC 2005 expedition), 2008 (Yacob Smirnitskyi)	Σ14PBDE concentrations in the Polar Mixed Layer of 0.3–11.2 pg l^{-1}, and up to one order of magnitude higher in deep-water masses	Salvadó *et al.*, 2016
PFAS	Seawater, snow, melt pond water	CAO (and Beaufort and Chuckchi shelves)	2012 (Polarstern ARK-XXII/3 expedition)	Surface water concentrations of total PFASs in the CAO ranged from 11−174 pg l^{-1} 13 PFASs were routinely detected: C6−C12 PFCAs; C6, C8, and C10 PFSAs; MeFOSAA; EtFOSAA; and FOSA Average ΣPFAS concentrations in snow and melt ponds on sea ice: 403 ± 405 pg l^{-1}.	Yeung *et al.*, 2017

Table 2.2. Reported contaminant concentrations in sediment of the Central Arctic Ocean (CAO).

Compound	Sample type	Location	Sampling year	Reported concentrations	Reference
Mercury (Hg)	Surface sediment	CAO	2009 (LOMROG09) 2005 (HOTRAX05) 2005 (HOTRAX05) 2005 (HOTRAX05) 1996 (Oden 96/12)	Lomonosov Ridge: 120 ng g^{-1} Lomonosov Ridge: 113 ng g^{-1} Mendeleev Ridge: 55 ng g^{-1} Yermak Plateau: 55 ng g^{-1} Lomonosov Ridge: 31 ng g^{-1}	Gleason *et al.*, 2017
PFAS (also organochlorine pesticides)	Surface sediment	Bering Strait, Chukchi Sea, border of CAO	2010 (4th CHINARE expedition, July–September)	Total concentration (dry weight) of Σ14PFAS: 1.27 ± 0.53 ng g^{-1}.	Kahkashan *et al.*, 2019

Table 2.3. Reported contaminant concentrations in biota of the Central Arctic Ocean (CAO).

Compound	Sample type	Location	Sampling year	Reported concentrations	Reference
Mercury (Hg), PCBs, chlorobenzenes, organochlorine pesticides, and PBDEs	Archived specimens of the scavenging amphipod *Eurythenes gryllus*, collected 2 075–4 250 m below the surface, on five expeditions to the western and central CAO	CAO: deep basin	1983 – 1998	∑104PCBs: 1 020—74 100 ng g^{-1} lw ∑7PBDEs: 27–1 140 ng g^{-1} lw ∑Hg: 55–1 023 ng g^{-1} ww	Bidleman *et al.*, 2013
PCBs	Bacteria	CAO: northern Barents Sea, Makarov Basin east of Lomonosov ridge at 88°N (Canadian Basin), North Pole area on the Eurasian Basin side at 89°N	2001	Concentrations of individual PCB congeners in bacteria: 0.5–5 ng g^{-1} OC (organic carbon).	Sobek *et al.*, 2006

2.3.2.4 Contaminant concentrations in biota from surrounding areas

Data are sparsely available for the CAO; data from areas surrounding the CAO were compiled as additional information (Table 2.4). In shelf seas surrounding the CAO, some long-term marine time-series can be found for mussels, fish, birds, and mammals (Figure 2.8; Rigét *et al.*, 2019). For the detection of trends in contaminant concentrations, bird eggs showed the highest statistical power of all animal tissues because they have a consistent composition, can be sampled at the same site each year, and are not influenced by factors such as age and sex (Rigét *et al.*, 2019). The lowest statistical power was found in fish liver and muscle, probably because of the low contaminant levels found in these samples. The following two subsections – "Seabirds and eggs" and "Marine mammals" – include additional information on contaminant concentrations in the respective biota from areas surrounding the CAO.

Figure 2.8. Map of locations with long-term marine time-series of contaminants in areas surrounding the Central Arctic Ocean (CAO). Symbols indicate animal group. Included also are freshwater fish and air monitoring stations. Reproduced with permission from AMAP (2016a).

Seabirds and eggs

A survey of ivory gull (*Pagophila eburnean*) eggs in colonies surrounding the CAO (northeast Canada, northeast Greenland, Svalbard, Franz Josef Land, and Severnaya Zemlya) in 2006 found that PCBs were amongst the highest contaminant concentrations (Lucia *et al.*, 2015). Spatial differences in concentrations were found, with the highest mercury levels in Canada, the highest PBDE levels in Frans Josef Land, and the highest PFAS levels in Greenland (Lucia *et al.*, 2015).

In the feathers of nine migratory seabird species, Hg concentrations were approximately threefold higher during the non-breeding period than during the breeding period. This was probably because of a higher food intake and lower plumage exchange during the non-breeding period in winter (Albert *et al.*, 2021). Spatial differences were found between the Atlantic and Pacific regions. Smaller seasonal differences and lower non-breeding Hg concentrations were observed in the Pacific region than in the Atlantic, probably pointing to differences in Hg concentrations between the two regions.

Marine mammals

Marine mammals in the Arctic live long and have thick blubber (lipid) layers. Mammals that feed on invertebrates, such as the bowhead whale (*Balaena mysticetus*) and walrus (*Odobenus rosmarus*), have lower contaminant concentrations in their tissue than those that feed on fish, such as seals, beluga whale (*Delphinapterus leucas*), and narwhal (*Monodon monoceros)* (O'Hara *et al.*, 1999). This is a consequence of bioaccumulation processes that increase contaminant concentrations each step up on the food chain. Therefore, the highest concentrations can be found not only in species that feed on other marine mammals, such as polar bear, but also in indigenous people of which the lipid rich tissues of marine mammals form a part of their diet (O'Hara *et al.*, 1999). Indigenous people living on St. Lawrence Island had much higher body burdens of PCBs in their blood than populations on the US and Canadian mainland; this was considered to be a result of the long-range transport of PCBs to the Arctic (Miller *et al.*, 2013).

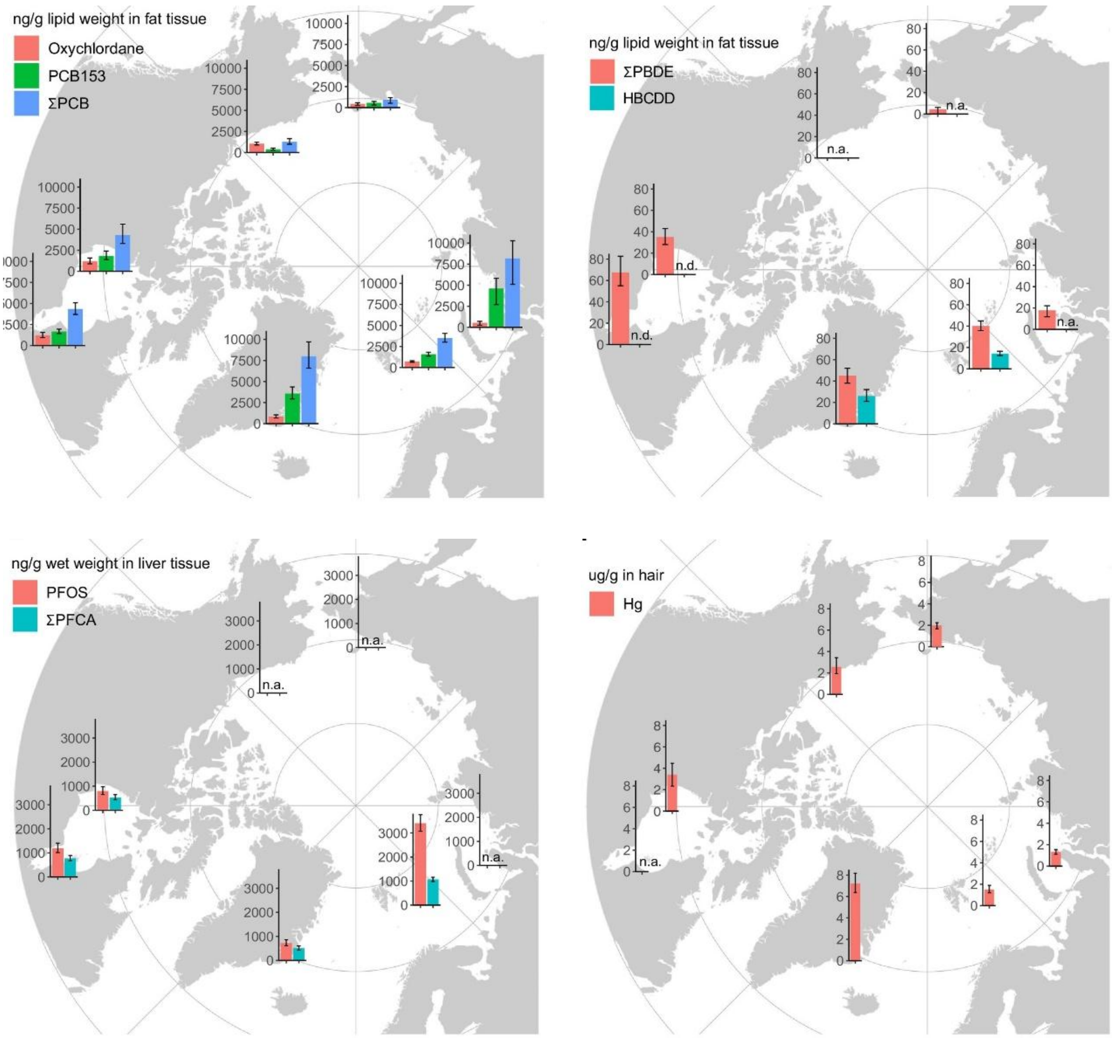

Figure 2.9. Circumpolar trends of contaminants in polar bear: ng g^{-1} lw ΣPCBs (upper left) and ng g^{-1} lw ΣPBDEs (upper right) in fat tissue, ng g^{-1} ww PFOS/ΣPFCA (ΣPFAS) in liver, and ng g^{-1} Hg in hair. Reproduced from Routti *et al.* (2019a).

Table 2.4. Reported contaminant concentrations in biota in areas directly surrounding the Central Arctic Ocean (CAO).

Compound	Sample type	Location	Sampling year	Reported concentrations	Reference
Mercury (Hg), PCBs, PBDEs, PFAS, and other compounds	Eggs	Circumpolar breeding grounds of the ivory gull	2006	0.06–3.9 μg g^{-1} ww Hg 244–3 389 ng g^{-1} ww Σ12PCB 2.10–55.3 ng g^{-1} ww Σ5BDE 18.6–118 ng g^{-1} ww Σ3PFAS (PFOA, PFNA, PFOS)	Lucia *et al.*, 2015
Mercury (Hg)	Feathers	Circumpolar breeding grounds of seabirds	2015–2017	*During breeding:* Overall mean Hg concentration: 1.20 ± 0.83 μg g^{-1} dw Highest Hg concentration in the West Atlantic: 0.41–6.97 μg g^{-1} Lowest Hg concentration in crested auklets (1.00 ±0.51 μg g^{-1}) and highest in rhinoceros auklets (3.47 ± 1.63 μg g^{-1}) *Non-breeding:* Overall mean Hg concentration: 3.60 ± 2.40 μg g^{-1} dw Highest Hg concentration in the West Atlantic: 5.42 ± 2.52 μg g^{-1} Lowest Hg concentration in crested auklets (1.45 ± 0.58 μg g^{-1}) and highest in rhinoceros auklets (6.89 ± 2.04 μg g^{-1})	Albert *et al.*, 2021
PCBs	Bowhead blubber and liver	Barrow, Alaska	1992–1993	26 bowhead blubber samples: mean of 459 ng g^{-1} lw 11 bowhead liver samples: mean of 980 ng g^{-1} lw	O'Hara *et al.*, 1999
PCBs	Polar bear (subcutaneous fat), ringed seal (blubber)	Areas surrounding the CAO	Polar bear: 1989–1993 Ringed: 1980s–1990s	Polar bear: ΣPCBs highest in bears from Svalbard, east Greenland and near M'Clure Strait (13–29 μg g^{-1} lipid) Ringed seal: ΣPCBs highest in Jarfjord, northern Norway, and the Yenisey Gulf (South Kara Sea) (~2.5-3.7 μg g^{-1} lipid)	Muir and Norstrom, 2000
Mercury (Hg), PCBs, PBDEs, PFAS, and other compounds	Polar bear: hair for Hg; adipose tissue (fat) for PCBs/PBDEs; and liver for PFAS	Areas surrounding the CAO	Hg: 2011–2017 PCBs/PBDEs/PFAS: 2012–2016	Ranges in geometric means: 1.3–7.2 μg g^{-1} Hg in hair 945–8 187 ng g^{-1} lw ΣPCBs in fat 4.4–68 ng g^{-1} lw ΣPBDEs in fat 527–1 070 ng g^{-1} ww ΣPFAS in liver	Routti *et al.*, 2019a
PCBs	Traditional food	St Lawrence Island, Bering Sea	2001–2003	Bowhead oil and blubber samples: > 300 ng g^{-1} ww Bearded and spotted seal, polar bear, and bowhead whale mungtak samples (blubber and skin): > 100 ng g^{-1} ww	Miller *et al.*, 2013

A recent review of contaminants in polar bears from the circumpolar Arctic showed that Hg, PCBs, PBDEs, PFOS, and other PFAS are the main contaminants to which polar bears are exposed (Routti *et al.*, 2019a). Circumpolar spatial trends varied largely between compounds (Figure 2.9).

2.3.3 Contaminant trends

Measurements in air at the Zeppelin Observatory at Svalbard show a general decrease in levels of most contaminants. Emission levels of Hg, however, have decreased only 14% since 1994, while emission levels in Europe have decreased by 61% over the same period.[1]

Time-series in biota from areas surrounding the CAO showed that PCBs and organochlorine pesticides (OCPs) have decreased in the Arctic during the last 20–30 years, although it must be noted that the main decrease of PCBs occurred before 2000 (Rigét *et al.*, 2019). PFOS and PBDEs showed a common trend of a concentration increase until about the mid-2000s followed by decreasing concentrations.

2.3.4 Radioactive contaminants

The Nordic and Barents seas have been exposed to radioactive contamination for more than half a century (see e.g. AMAP [2015]). The main sources have been global fallout following atmospheric nuclear weapons testing in the 1950s and 1960s, long-range transport of contamination from the European reprocessing plants Sellafield and La Hague, and the Chernobyl accident in 1986.

There are also a number of potential sources for radioactive contamination in the surrounding areas of the CAO (e.g. Jensen *et al.*, 2017). On the Barents Sea coast of the Kola Peninsula, the Kola Nuclear Power Plant can be found, as well as temporal storage sites for spent nuclear fuel and radioactive wastes and bases for nuclear-powered vessels. Further, large quantities of solid radioactive waste are dumped in the Kara Sea and in fjords at the east coast of Novaya Zemlya. In addition, there are three sunken nuclear submarines with spent nuclear fuel resting on the seabed in the Norwegian, Barents, and Kara seas. One of these, the Komsomolets, which rests at 1 673 m in the Norwegian Sea, is leaking radioactive contamination to the marine environment (e.g. Gwynn *et al.*, 2018; Heldal *et al.*, 2019). The monitoring of radioactive contamination in the marine environment in these areas is, therefore, of high importance.

In recent decades, there has been a slow decrease in levels of most anthropogenic radionuclides in the Barents Sea because of decreasing discharges from the European reprocessing plants, the reduced impact of fallout from the Chernobyl accident, radioactive decay of radionuclides, and their dilution in the water masses. Results from Norway's national monitoring programme Radioactivity in the Marine Environment (RAME) show that activity concentrations of cesium-137 (137Cs) in fish and other marine organisms in the Barents Sea are generally below 0.2 Bq kg^{-1} fresh weight (e.g. Skjerdal *et al.*, 2020). This is very low compared with the maximum permitted level for radioactive cesium in food set by the Norwegian authorities after the Chernobyl accident (600 Bq kg^{-1} fresh weight). The present levels of radioactive contamination in seawater and sediments in the Barents Sea are also low, with activity concentrations of 137Cs generally less than 2 Bq m^3 and 10 Bq kg^{-1}, respectively (Skjerdal *et al.*, 2020).

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[1] Indicators in the Barents Sea. Last accessed June 2025. Environment Norway. *In Norwegian*. https://miljostatus.miljodirektoratet.no/tema/hav-og-kyst/havindikatorer/barentshavet/forurensende-stoffer/lufttilforsler-av-miljogifter-til-barentshavet/

2.3.5 When do contaminants occur

Contaminants are continuously transported into and within the CAO and can be considered widespread. Sediments, especially in the deep sea, are thought to act as ultimate sink for contaminants (e.g. Sobek and Gustafsson, 2014; Zhang *et al.*, 2017).

2.4 Marine litter, including microplastics

Bjørn Einar Grøsvik and Jessica Nilsson

2.4.1 Definition of marine litter

Marine litter is defined as any persistent, manufactured, or processed solid material, especially plastic, that is discarded, disposed of, or abandoned in the marine environment. Litter is one of the most pervasive stressors affecting marine ecosystems globally (UNEP, 2009, 2016, 2021). Without meaningful action, plastic waste in aquatic ecosystems is projected to nearly triple by 2040 (UNEP, 2021). Marine litter follows the definitions used in PAME (PAME, 2019a; Information Box 2.1). The definitions do not supersede, modify, or otherwise affect the meaning of these terms as they are, or may be, used in any multilateral instrument or in the national laws and regulations of the Arctic States.

Information Box 2.1: Definitions

Land-based sources: Sources of pollution that originate from activities on land. The particles or substances released from these sources are dependent on a pathway to reach the ocean.

Macroplastics: Marine litter (see definition below) composed of plastic items greater than 5 mm in size.

Marine debris: Any persistent, manufactured, or processed solid material discarded, disposed of, lost, or abandoned in the marine and coastal environment. Examples may include plastic, machined wood, textiles, metal, glass, ceramics, rubber, and other persistent man-made material.

Marine litter: Marine debris.

Microplastics: Particles or fragments of plastic measuring less than 5 mm in diameter.

Microlitter: Particles or fragments of persistent, manufactured, or processed solid material less than 5 mm in diameter

Nano-, micro-, and macroplastic litter: Plastic litter exists in various sizes and is often commonly defined as nanoplastic (particles with a size equal to, or smaller than 100 nm [1/10 000 mm]), microplastic (items smaller than 5 mm in diameter), and macroplastic (items larger than 5 mm; Koelmans *et al.*, 2015).

Nanoplastics: Plastic particles with a size equal to or less than 100 nm (1/10 000 mm)

Plastic pellets: Plastic spherules or granules with sizes between 1 and 5 mm produced as feedstock for plastic production.

Sea-based sources: Sources of pollution that originate from activities at sea. These sources are not dependent on pathways to reach the ocean.

2.4.2 Initiatives on mitigation and guidelines for harmonization and monitoring in the Arctic

Marine plastics, microplastics, and their toxicity have been examined and identified (AMAP, 2017a), and a plan and technical guidelines for monitoring microplastics and litter in the Arctic has been developed (AMAP, 2021a,b). Other projects include Solid Waste Management in Remote Arctic Communities (SDWG, ongoing), Best Waste Management Practices for Small and Remote Arctic Communities (S/DWG, 2019), and the Kola Waste project (ACAP, 2021), which all contribute to the prevention of marine litter through identifying and cleaning up unauthorized waste disposal sites in the Saami territory of the Murmansk region, many of which are located on riverbanks or even on the coast (ACAP, 2021). Further work undertaken within the Arctic Council involves responses to the distribution and effects of plastic pollution (PAME, 2021a). This includes studies on the effects on Arctic seabirds and sea ducks (CAFF, 2021a,b,c) and on plastic ingestion by shorebirds, which includes a knowledge gap analysis (CAFF, 2021a).

It is important to use the same sampling methodology for assessing plastic litter so that comparisons can be made scientifically across the Arctic Ocean, including the CAO (AMAP, 2021a; PAME, 2019a). The Arctic Council's Protection of the Arctic Marine Environment (PAME) developed a model to research biological connectivity, and as this model investigates passive movement, it can also be used for performing risk analysis forecasting the movement of litter and oil spills (PAME, 2021a).

2.4.3 Where does litter occur in the CAO

Marine litter is present in all parts of the ocean (figures 2.10 and 2.11), even where there is no or little population (AMAP, 2021b,c; PAME, 2019a; UNEP, 2021). The movement of litter is controlled by ocean tides, currents, waves, and winds, with floating plastics accumulating (UNEP, 2021). Marine litter and microplastics may be transported into the CAO by ocean currents, sea-ice drift, and the atmosphere (Bergmann and Klages, 2012; Tekman *et al.*, 2017; Evangeliou *et al.*, 2020). Distant regions are a significant source (Bergmann *et al.*, 2022), as litter is brought in to the Arctic Ocean by North Atlantic and the North Pacific water. Buoyant marine plastic particles coming from the Eurasian riverine–coastal areas may flow all the way from the greater North Sea area via the Barents, Kara, and Laptev seas into the CAO (Huserbråten *et al.*, 2022). The many Arctic rivers that together carry about 11% of the globe's freshwater into the Arctic Ocean (Yakushev *et al.*, 2021) also transport litter and microplastics from the human settlements along the way (Figure 2.12). However, it is estimated that discharges from fishing and shipping contribute substantially more litter per year than those from rivers (10^5 tonnes plastic year^{-1} from fishing and shipping compared with 10^{-1} year^{-1} from river inflow [Dewey and Mackie, 2023]).

Relatively fresh polyester fibres are found to be delivered to the eastern Arctic Ocean via Atlantic Ocean inputs and/or atmospheric transport from the south. This indicates the global input of textile fibres in domestic wastewater from home laundry reaching this remote region (Ross *et al.*, 2021). Relatively large quantities of fibres enter the Arctic from the North Atlantic, while fewer and older fibres in the western Arctic may result from smaller (and potentially older) inputs from the Pacific and Atlantic oceans (Kim *et al.*, 2021). The western Arctic Ocean ice zone may therefore play both a role as a sink of global microplastics as well as a source of Arctic microplastics.

Back-tracking of stranded litter on Svalbard and in the Barents Sea has shown that most of the litter observed originates from regional sea areas, with fisheries and shipping as important contributing activities (Strand *et al.*, 2021).

Although no commercial fishing is carried out in the high seas of the CAO because of the fishery moratorium until 2035, abandoned, lost, or discarded fishing gear may drift into the ecoregion on ocean currents from adjacent areas where active fisheries take place (PAME, 2019a; European Union, 2021).

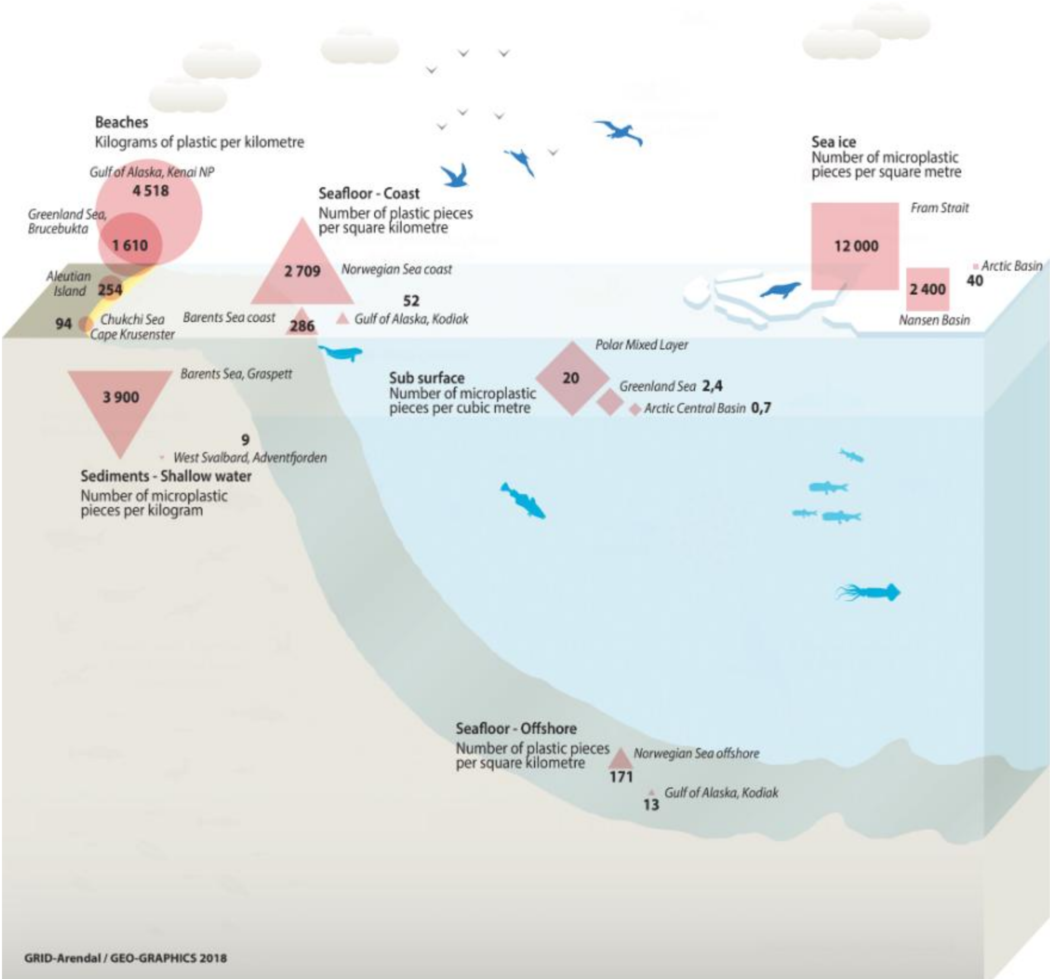

Figure 2.90. Distribution of Arctic marine litter and microplastics. Reproduced with permission from PAME and GirdArendal.

Knowledge on marine litter, including microplastics, in the Arctic marine region primarily stems from information that is more prevalent in areas where human activities are concentrated or for specific research topics (e.g. seabirds; Baak *et al.*, 2020). The amount of marine litter found in the Arctic varies greatly from 63 kg km^{-1} of plastic on the southeastern shores of Chukchi Sea coast up to 4 500 kg km^{-1} of plastic in the Kenai National Park in the Gulf of Alaska. Although the national park is sub-Arctic, it can be a source for Arctic marine litter because of the ocean currents (Polasek *et al.*, 2017).

Atmospheric transport of microplastics has recently been reported in ice floes from the Fram Strait and Svalbard (Bergmann *et al.*, 2019) and from snow samples from Baffin Bay (Huntington *et al.*, 2020; Table 2.5), and such transport is also modelled by Evangeliou *et al.* (2020).

High levels of microplastic particles have been reported in sea ice (Peeken *et al.*, 2018) and in marine sediments from the Fram Strait, which suggests sea ice as a transport vehicle (Bergmann *et al.*, 2017). The microplastic quantities reported in sediments from the Fram Strait are among the highest recorded in benthic sediments. This reporting corroborates both the deep sea as a major sink for microplastics and the presence of accumulation areas in this remote part of the world, fed by plastics transported to the North via the Thermohaline Circulation (Bergmann *et al.*, 2017). However, at present, there is relatively little knowledge and understanding of the distribution of marine litter in the CAO and the coastal areas around it (PAME, 2019a).

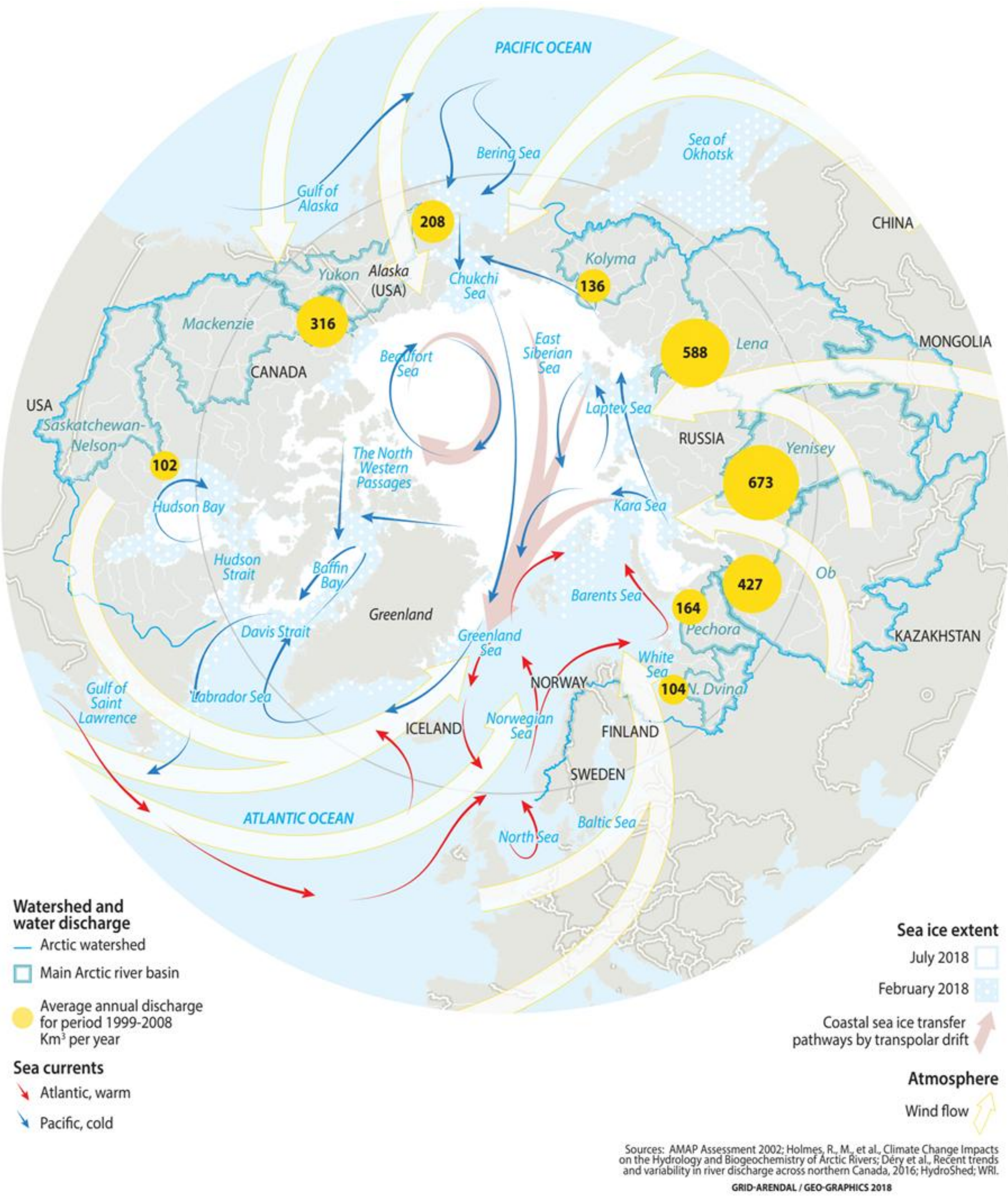

Figure 2.101. Arctic marine litter entry and dispersion pathways. Reproduced with permission from GridArendal.

Microplastics are found in the CAO, including the under-ice habitat, where polar cod (*Boreogadus saida*) were found to ingest it (Kühn *et al.*, 2018; Table 2.5). There is growing evidence that Arctic Sea ice entraps microplastic several orders of magnitude higher than seawater and thus can be a temporary sink and transport vector of microplastic in the Arctic Ocean (Kim *et al.*, 2021).

The presence of microplastics in Arctic fauna has been reviewed by Collard and Ask (2021) and in Arctic invertebrates together with recommendations on sampling protocols and potential indicator species (Grøsvik *et al.*, 2022). Levels of microplastics in the CAO and adjacent areas from different matrices are shown in Table 2.5.

2.4.4 When does litter occur in the CAO

Litter is continuously transported into and within the CAO and can be considered widespread (Figure 2.12).

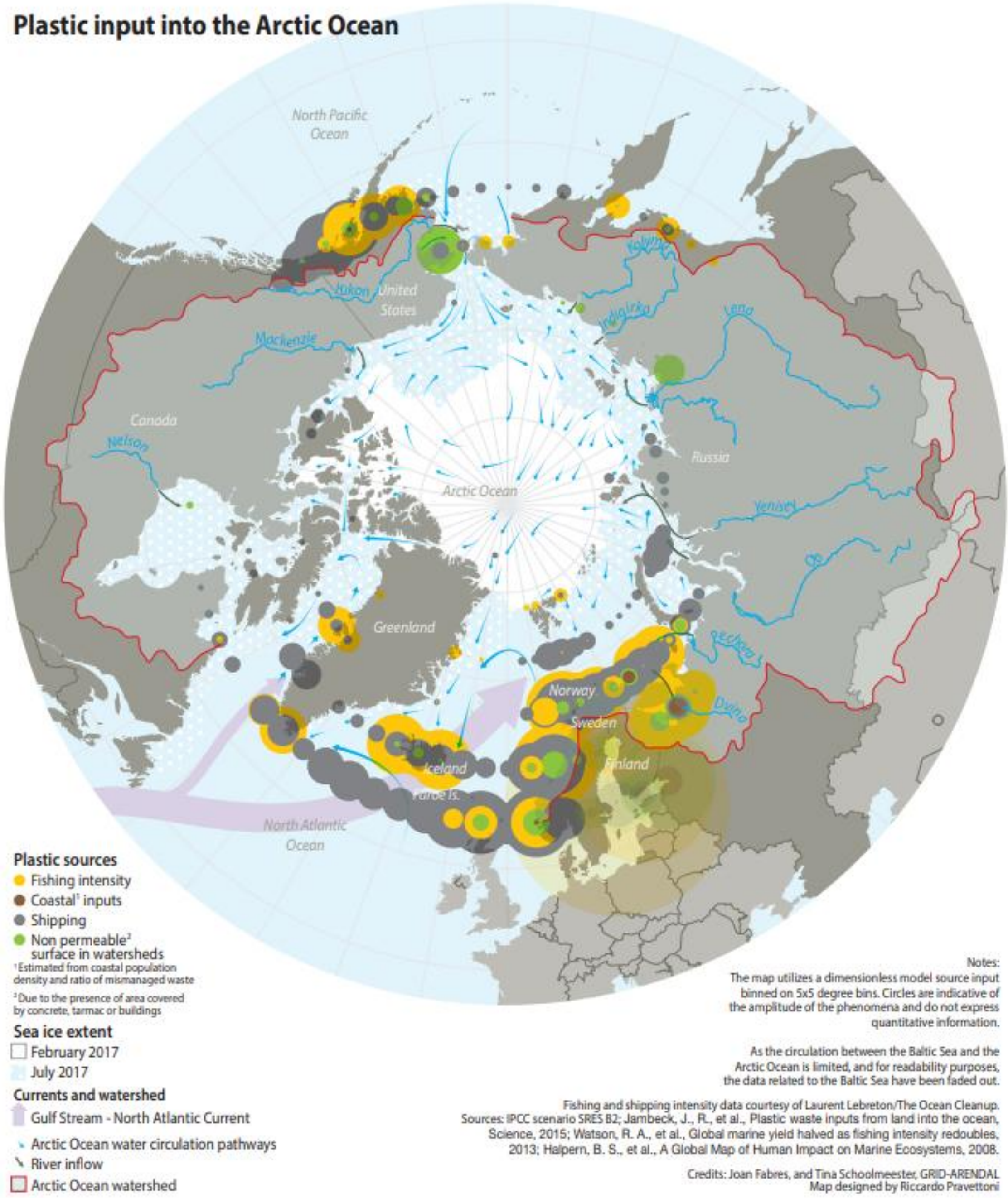

Figure 2.112. Plastic input into the Arctic Ocean is sourced by oceanographic currents, water shed, rivers, and anthropogenic activities at sea (PAME, 2019a). Reproduced with permission from PAME and GridArendal.

Table 2.5. Plastic in different matrixes in the Central Arctic Ocean (CAO) and adjacent areas. Abbreviations: ww = wet weigh, MP = microplastics.

Region	Matrix	Concentration	Reference
Fram Strait and Svalbard	Snow: > 11 µm	0–14.3 x 10^3 l^{-1}	Bergmann *et al.*, 2019
Hudson Bay to Baffin Bay	Snow: > 10 µm	1 MP in one of 7 samples	Huntington *et al.*, 2020
Central Arctic Ocean	Water under ice flow: > 100 µm	0–18 MPs m^{-3}	Kanhai *et al.*, 2020
Central Arctic Ocean	Sea ice: > 100 µm	2–17 MPs l^{-1}	Kanhai *et al.*, 2020
Fram Strait	Sea ice: > 11 µm	4.2 x 10^6 –1.2 x 10^7 MPs m^{-3}	Peeken *et al.*, 2018
North of Svalbard	Sea ice: > 11 µm	1.1–2.9 x 10^6 MPs m^{-3}	Peeken *et al.*, 2018
Western Arctic Ocean	Sea ice: > 100 µm	11.4 ± 9.12 x 10^3 MPs m^{-3}	Kim *et al.*, 2021
Arctic Ocean	Surface water: > 63 µm	21–65 MPs m^{-3}	Ross *et al.*, 2021
Central Arctic Ocean	Surface water: > 300 µm	7.72 MPs m^{-3}	Huang *et al.*, 2022
Central Arctic Ocean	Surface water (8.5 m depth): > 250 µm	0–375 MPs m^{-3} Median: 0.7 MPs m^{-3}	Kanhai *et al.*, 2019
Central Arctic Ocean	Deep and bottom waters: > 250 µm	0–104 MPs m^{-3}	Kanhai *et al.*, 2019
Central Arctic Ocean	Atlantic water: > 250 µm	0–95 MPs m^{-3}	Kanhai *et al.*, 2019
Barents Sea	Surface water: > 100 µm	0.85 MPs m^{-3}	Pakhomova *et al.*, 2022
North Atlantic	Surface water: > 100 µm	0.56 MPs m^{-3}	Pakhomova *et al.*, 2022
Siberian Arctic	Surface water: > 100 µm	0.71 MPs m^{-3}	Pakhomova *et al.*, 2022
Hudson Bay to Baffin Bay	Surface water: > 100 µm	0.22 ± 0.23 l^{-1}	Huntington *et al.*, 2020
Northwest of Svalbard	Surface water: > 300 µm	3 819–9 287 MPs km^{-2}	Hänninen *et al.*, 2021

Table 2.5 (cont.)

Region	**Matrix**	**Concentration**	**Reference**
Fram Strait	Surface water: > 300 µm	11 852 MPs km^{-2}	Hänninen *et al.*, 2021
Hudson Bay to Baffin Bay	Sediment: Fragments > 0.28 µm Fibres > 205 µm Films > 0.25 µm	1.93 ± 4.12 g^{-1}	Huntington *et al.*, 2020
Fram Strait	Sediment: > 11 µm	42–6 595 MPs kg^{-1}	Bergmann *et al.*, 2017
Hudson Bay to Baffin Bay	Zooplankton: > 100 µm	3.51 ± 4.00 g^{-1}	Huntington *et al.*, 2020
Chukchi Sea and Bering Sea	Invertebrates: > 100 µm	0.02–0.46 MPs g^{-1} ww	Fang *et al.*, 2018
Barents Sea	Polychaetes: > 45 µm	0.2–2.4 MPs indiv^{-1}	Knutsen *et al.*, 2020
Chukchi Sea	Acticidae und., *Chionoecetes opilio* and *Ctenodiscus crispatus*: > 100 µm	0–10 MPs indiv^{-1}	Fang *et al.*, 2021
Svalbard	Bivalve (*Hiatella arctica*): > 10 µm	1–184 MPs indiv^{-1}	Teichert *et al.*, 2021
Arctic Ocean	Stomach of polar cod: > 100 µm	2 MPs in 72 fish	Kühn *et al.*, 2018
Svalbard	Northern fulmar: > 5 mm	0.08 g individual^{-1} or 15.3 pieces individual^{-1}	Trevail *et al.*, 2015
Greenland Sea	Stomach of hooded seal pup: > 5 mm	2 pieces	Pinzone *et al.*, 2021

3 Ship traffic

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3.1 Ship traffic in the CAO

North of the Arctic Circle, maritime ship traffic has increased, with a Pacific to Atlantic east–west direction and with pronounced seasonality, and this increase is happening as sea ice is diminishing (Berkman *et al.*, 2022a). The sailed distance (Information Box 3.2) within the Arctic LMEs (Information Box 3.1; Figure 3.2) varies, with the Barents Sea being the most active (84% of the traffic in the Arctic LMEs, Figure 3.1), followed by the Kara, Chukchi, Greenland, and Laptev seas. The northern Canadian Archipelago has the lowest sailed distance.

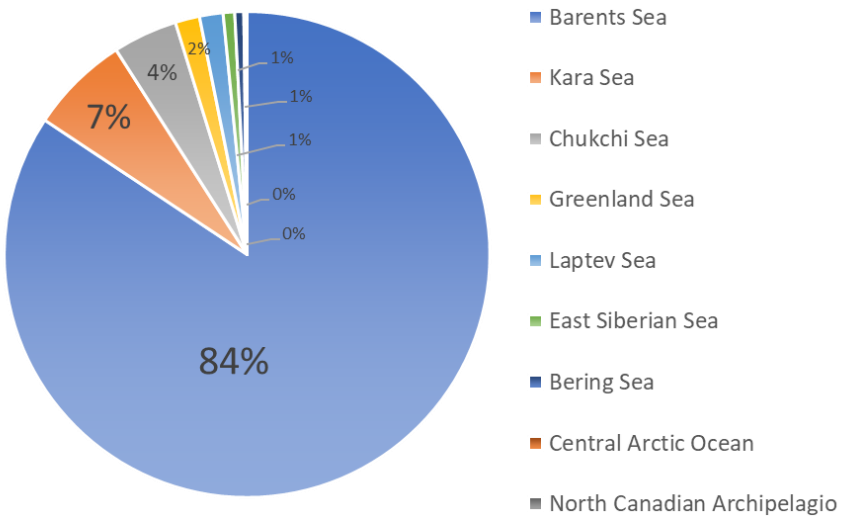

Figure 3.1. The distribution of sailed distance (the mean during 2012–2020) per large marine ecosystem (% nautical miles, nmi) of all ships (see also Information Box 3.2).

Compared to the Barents Sea, there are few ships in LME of the CAO. Ship movements in the ecoregion indicate direct transit lines to the North Pole (e.g. to the Barneo ice camp). Others are either peripheral across extended, confined regions, or are two-ship parallel transits relating to maritime activities, including fishing and research activities, that could be further quantified (Visalli *et al.*, 2020).

International law requires that every ship be registered in a country, known as its flag state. A ship and its crew are subject to the laws of its flag state even well outside waters subject to the flag state's jurisdiction. A ship owner can register their ship in flag registries other than their own nation. Up to 2019, the number of flag states operating in the CAO increased from 5 to 22, with the Russian Federation, US, and Panama as the dominant flag states (Berkman *et al.*, 2020). In the period 2012–2022 (Table 3.1), a total of 15 different ship flags operated in the ecoregion.

Russian-flagged vessels (RUS), which were present each year, operated for the most hours in the area, with a maximum of 4 574 hours in 2020 (Table 3.1). German-flagged vessels (GER) were present all years except 2013 and 2021 and with maximum operating hours in 2020. Vessels flagged in Canada (CAN) were present all years except 2012 and had the most activity in 2014 and 2015, while Swedish (SWD) and Chinese (CHR) vessels operated in some years and were most active in 2018 and 2021, respectively. US did not have any ship records before 2014, while Norway did not have any recorded before 2018. The US was most active in 2015, while Norway had the most activity in 2021 (Table 3.1).

Information Box 3.1: Large marine ecosystems (LMEs)

The Central Arctic Ocean (CAO) is surrounded by eight LMEs. The Barents Sea LME is the most ship-trafficked area, followed by the Kara Sea and the Chukchi Sea LMEs (Figure 3.1). In the period 2012–2020, the total distance sailed (nmi) in the Barents Sea LME ranged from a minimum of 2.7 million nm in 2013 to a maximum of 8.8 million nmi in 2020.

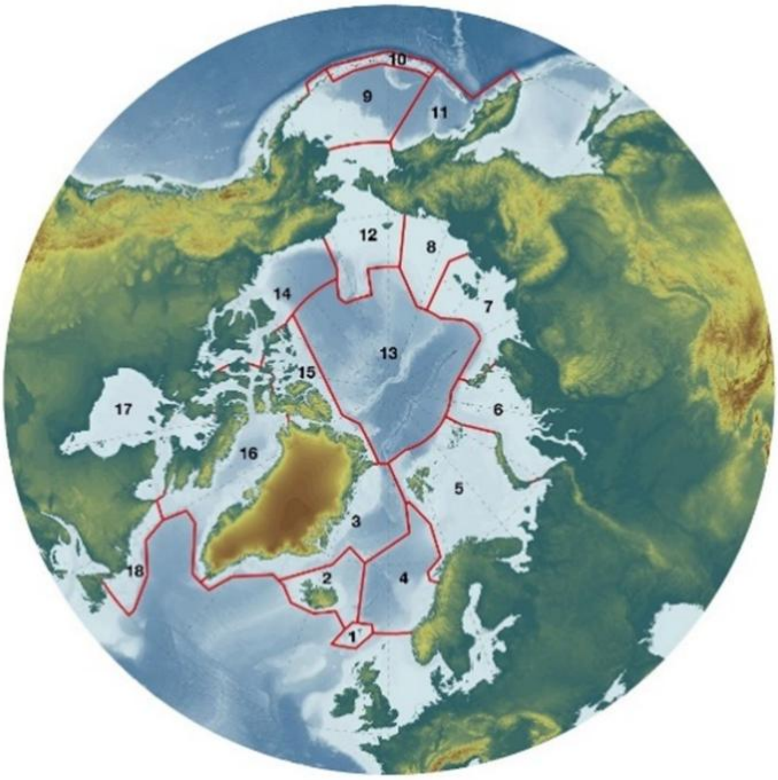

Figure 3.2. Map of the Arctic large marine ecosystems (LMEs) including the Central Arctic Ocean (13), and the LMEs bordering it: The Barents Sea (5), Kara Sea (6), Laptev Sea (7), East Siberian Sea (8), Bering Sea (9 and 11), Aleutian Islands (10), Northern Bering-Chukchi (12), Beaufort Sea (14), Canadian High Arctic-North Greenland (15), Baffin Bay (16), Hudson Bay (17) and Labrador (Newfoundland (18).

Read more on LMEs and where this map comes from here:

- **Arctic LMEs described by PAME – PAME projects homepage. Last accessed November 2025. https://www.pame.is/projects/ecosystem-approach/arctic-large-marine-ecosystems-lme-s**
- **Arctic LMEs described by PICES – PICES Regional Reports for Regions 13, 14, 15, and 16. Last accessed November 2025. PICES_NPESR3_Region13_Report.pdf; PICES_NPESR3_Region14_Report.pdf; PICES_NPESR3_Region15_Report.pdf; and PICES_NPESR3_Region16 Report.pdf.**

Table 3.1. The annual number of operating hours per flag state in the period 2012–2022 within the Central Arctic Ocean (CAO) large marine ecosystem (LME; data from the ASTD, see Information Box 3.2). Blank fields means that no ship was recorded during that period.

Flag code	Flag state	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
RUS	Russia	1 047	1 278	2 738	1 215	555	551	1 524	2 919	4 574	911	2 590
GER	Germany	1 122		1 648	848	779	104	645	2 308	4 592		89
CAN	Canada		152	1 342	1 696	968	193	164	191	146	193	58
SWD	Sweden	517	62	622		812		1 110			857	
CHR	China	183		434		434	353	500	5	665	754	
USA	United States				949	91		319	330		385	472
NOR	Norway							144	584		800	540
KOR	Republic of Korea	161	55	197	250	121	118	87	138	155	248	195
FRA	France									96	229	659
PAN	Panama			341	191	106						
NTH	Netherlands									132		
BAH	Bahamas							16	27			
NIS	Norway International Ship Register	19									20	
VAN	Vanuatu	21										
MAI	Marshall Islands							12				
Unknown		19	239	64	1 109		12	63	395	718	26	19
Total	Hour year^{-1}	3 089	1 786	7 386	6 258	3 866	1 331	4 584	6 897	11 078	4 423	4 622

Information Box 3.2: How ship data were accessed and applied

In this chapter, we have used the Arctic Ship Traffic Database (ASTD) system. This database uses data collected by receipt of automatic identification system (AIS) transmissions using satellites from Norway and US. The ASTD provides a wide range of historical information, including ship tracks by ship type, information on number of ships in over 60 ports/communities across the Arctic, detailed measurements of emissions by ships, shipping activity in specific areas (e.g. the EEZs, Arctic LMEs, and the Polar Code 2024 area), and fuel consumption by ships. The ASTD defines 15 different ship types and nine different measures, including sailed distance, number of ships, operating hours, fuel consumption, and a set of emissions.

It is important to be aware that ships can turn off their AIS temporarily, to either hide their locations from competitors or because of emergencies such as avoiding piracy. This underscores the limitation of over-reliance on AIS tracking. In fact, vessels frequently disable their devices in productive fishing grounds, likely to hide their locations from competitors. Vessels also disable their devices in historically dangerous waters prone to piracy, likely to avoid attacks. Investigations show that disabled AIS transponders obscure about 6% of all global fishing vessel activity (Welch *et al*., 2020).

Only ships over 300 gross tonnage are required to carry AIS. The ASTD also does not include military shipping activities.

For more information:

- Arctic Ship Traffic Data (ASTD) project. Last accessed June 2025. PAME. https://pame.is/ourwork/arctic-shipping/current-shipping-projects/astd/
- ASTD data information document. Last accessed June 2025. PAME. https://pame.is/images/03_Projects/ASTD/ASTD_Data_v5.pdf
- Welch et al. (2022)

3.2 Spatial coverage of ship traffic

The sea-ice cover in the CAO is at its maximum in March (see light and dark blue shading in Figure 3.3) and at its minimum in September (only dark shading in Figure 3.3). The ice cover restricts the types of ships operating in the area and where they can operate. However, the September ice is now shrinking at a rate of 12.6% decade^{-1} compared to its average extent during 1981–2010.[2]

Ten different ship types were reported in the ecoregion for the period 2012–2022 (Table 3.2). Because the Arctic Ship Traffic Data (ASTD) database does not include military vessels and is a voluntary registration system, it is anticipated that the numbers in Table 3.2 are minimums. Icebreakers (mainly scientific vessels) made up the largest category of individual vessels in all years, with a maximum of 15 ships in 2020. Despite some ships entering the area multiple times within a given year, they will only be accounted for once. Cruise ships (both icebreakers and non-icebreakers) were present most years (one to four ships), while other ship types were only recorded in a few years and with fewer than two ships during the entire year. The highest number of ships was recorded during 2018–2020.

[2] Arctic Sea ice minimum extent. Last accessed June 2025. NASA. https://climate.nasa.gov/vital-signs/arctic-sea-ice/

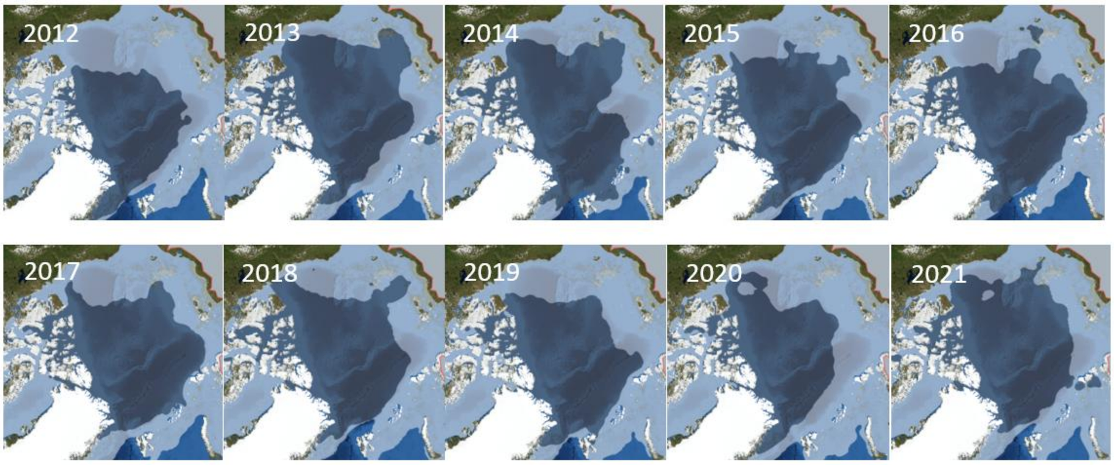

Figure 3.3. The annual (2012–2021) maximum ice cover (light blue and dark blue colour) and minimum ice cover (dark blue colour) of the Central Arctic Ocean (CAO). The total mill km² of ice in September in 2012 = 3.4; 2013 = 5.05; 2014 = 5.03; 2015 = 4,43; 2016 = 4,17; 2017 = 4.67; 2018 = 4.66; 2019 = 4.19; 2020 = 3.82; 2021 = 4.72; 2022 = 4.67.

Table 3.2. Number of ships in the Central Arctic Ocean (CAO) for 10 different ship types during 2012–2022. (Data from the ASTD, see Information Box 3.2). Blank fields means that no ships were recorded in this period.

	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Icebreaker ships	11	7	13	13	10	6	14	13	15	10	11
Cruise ships	1	2	2	2				4	2	2	1
Fishing vessels		1					1		2		
Container ships						1			1		
General cargo ships									2		
Oil product tankers									1	1	
Passenger ships							2				
Bulk carriers							1				
Chemical tankers								1			
Service offshore vessels								1			
Total number of ships	**12**	**10**	**15**	**15**	**10**	**7**	**18**	**19**	**23**	**13**	**12**

Shipping activity was highest in 2014 and 2020, while 2017 saw the lowest levels of sailing activity and operational hours (Figure 3.4). Icebreakers had the most operating hours and longest sailed distance inside the ecoregion followed by cruise ships.

Other ship types, mainly following the Northeast Passage, made a few short incursions into the ecoregion. However, in 2020, general cargo ships (755 nmi over 143 hours) and container ships (441 nmi over 142 hours) sailed greater distances and operated longer within the ecoregion than in any other years. This was associated with the record low ice cover that year (Figure 3.3).

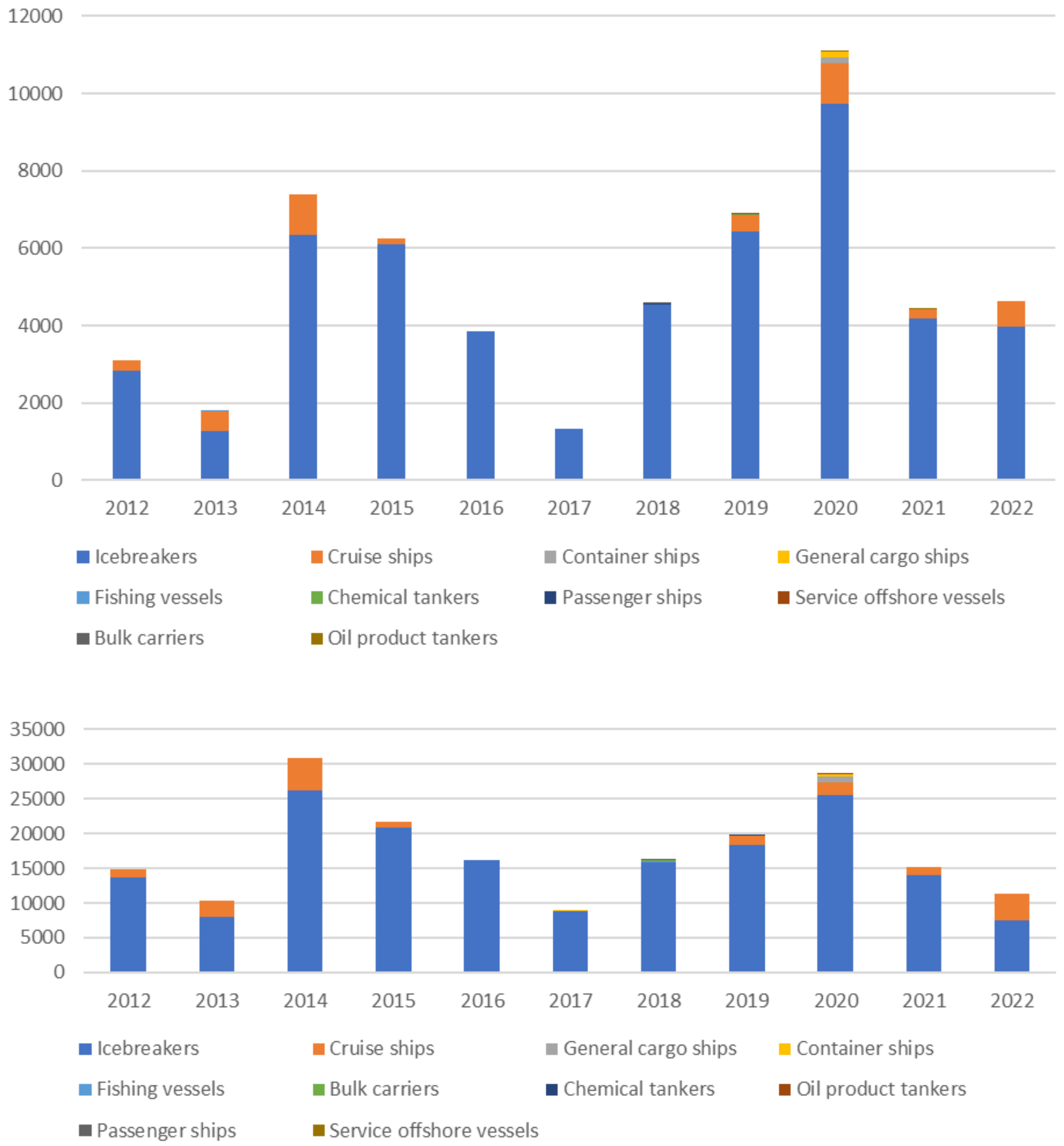

Figure 3.4. The summed annual operating hours (upper panel) and nautical miles sailed (lower panel) by 10 different ship types within the Central Arctic Ocean (CAO) during 2012–2022. Data from the ASTD (see Information Box 3.2).

The spatial distribution of ships within the ecoregion spread out northwards from the Fram and Bering straits, as illustrated by the most common ship type (icebreakers) in the busiest months (September and October) in 2014 and 2020 (Figure 3.5).

An increasing proportion of the new expedition cruise ships deployed in the Arctic, marketed to tourists looking for an authentic experience of nature[3], can also be expected to expand in the ecoregion.

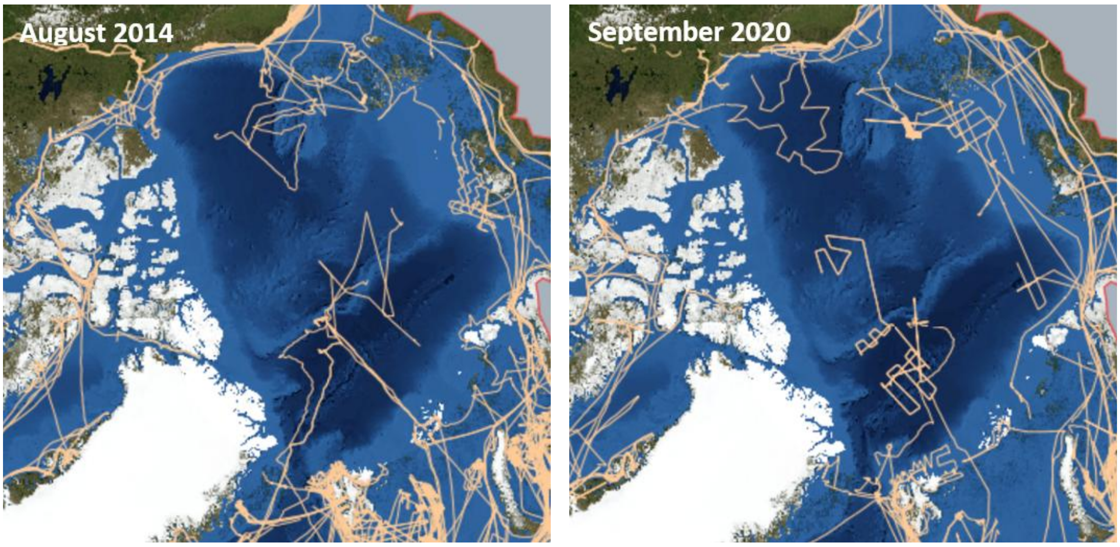

Figure 3.5. The spatial distribution of icebreakers in the Central Arctic Ocean (CAO) in August 2014 (lines in the figure in the left panel) and in September 2020 (lines in the figure in the right panel), where maximum operating hours were recorded by the ASTD.

3.3 Temporal occurrence of ship traffic

During most years, the most ship operating hours in the CAO occur in the months of July, August, and September (Figure 3.7). However, in 2020, there was continuous activity during January–May. In 2019 and 2022, there was relatively high activity recorded during the last part of the year, in November and December (Figure 3.7).

When the annual September ice cover is compared with the total ship operating hours during the same month in the ecoregion, no clear pattern was observed (Figure 3.8). This may be explained by the presence of icebreakers, which do not depend on lower ice cover to operate.

In the ecoregion, the duration of the icebreaker season ranged from 4 months in 2017 to 11 months in 2020, while cruise ships, which are present almost every year, operate mostly during July–October (Table 3.3).

From 2018 to 2020, the duration of the season for other ships varied from one to three months (Table 3.3).

[3] Forskningsskipet Kronprins Haakon og cruiseskipet Le Commandant Charcot møttes på Nordpolen. 2022. High North News. *In Norwegian.* https://www.highnorthnews.com/en/forskningsskipet-kronprins-haakon-og-cruiseskipet-le-commandant-charcot-mottes-pa-nordpolen

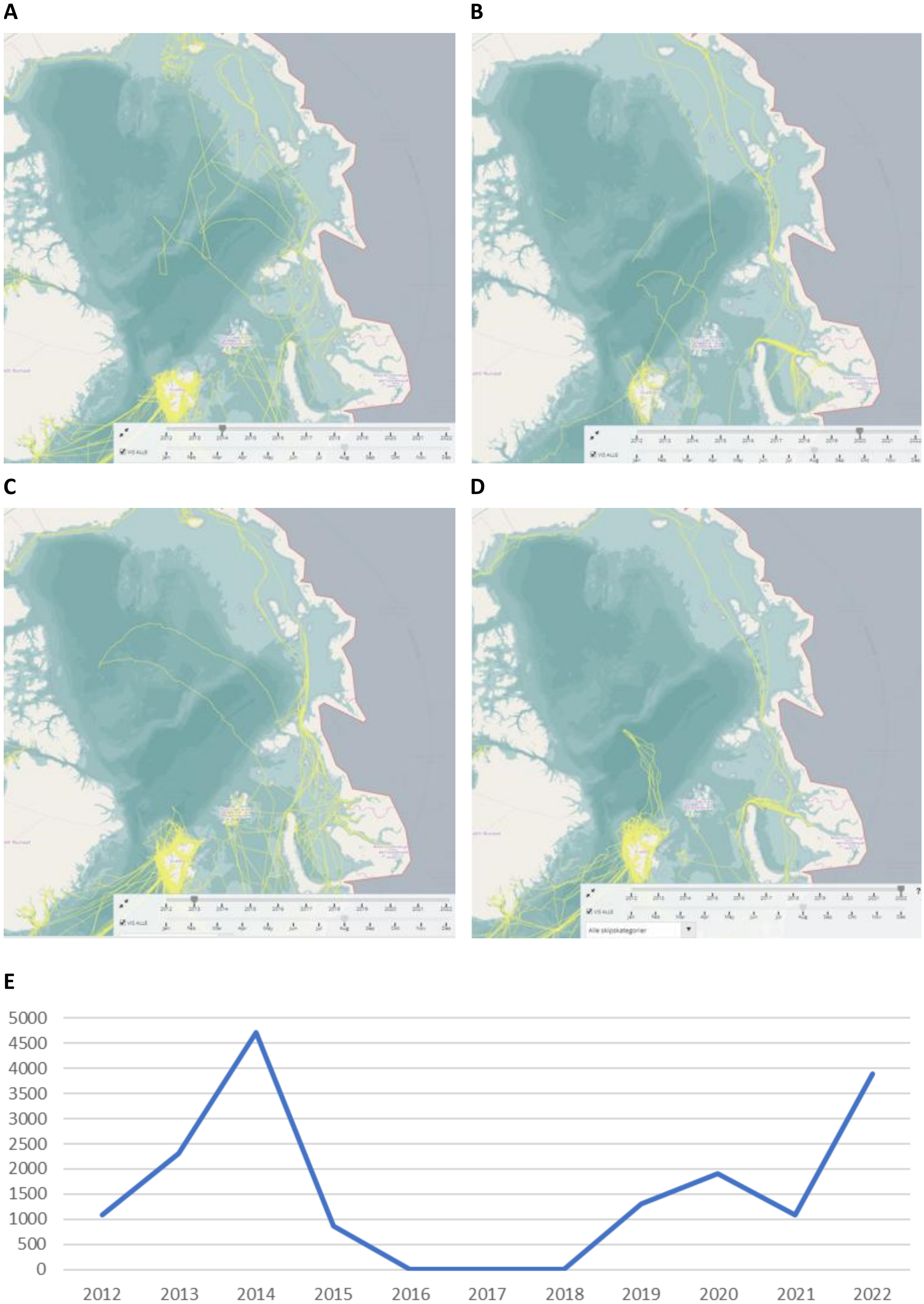

Figure 3.6. Cruise ships in the Central Arctic Ocean (CAO) as the annual spatial distribution of individual sailing routes in 2012 (A) and 2014 (B) and again in 2020 (C) and 2022 (D) (2022 only during January–September); and the sailed distance (nmi, from ASTD) for cruise ships within the CAO large marine ecosystem (LME) during 2012–2022 (panel E). Data and figures from the ASTD (see Information Box 3.2).

Table 3.3. The number of monthly operating hours per ship type during 2012–2022 in the Central Arctic Ocean (CAO). Numbers in bold are maximum values. Icebreakers includes both research, towing/pushing, and "unspecified". Data from the ASTD (see Information Box 3.2). Blank fields means that no ships were recorded in that period.

Year	Ship type	January	February	March	April	May	June	July	August	September	October	November	December
2012	Icebreaker ships						44	**237**	**1 271**	**1 169**	**114**		
	Cruise ships								**83**	**172**			
2013	Icebreaker ships						89	**253**	**356**	**507**	**76**		
	Cruise ships						428			**62**			
	Fishing vessels							**16**					
2014	Icebreaker ships						102	**843**	**2 702**	**2 287**	**417**		
	Cruise ships					18			**802**	**214**			
2015	Icebreaker ships	**477**	**235**	250	125		263	**308**	**1 833**	**2 353**	**271**		
	Cruise ships								**145**				
2016	Icebreaker ships						121	**268**	**1 566**	**1 430**	**480**		
2017	Icebreaker ships						134	**353**	**614**	**216**			1
	Container ships			2	9								
2018	Icebreaker ships						179	**222**	**2 004**	**1 753**	**388**		
	Passenger ships								**16**				
	Bulk carriers								**12**				
	Fishing vessels					10							
2019	Icebreaker ships		28				205	**406**	**1 570**	**1 264**	**1 480**	**720**	**743**
	Cruise ships								**27**	**30**	**8**		**378**
	Chemical tankers	24											
	Service offshore vessels								**14**				

Table 3.3 (cont.)

Year	Ship type	January	February	March	April	May	June	July	August	September	October	November	December
2020	Icebreaker ships	**744**	**694**	**914**	**720**	**619**	**73**	**123**	**1 344**	**2 709**	**1 599**	196	
	Cruise ships		**497**	**462**						**96**			
	Container ships							**26**	**86**	**31**			
	General cargo ships							**17**	**68**	**57**			
	Oil product tankers								3				
2021	Icebreaker ships						3	**351**	**1 665**	**1 600**	**544**	11	0
	Cruise ships									**250**			
2022	Icebreaker ships	2						**497**	**840**		**1 156**	721	748
	Cruise ships							**335**	**324**				

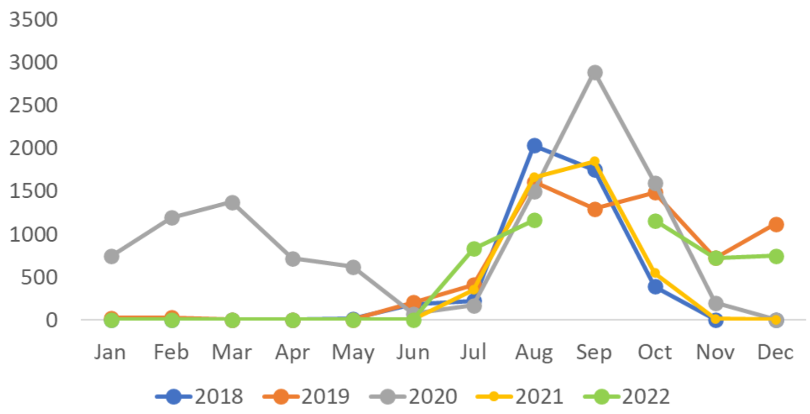

Figure 3.7. The monthly operating hours by all ships within the Central Arctic Ocean (CAO) during 2018–2022. Data from the ASTD (see Information Box 3.2).

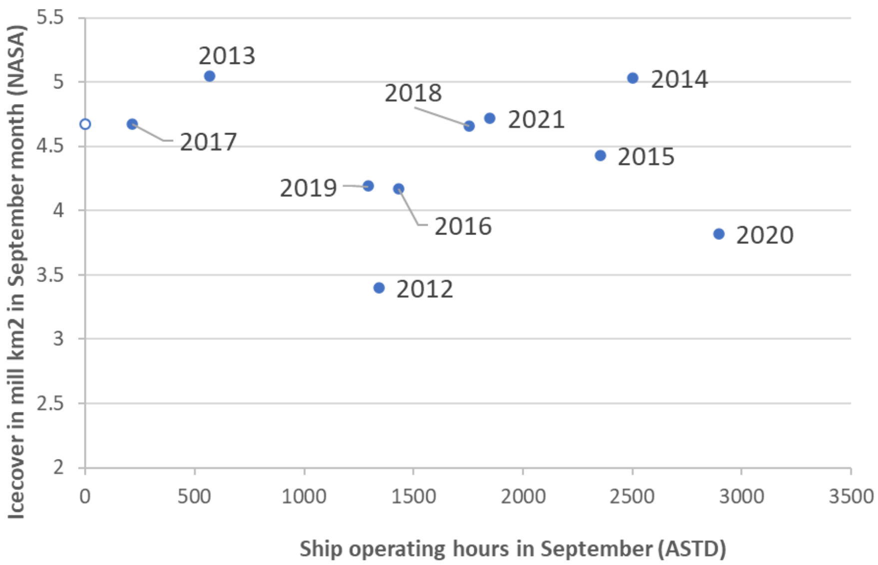

Figure 3.8. Scatterplot of ship operating hours in the Central Arctic Ocean (CAO) in September and the ice cover in September of the Arctic during 2012–2021. Data from the ASTD (see Information Box 3.2).

4 Tourism

Lis L. Jørgensen, Hauke Flores, Kevin Hedges, Paul Arthur Berkman, and Jacqueline M. Grebmeier

4.1 Tourism in the CAO

People visit the CAO ecoregion through different means, both by travelling on cruise ships and by being transported by air onto the icecap to stay in established tent camps. Groups of adventurers are also crossing the icecap by ski. With the realization that climate change has begun to significantly transform the polar regions, with areas opening up during summer in the next 10–20 years, the Arctic has now become a destination of “last chance tourism” (Lemelin *et al.*, 2010). This expression describes tourism that aims to witness features of nature that will soon disappear, such as glaciers and ice-associated wildlife (Varnajot and Saarinen, 2021). The further breakup of the Arctic sea-ice cover will promote this development by improving the accessibility of the ecoregion for less ice-capable vessels. Overall, tourism in the Arctic region is expected to continue its growth in the foreseeable future. One market segment that has particularly grown is expedition cruising: cruises with relatively small boats (of 100–200 passengers) of tourists looking for an authentic experience of nature. Expedition cruising now accounts for about 25% of the cruise passengers in the high-Arctic region (Tetu *et al.*, 2019). Around 1 000 tourists visit the North Pole every year, mainly hosted by Russian tour operators (Lukina *et al.*, 2020).

Most national tourism offices in Arctic countries have formed strategies to promote domestic Arctic tourism. Tourist services are characterized by the uniqueness and comprehensiveness of the tourist offer. However, the Arctic is a very vulnerable region, where even a small number of tourists can cause irreparable harm to the environment (Timoshenko, 2020), and where meeting basic principles of sustainability in the development of tourist destinations must be investigated (Timoshenko, 2019). Timoshenko (2020) defines the most promising tourist attractions in the Russian Arctic as (i) travelling or cruising on the atomic icebreakers of Rosatomflot, (ii) transiting through the Arctic Circle, (iii) visiting the North Pole, (iv) active and extreme sports (like ice diving, parachuting, and hot air ballooning), and (v) adventure tourism.

Information Box 4.1: Tourism in the CAO

Since 1991, the Quark Expeditions (2024) have brought about 500 people each year to visit the North Pole with the help of powerful nuclear icebreakers. In July 1999, the expedition company achieved the first circumnavigation of the Arctic Ocean. In 2008, it hosted the first maiden voyage to the North Pole of the nuclear icebreaker. In 2019, its 60th expedition cruise to the North Pole took place before the COVID-19 pandemic. The expeditions include sightseeing by helicopter and possibly taking a tethered hot-air balloon ride at 90°N.

For more information:

- North Pole expeditions by Quark Expeditions. Last accessed November 2025. https://explore.quarkexpeditions.com/north-pole
- Blog post on Quark Expeditions maiden voyage to the North Pole. Last accessed November 2025. https://explore.quarkexpeditions.com/north-pole/north-pole-dreaming-journey-to-the-top-of-the-world

Tourist activities, therefore, include cruise ships, aircraft, and automobiles on the ice. Tourism in the Arctic has rapidly increased in the past two decades and is likely to further grow after the COVID-19 pandemic (Runge *et al.*, 2020). A growing proportion of the human population can afford traveling to remote locations, and a growing tourism sector in the Arctic region has benefitted from sea-ice decline and the resulting increasing accessibility of the Arctic region, which has enabled the development of new touristic products (reviewed by Tetu *et al.*, 2019).

4.2 Spatial coverage of tourism

An increasing proportion of the new expedition cruise ships deployed in the Arctic can be expected to also expand in the CAO.

Russia owns the largest portion of the Arctic, and its current most exclusive Arctic tourism offer is a cruise to the North Pole. This is a growing industry still limited by the underdevelopment of transport and logistics channels in the Russian Arctic (Lukina *et al.*, 2020, Table 4.1). However, the development of ecotourism, and extreme-, event-, scientific-, cognitive-, and ethnographic tourism is considered a promising direction of development of Russian Arctic tourism.

Table 4.1. Examples of tourist activities in the Central Arctic Ocean (CAO; excluding tourist cruise ships.

Activity at the North pole	Transport	Year	Period
Russian camp of Barneo[1] close to the North Pole; for scientists and tourists	Includes aircraft, helicopter, bulldozers	Annually since 2000 to 2018; cancelled 2019–2021 during COVID-19 pandemic	March–April
The Adventure Consultants ski expedition	Aircraft	2022	April
The Quark Expedition to the North Pole	Icebreaker, helicopter, hot-air balloon	Since 1991	Ideally June and July
Underwater exploration of the North Pole	Submarines	1998 1999 2005	April
Russian Marine Live-Ice Automobile Expedition[2]	Cars	2009	April
Skiing crossing the ice cap	1–2 explorers on skies	1990 1994 2006 2007 2019 2001	March–May March–April Jan–March May–June Sep–Dec ?

[1] Camp Barneo. Last accessed June 2025. Wikipedia. https://en.wikipedia.org/wiki/Barneo

[2] Marine Live-Ice Automobile Expedition. Last accessed June 2025. Wikipedia. https://en.wikipedia.org/-wiki/MLAE-2009

Journeys to the North Pole by air (landing by helicopter or on a runway on the ice) are or have been available to small groups of tourists through adventure holiday[4] companies.

The temporary seasonal Russian camp of Barneo[5,7], deployed on drifting ice, is a unique tourism experience of the Russian Arctic. The base allows the conduct of scientific research and can accommodate travellers and tourists simultaneously.

In 1937, the first plane landed on an ice floe at the North Pole. This voyage marked the beginning of the first drifting station SP-1, which successfully operated on the ice for nine months. Since that time, there have been improvements in flight technologies, and camps on Barneo have made Arctic tourism more accessible (Figure 4.1; Timoshenko, 2021).

In 2002, the Barneo[5,6] camp was established a short distance from the North Pole and served scientific researchers as well as tourism. The establishment of the Barneo, usually during March–April, involves helicopter search, one or two bulldozers (Figure 4.1) to make a 1 200 m long runway, aircraft flights for passengers and equipment into the ice cap [7].

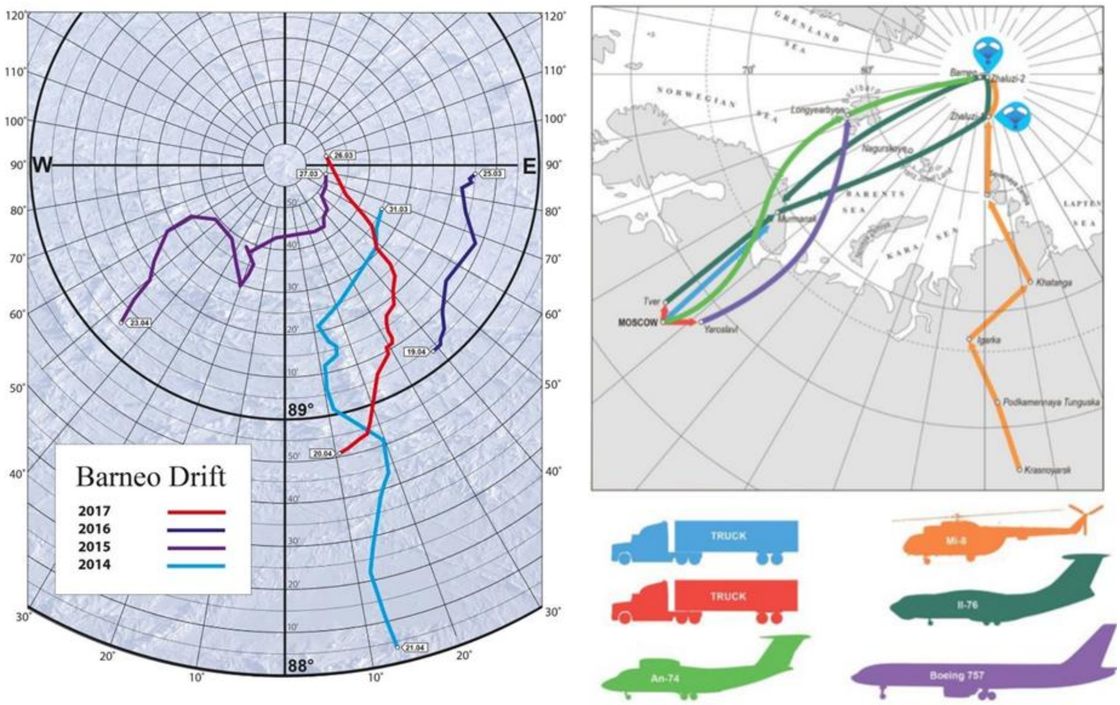

Figure 4.1. Transport to and from the Barneo camp Facebook page (Barneo camp, 2017).

After the camp is set up, flights to the camp are made by a AN-74 airplane[8]. This is a "light" airplane to reduce the risk of breaking through the ice. Airports on Longyearbyen (Svalbard), Khatanga Tamyr Peninsula (Siberia), and Franz Josef Land (Russia) are used as starting points to reach the camp.

[4] Adventure travel. Last accessed June 2025. Wikipedia. https://en.wikipedia.org/wiki/Adventure_travel

[5] Camp Barneo. Last accessed June 2025. Facebook. https://www.facebook.com/BarneoRu/

[6] Camp Barneo. Last accessed June 2025. Wikipedia. https://en.wikipedia.org/wiki/Barneo

[7] North Pole campers pack up after shortest ice drift ever. 2018. The Barents Observer. https://thebarentsobserver.com/en/arctic/2018/04/north-pole-campers-pack-after-shortest-ice-drift-ever

[8] AH-74. Last accessed June 2025. Wikipedia. https://ru.wikipedia.org/wiki/%D0%90%D0%BD-74

This type of aircraft may carry from 10 to 52 people depending on modification and cargo (equipment, instruments, scientific equipment, etc.) and there may be several flights per day if weather conditions are favourable. Up to 300 people stay on the camp annually[9], which can accommodate 100 guests and about 40 staff members per day[10].

Some of the heavy equipment, such as bulldozers, are landed by parachute and undocumented sources indicate that heavy equipment may stay on the ice when the camp is left. Barents observer writes that "given 20 years of operations some 20 to 40 bulldozers may have reached the Arctic seafloor down to 4 000 meters"[11]. Less heavy cargo landed by aircraft are brought back from the ice[12], and some garbage may be burned. Sewage may be left because the bathroom facility is a 0.5 m deep depression in the ice.

Noise, which can be considerable, comes from the camp due to aircraft, snowmobiles, and bulldozers.

Polar bears are visiting the area around the camp[13,14].

4.2.1 Other tourist activities

In 2019, before the COVID-19 pandemic, the Quark Expeditions started its 60th expedition cruise to the North Pole with icebreaker vessels. This expedition included sightseeing by helicopter and the possibility of taking a tethered hot-air balloon ride at 90°N.

The first attempt at underwater exploration of the North Pole was made in April 1998 but ended in a fatality. The next attempted dive was in April 1999 and was successful.

In 2005, the United States Navy submarine USS Charlotte (SSN-766)[15] surfaced through 155 cm (61 in) of ice at the North Pole and spent 18 hours there.

In July 2007, a British endurance swimmer completed a 1 km swim at the North Pole. An attempt to paddle a kayak to the North Pole in late 2008, following the erroneous prediction of clear water to the Pole, was stymied when the kayaker's expedition found itself stuck in thick ice after only three days. The expedition was then abandoned.

In August 2007, the Russian scientific expedition Arktika 2007[16] made the first ever manned descent to the ocean floor at the North Pole, to a depth of 4.3 km (2.7 mi). The descent took place in two Mir submersibles[17].

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[9] Barneo is not Borneo. About the work of a chef on the drifting station. 2020. TACC. https://tass.ru/arktika-segodnya/8472727

[10] Barneo - a journey to the North Pole. 2016. Jet Travel. https://www.jettravel.ru/about/photogallery/index.php?page=post&blog=another_planet&post_id=barneo-a-journey-to-the-north-pole

[11] More than 20 bulldozers, one aircraft, and tons of other gear spread around the Arctic seafloor by Russia's ice base. 2020. The Barents Observer. https://thebarentsobserver.com/en/arctic/2020/02/about-20-bulldozers-have-sunk-arctic-seafloor-one-more-coming-soon

[12] Barneo Base. Polar city on a drifting ice floe. 2018. Live Journal. https://kovlam.livejournal.com/3043915.html

[13] Blog entry. 2015. Live Journal. https://barneo-polus.livejournal.com/

[14] Blog entry. 2015. Live Journal. https://barneo-polus.livejournal.com/47967.html

[15] USS Charlotte. Last accessed June 2025. Wikipedia. https://en.wikipedia.org/wiki/USS_Charlotte_(SSN-766)

[16] Arktika 2007. Last accessed June 2025. Wikipedia. https://en.wikipedia.org/wiki/Arktika_2007

[17] Mir (submersible). Last accessed June 2025. Wikipedia. https://en.wikipedia.org/wiki/Mir_(submersible)

In April 2009, the Russian Marine Live-Ice Automobile Expedition (MLAE-2009)[18] reached the North Pole, with seven participants travelling on two custom-built 6 × 6 low-pressure-tire all-terrain vehicles (ATVs). During March–May four years later, MLAE 2013, also with seven participants on two ATVs, travelled from Golomyanny Island (Severnaya Zemlya Archipelago) towards the North Pole across drifting ice and continued to the Canadian coast. It took 55 days across ~2 300 km of drifting ice and about 4 000 km in total. The expedition was totally self-dependent and used no external supplies.

Skiing across the Arctic ice cap has been done on various occasions: (i) March–May 1990 by two explorers over 58 days travelling 800 km from Canada to the North Pole, (ii) March–April 1994 by one explorer travelling from Cape Arctic on the Severnaya Zemlya archipelago[19] to the North Pole, (iii) January–March 2006 by two explorers also travelling from Cape Arctic to the North Pole, (iv) May–June 2007 by two explorers travelling from the North Pole to Frans Josef Land, (v) 2001 by one explorer over 82 days from Siberia to Canada via the North Pole, and (vi) September–December 2019 by two explorers over 87 days across the Arctic ice cap from Alaska via the North Pole to Svalbard.

4.2.2 Pressures on the biological ecosystem from human activities on the ice

The tourist activities described in sections 4.1 and 4.2 show a continued and most likely growing interest in transporting tourists and explorers onto the CAO icecap, and most likely all the way to the North Pole. Assessing the impact of these human activities on the ecoregion's nature requires information on pressures such as pollution (e.g. emissions, noise, and light). This is, as far as is understood, a knowledge gap. A further expansion of "last chance tourism" and the associated footprint may also set species at risk of disappearing (Lemelin *et al.*, 2010; Groulx *et al.*, 2016). The viewing of vulnerable species, such as polar bears, narwhals, and beluga whales, as part of wildlife watching trips, is putting additional pressure on species already threatened by climate change (Atwood *et al.*, 2016; Halliday *et al.*, 2018, 2020).

4.3 Temporal occurrences of tourism

Camp Barneo hosts guests who stay in the camp for up to 10 hours before leaving. Many Arctic explorers use Barneo as the starting point for skiing the last degree up to the North Pole, a tour that takes about one week, depending on ice drift and weather. Trips from the camp to the North Pole itself may be arranged by helicopter. In April 2022, Adventure Consultants[20] brought people to the camp by light aircraft from Longyearbyen, Svalbard, to land on the ice at 89°N and the start of a trek.

The normal duration of the camp's operation is about four weeks, with guests visiting the camp for up to three weeks. In 2017 and 2018, the camp was disassembled after 12 days and very few tourists visited it.

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[18] Marine Live-ice Automobile Expedition. Last accessed June 2025. Wikipedia. https://en.wikipedia.org/-wiki/MLAE-2009

[19] Severnaya Zemlya. Last accessed June 2025. Wikipedia. https://en.wikipedia.org/wiki/Severnaya_Zemlya

[20] North-Pole skiing tours. Last accessed June 2025. Adventure consultants. https://www.adventureconsult-ants.com/expeditions/arctic/north-pole-ski-the-last-degree/

5 Military activity

Paul Arthur Berkman, Petter H. Kvadsheim, Jacqueline M. Grebmeier, Pauline Snoeijs-Leijonmalm, Greg Fiske, and Matthew T. Bell, Jr.

5.1 Military activity in the CAO

This chapter serves to describe, without geopolitical orientation, military pressures on the ecosystem in the CAO high seas, specifically in view of IEAs as framed by ICES (ICES, 2023b; WGICA, 2023). The section also has relevance to the binding Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean (CAO High Seas Agreements 2018; Vylegzhanin *et al.*, 2020; Balton, 2021) with its precautionary approach (Pan and Huntington, 2016; Berkman *et al.*, 2022b), noting that military activities are increasing in the Arctic region and in the Arctic Ocean (Good Morning America, 2024; Uryupova, 2023).

Military is defined as relating or belonging to the armed forces (Cambridge Dictionary, 2023). Militaries are established to protect and defend national interests, noting "the art of war is of vital importance to the State" and the "supreme art of war is to subdue the enemy without fighting" (Tzu, S. 5th Century BCE.). Militaries involve nations individually as well as collectively with alliances, as is the case with the North Atlantic Treaty Organization (NATO, 2023), which includes all Arctic states, except the Russian Federation, either as current or potential members.

With NATO (2022a), for example, there are five domains associated with the armed forces: air, land, maritime, cyberspace and space. NATO states have an active Arctic interest (NATO, 2024; Stoltenberg, 2022; Stoltenberg and Trudeau, 2022), as does the Russian Federation, and together these encompass the military pressures, along with those from non-Arctic states (Wilson Center, 2023), being assessed by WGICA (WGICA, 2023).

Militaries operate at security timescales to address immediate risks of instabilities, in contrast to sustainability timescales, which operate with urgencies across generations (Berkman *et al.*, 2022a). With NATO (2022b), as with all militaries, assets and personnel are deployed at "strategic, operational and tactical levels." Moreover, military operations other than war (MOOTW), recognize a constant state of readiness by "armed forces" during peacetime, involving exercises, as well as during periods of conflict (Homeland Security, 2023). As noted by a former NATO Supreme Allied Commander Europe (Stavridis, 2010): "Not all military capabilities are designed for force. Rather, the totality of today's military forces represents a broad range of capability that has utility for an even broader spectrum of use."

5.2 Spatial coverage of military activity in the CAO

Because armed forces seek to be stealthy, details on where military activities occur are limited, and data access is restricted. With respect to informed decision-making (Berkman *et al.*, 2022a) by nations individually and collectively, this chapter is written to be inclusive (who, what, when, where, why, and how) with open science (Berkman *et al.*, 2022b), which is enhanced in international spaces (Berkman *et al.*, 2011) that include the CAO high seas (Berkman, 2009; Berkman and Young, 2009).

The CAO high seas is an area beyond national jurisdictions (ABNJ) and is, along with surrounding sea zones within national jurisdictions, established under international law of the sea, to which all Arctic states and indigenous peoples' organizations "remain committed" (Arctic Council Secretariat, 2013). The WGICA study area includes both the CAO High Seas and surrounding areas within EEZs under national jurisdictions (see Section 1). Consequently, to build common interests rather than resolve conflicts (Berkman, 2009), this chapter only covers the CAO high seas and common interests without consideration of military pressures within the respective national 200-nmi EEZs. (Berkman and Young, 2009; United Nations Convention of the Law of the Sea [UNCLOS], 1982).

The IEA method used by WGICA only considers existing and direct effects of human pressures on ecosystems. The limited geographic context of this chapter is also a practical consideration, noting if ever military pressures extend from national jurisdictions into the CAO high seas, the military disaster would be global at the margin of impacts with low likelihood (Impact = Magnitude × Likelihood).

With IEA assessments of military and other pressures in the CAO high seas, it is noteworthy that the Russian Federation has been creating Arctic laws since the early 19th century (Berkman *et al.*, 2019) and dominates human presence in the Arctic Ocean today, as reflected by maritime ship traffic (Figure 5.1), mostly beyond the multiyear sea ice (NSIDC, 2024).

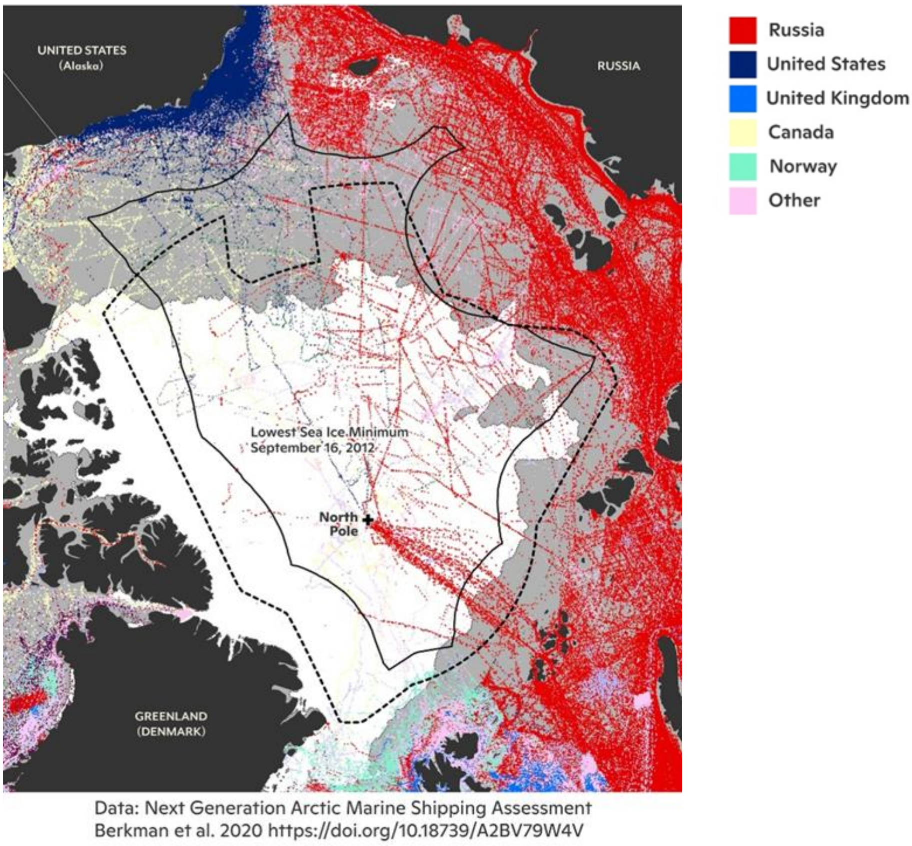

Figure 5.1. Geographic distribution of human presence in the WGICA study area in the Central Arctic, showing the Central Arctic Ocean (CAO) high seas under law of the sea (solid line) and the CAO large marine ecosystem (LME) area (dashed line) with flag states of maritime ship traffic, assessed with satellite automatic identification system (S-AIS) data during 2009–2018, using space–time cube methods (ESRI, 2024) with BigQuery Enterprise Data Warehouse (BigQuery, 2024) in the cloud. The map shows the most common flag state found in each 4 km^2 pixel, noting other flags states may be found in those pixels throughout the time-series, which involves 173 000 000 S-AIS records north of the Arctic Circle (Berkman *et al.*, 2022b, 2022c). This figure is a baseline to assess changes in the distribution of ship tracks among the top five nations contributing to Arctic maritime ship traffic, noting the dominance of Russian flagged vessels along the Northern Sea Route.

5.3 Temporal occurrences of military activity

Military pressures are assumed to be continuous or anecdotal because information on the activities of armed forces, such as special national and international exercises, is classified. Where declassified data are available, there is low temporal and spatial resolution of military pressures. This is illustrated by the upward-looking sonar data from submarines that has been available since 1958 and used to interpret sea-ice thickness (Bourke and Garrett, 1987), but with coarse data over long transects across the Arctic Ocean obscuring the detection of sea ice thinning by decades (Rothrock *et al.*, 1999; Wadhams, 2000). The public details that are available also illustrate ongoing military pressures in the Arctic Ocean (Wilson Center, 2023), mostly over the continental shelf seas of the five Arctic coastal states surrounding the CAO High Seas (Table 5.1).

In addition to being difficult to detect where and when military activities occur, it is also complicated to disambiguate "military pressures" from pressures associated with other government assets. Warships are defined in Article 29 of UNCLOS as "belonging to the armed forces of a State," but enforcement vessels generically would be armed. "Enforcement" vessels are among the unspecified vessels and icebreakers that can be observed with satellite automatic identification system (S-AIS) data in the CAO high seas (Figure 5.2) as well as surrounding seas (Berkman *et al.*, 2022c).

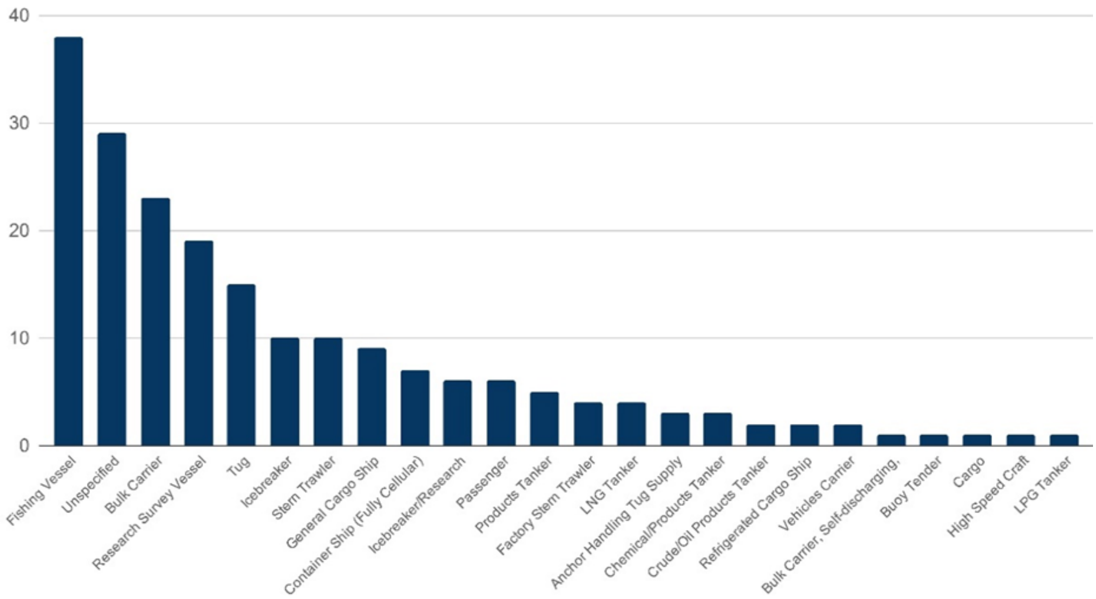

Figure 5.2. Diversity of vessel types in the Central Arctic Ocean (CAO) high seas from 01 September 2009 to 31 December 2018, involving 185 vessels identified with S-AIS data. Reproduced with permission from Berkman *et al.*, 2022c.

In the context of "enforcement" vessels and icebreakers, the Arctic Coast Guard Forum (ACGF)[21] of the eight Arctic states involves ministries of defence, which have scope over armed forces, as well as other ministries. For example, the United States Coast Guard falls within the Department of Homeland Security rather than the Department of Defence, noting the 2022 voyage of the icebreaker Healy to the North Pole was in support of "national security objectives" in a multipurpose context (Figure 5.3).

[21] https://www.arcticcoastguardforum.com/

Table 5.1. Temporal and spatial distribution of declassified military activities in the WGICA study area (Section 1) and in areas bordering the WGICA study area (Figure 1.1).

When* [#]	**What***	**Where***
1958–present every second year [1,2]	ICEX (US with international partners)	Arctic Ocean
1961–2010, markedly increasing after 1990 [3]	Submarine-launched ballistic missile (SLBM) testing in the Arctic Ocean	Arctic Ocean, Kola Peninsula, Barents Sea
2009 and 2010 [4]	Russia carried out test launches of two Sineva intercontinental ballistic missiles from two Delta IV class nuclear-powered submarines in service with the Northern Fleet, located under ice floe near the North Pole.	Near the North Pole
2009–2022 winter annually [5]	Nanook–Nunakput (Canada with international partners)	Northwest Passage (outside CAO high seas)
2014 and 2016 [6]	Russian military Flying Squad – a combat group of Chechen special forces	Landed on Svalbard (outside CAO high seas)
2018 [7]	Ice Exercise (ICEX) (US and NATO allies)	Beaufort Sea (outside CAO high seas)
2021–2022 [8,9]	Russian naval exercise interacting with fishing fleets	Barents Sea (outside CAO high seas)
2021 [10]	Russian missile test site on Novaya Zemlya	Barents Sea (but outside CAO high seas)
2021 [11]	Zapad 2021 (Russia and Belarus)	Barents Sea, Kara Sea and Laptev Sea (outside CAO high seas)
2022 [12]	Naval exercise led by Denmark with international partners	500 km north of the Arctic Circle
2022 [13]	Cold Response (Norway with international partners)	Norwegian Sea (Barents Sea) (outside CAO high seas)
2022 [14]	Umka-2022 (Russia)	Chukchi Sea (outside the CAO high seas)
2023[15]	Joint Viking Warrior2023 (Norway with international partners)	Norwegian Sea (Barents Sea) (outside CAO high seas)
2024[16]	Operation Ice Camp (US and NATO allies) – evolved from ICEX (above)	Beaufort Sea (outside CAO high seas)
2024[17]	Ocean 2024 (Russia and China)	Arctic Ocean (Northern Sea Route) from the Pacific to the Mediterranean, Caspian and Baltic Seas

* See: CSIS (2025) and NATO (2025).

[1] ICEX: US Navy Mission in Arctic. Last accessed 2025. Wikipedia. https://en.wikipedia.org/wiki/-ICEX:_US_Navy_Mission_in_Arctic;

[2] Navy's Arctic Ice Exercise Features Multinational Participation. 2018. US Department of Defence. https://www.defense.gov/News/News-Stories/Article/Article/1461302/navys-arctic-ice-exercise-features-multinational-participation/;

[3] Berkman (2010). Foreword by Adm. James G. Stavridis, NATO Supreme Allied Commander for Europe.

[4] Ria Novosti. 2009. Russia Test Launches Second Sineva Ballistic Missile in two days. 18 July 2009 [Cited in Berkman (2010)].

[5] Operation NANOOK. 2025. Government of Canada. https://www.canada.ca/en/department-national-defence/services/operations/military-operations/current-operations/operation-nanook.html;

Table 5.1 – footnotes (cont.)

[6] Chechen special forces instructors landed on Svalbard. 2016. The Barents Observer. https://thebarentsobserver.com/en/2016/04/chechen-special-forces-instructors-landed-svalbard

[7] U.S. Navy and NATO allies kick off five-week Arctic exercise. 2018. High North News. https://www.highnorthnews.com/en/us-navy-and-nato-allies-kick-five-week-arctic-exercise

[8] Norwegian Ocean-Going Fishing Vessel Fleet Annoyed by New Russian Military Exercise in the Barents Sea. 2022. High North News. https://www.highnorthnews.com/en/norwegian-ocean-going-fishing-vessel-fleet-annoyed-new-russian-military-exercise-barents-sea;

[9] Fishermen troubled by escalating Russian war games. 2021. The Barents Observer. https://thebarentsobserver.com/en/security/2021/09/fishermen-troubled-escalating-russian-war-games

[10] Russia readies Burevestnik testing at Novaya Zemlya. 2021. The Barents Observer. https://thebarentsobserver.com/en/security/2021/08/russia-readies-burevestnik-testing-novaya-zemlya

[11] How to ambush an Arctic seaport. Russian marines stage a show. 2021. The Barents Observer. https://thebarentsobserver.com/en/security/2021/09/how-ambush-arctic-seaport-russian-marines-stage-show;

[12] Denmark heads naval force at missile live-fire exercise. 2022. Danish Defence. https://www.forsvaret.dk/en/news/2022/denmark-heads-naval-force-at-missile-live-fire-exercise/

[13] Exercise Cold Response 2022 – NATO and partner forces face the freeze in Norway. 2022. NATO News. https://www.nato.int/cps/en/natohq/news_192351.htm.

[14] Russia conducts military drills in Arctic sea opposite Alaska. 2022. Reuters. https://www.reuters.com/world/russia-conducts-military-drills-arctic-sea-opposite-alaska-2022-09-16/

[15] National Exercises and activities. 2025. NATO. SHAPE | Allied National Exercises and Activities (nato.int); Joint Viking 2023. 2024. Norwegian Armed Forces. Joint Viking 2023 - Norwegian Armed Forces (forsvaret.no)

[16] Navy launches operation ice camp 2024 in the Arctic Ocean. 2024. Commander Submarine Force Atlantic. https://www.sublant.usff.navy.mil/Press-Room/News-Stories/Article/3702201/navy-launches-operation-ice-camp-2024-in-the-arctic-ocean/

[17] Rob Bauer. Speech at the Arctic Circle Assembly by Chair of the NATO Military Committee (19 October 2024). https://www.nato.int/cps/en/natohq/opinions_229551.htm

Figure 5.3. US Coast Guard Icebreaker Healy at the North Pole with crew and science team on 02 October 2022 (Woody, 2022).

6 Science activity

Jacqueline M. Grebmeier, Barbara Niehoff, and Bodil A. Bluhm

The CAO is an emerging field for polar science. The rapidly changing sea ice conditions associated with climate warming and linked to atmospheric and oceanographic components has a high potential for cascading ecosystem changes in the high Arctic and surrounding Arctic seas. Simultaneously, these changes are increasing opportunities for human use (such as transportation and potential fisheries). These changes and opportunities highlight the critical current need to determine the drivers and impacts of an opening Arctic Ocean and the need to understand ocean status and trends both now and into the future. Over several decades, research conducted in the CAO (from drifting ice stations, icebreakers, and submarines) has created a basic foundation for our understanding of the region. However, because of a still limited understanding of the fundamental characteristics and processes in the region and their modifications in recent years, predicting these changes and their pan-Arctic linkages remains difficult. To address such knowledge gaps, several international projects have undertaken recent (since 2019) studies (Table 6.1) to investigate the current CAO ecosystem and its environmental drivers, with future field activity in the planning stage. Sections 6.1.1–6.1.10 describe some of these recent programmes.

6.1 Science activity in the CAO

The summaries in sections 6.1.1–6.1.10 provide overviews of the larger science activities that have occurred in the CAO over the past four years, both single-year cruises and programmes with a focus on long time-series. Table 6.1 provides an overview summary of these science activities, including the benefits and future plans. Efforts such as the ones outlined in the following sections have provided valuable baseline assessments of the present state of the ecosystem that can be used as a benchmark against which future system modifications can be evaluated.

All the ongoing and planned CAO science programmes are essential for understanding the status and trends of the high Arctic ecosystem and associated environmental drivers. Only through a network of shared activities, data exchange, and coordinated activities can we evaluate the ecosystem status of the CAO and the trajectory of change that will occur with climate warming and human-induced activities that have both regional and global implications for the health of the planet.

6.1.1 Synoptic Arctic Survey (SAS)

Multiple countries deployed ships from the shelf to the AO as part of the International Synoptic Arctic Survey (SAS, 2024) during 2020–2022 to provide for a pan-Arctic understanding of core ocean variables on a quasi-synoptic, spatially distributed basis using coordinated, international efforts (Paasche *et al.*, 2019). The SAS field programme and ongoing synthesis activities are components of a researcher-driven initiative that aims to enhance ongoing ocean monitoring through ship-based *in situ* measurements focused primarily on the CAO ecosystem, carbon cycle, and associated hydrography. In the longer term, a main objective is to assess the rapidly changing and evolving ecosystem through decadal monitoring to enable detection and prediction of environmental and ecological changes. Unknowns, such as whether commercial fisheries could develop in the CAO beyond national economic zones (The Central Arctic Ocean Fisheries Agreement [CAOFA], 2021)and concerns about food security in the case of migratory species for Arctic indigenous coastal communities, are just two examples of societal needs that can be addressed by a better understanding of the status and trends of the Arctic system.

Table 6.1. Overview summary of large-scale Central Arctic Ocean (CAO) research activities during 2020–2022 (see text for acronym descriptions and other individual projects).

CAO research activity	Key objectives
Synoptic Arctic Survey	International ship-based transects in pan-Arctic framework from shelf to high Arctic basins conducted in 2020-2022.
MOSAiC	The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) was an international research expedition 2019–2020 to study the physical, chemical, and biological processes that coupled the Arctic atmosphere, sea ice, and ocean.
NABOS	Nansen and Amundsen Basin Observing System (NABOS) in alternating years (2021 and 2023) evaluated upper water column hydrography impacted by climate change in the marine regions of the Siberian Arctic, including transects from the slope to the Arctic basin.
JOIS-BGOS	The Joint Ocean Ice Study (JOIS)-Beaufort Gyre Observing System (BGOS) is an annual international, sustained measurement programme of upper water column hydrography sampling the Arctic Ocean north of Alaska into the Canada Basin, led by Canada and US.
Nansen Legacy	The Nansen Legacy project was a large, multidisciplinary Norwegian-led programme to make climate and ecosystem field studies from 2018 and 2022. The effort included multistressor experiments such as effects of combinations of pollutants and increased temperature on CAO zooplankton.
Arctic PASSION	The Arctic PASSION*:* Pan-Arctic Observing System of Systems Implementing Observations for Societal Needs had Arctic field programmes during 2021–2022 with oceanographic ship-based and mooring data collections.
HAUSGARTEN	The Long-term Ecological Research observatory HAUSGARTEN in the Fram Strait, maintained by Germany, has collected annually as a time-series of hydrographic and biological data since 1999. A marine litter observatory is related to this LTER.
SUDARCO	Sustainable Development of the Arctic Ocean (SUDARCO) project focuses on the Fram Strait and Eurasian Arctic Basin area to improve the knowledge base of the physical, chemical, and biological systems and their links to support future management decisions with cruises in 2023 and 2024 (2022–2026). Plastics research is part of SUDARCO.
GO-SHIP	The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) brings together scientists with interests in physical oceanography, the carbon cycle, marine biogeochemistry, and ecosystems. Efforts to do studies in the CAO are ongoing.

During 2020–2022, the SAS was organized around the overarching question "What are the present state and major ongoing transformations of the Arctic marine system?" Multiple ongoing national programmes and leads involved in the SAS include the Nansen Legacy Project (Norway; 2023), the ongoing Pacific Arctic Climate Ecosystem Observatory (PACEO) in the Chukchi Borderland and into the Arctic Basin (Republic of Korea), the Joint Ocean Observing System/Beaufort Gyre Observing System (Canada), direct SAS field activities (Canada, China, Denmark, Germany, Italy, Japan, Norway, South Korea, Sweden, Switzerland, Russia, Sweden, and US; see Figure 6.1), field and networking observatory efforts through the Arctic PASSION programme (Germany), annual ship activities associated with the HAUSGARTEN Observatory (Germany), the Nansen and Amundsen Basins Observational System (NABOS, US) efforts, periodic cross-basin programme under the CHINARE programme (China), and the planned GO-SHIP (2024) programme across the CAO. Further information and updates are available on the Synoptic Arctic webpage.[22]

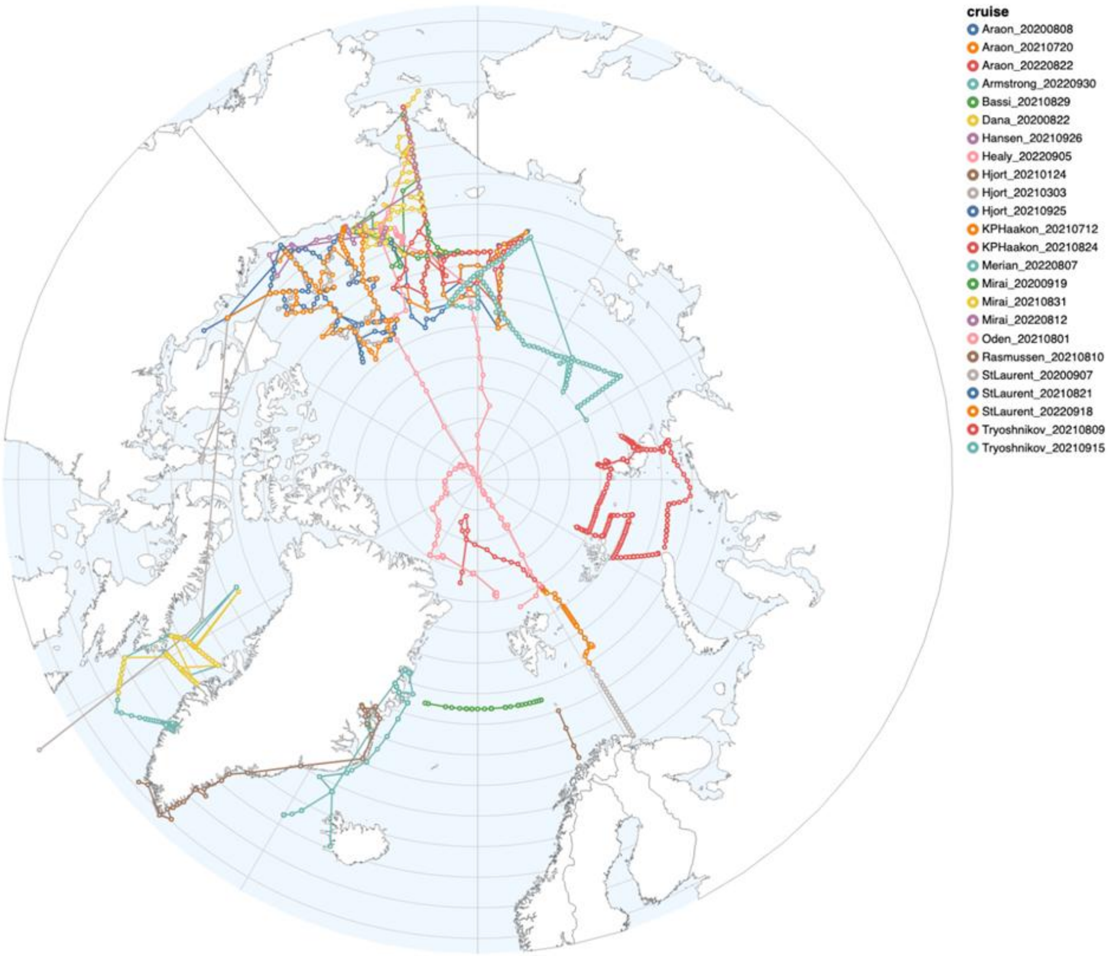

Figure 6.1. Schematic of ship occupations to the Central Arctic Ocean (CAO), as part of the Synoptic Arctic Survey 2020–2022. The effort of some of these occupations includes the occupancy of stations from the surrounding marginal shelf seas. See https://synopticarcticsurvey.w.uib.no/ for further details and any updates to this cruise map. Note this map does not include other shelf-only activities, which are numerous. Reproduced with permission from University of Bergen, ref. Maria Teresa Bezem.

6.1.2 MOSAiC field programme 2019–2020

The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition was a major one-year expedition (2019–2020) into the central Arctic supported through multinational efforts led by Germany. MOSAiC studied the Fram Strait and northern Eurasian Basin using the RV Polarstern, which that was frozen into the Arctic sea ice to study the climate processes of the CAO through atmospheric, sea ice, and upper ocean processes. The resulting data are used to improve the representation of these processes in global climate models and to contribute to more reliable climate projections. Building upon the success of MOSAiC, a new multidisciplinary and multinational project was initiated in 2023: EcoOmics, led by Germany, will evaluate biodiversity change in the Arctic Ocean through identifying

[22] Synoptic Arctic Survey homepage. Last accessed June 2025. https://synopticarcticsurvey.w.uib.no/

unique species and assessing their extinction risk to guide future conservation efforts. Further information about MOSAiC is available on the programme webpage.[23]

6.1.3 NABOS

The Nansen and Amundsen Basin Observing System (NABOS) programme is a decades-long effort to build a cohesive picture of climate change in the marine regions of the Siberian Arctic, including transects from the slope to the Arctic Basin. It focuses on boundary current transport of Atlantic water and how this water interacts with shelf waters and the deep basin interior, along with upper-ocean and sea-ice characteristics, and changes in Arctic Ocean circulation. Physical and chemical measurement are at the core of the study, but biological measurements are being added in 2025. Further information is available on the programme webpage.[24]

6.1.4 JOIS-BGOS

The Joint Ocean Ice Study (JOIS)-Beaufort Gyre Observing System (BGOS) is an annual international, sustained measurement programme sampling the Arctic Ocean north of Alaska, led by Canada and the US. Since 2003, annual cruises have been evaluating the major sea ice and freshwater changes occurring in the Beaufort Gyre of the Canadian Basin through the sampling of the physical and chemical properties of the upper water column and sea ice. Moorings provide annual time-series data collections. Further information is available on the programme webpage.[25]

6.1.5 Nansen Legacy 2021 SAS cruise

The Nansen Legacy project was a large Norwegian-led programme to facilitate climate and ecosystem field studies from 2018 and 2022 using the Norwegian icebreaker RV Kronprins Haakon as a main research platform. Besides ship-based sampling, the programme used underwater robotics, year-round moored observing platforms and satellite-based observations, and state-of-the-art modelling tools to investigate the dynamics of the physical and biological components of the northern Barents Sea into the Arctic Basin, in order to understand present and future dynamics of the Polar North. In 2021, the Nansen Legacy extended its study into the CAO (Fransson *et al.*, 2022) with its SAS cruise. An overview of the Nansen Legacy research activities and future plans are summarized in the project's annual reports (Nansen Legacy, 2019–2023), and the final report.[26] Further information can be found on the programme website.[27]

6.1.6 Arctic PASSION

The Pan-Arctic Observing System of Systems Implementing Observations for Societal Needs (Arctic PASSION) project's goal was to coordinate observing systems across disciplines, sectors, and communities. As part of this, several cruises from different countries took place during late summer and early autumn 2021 and 2022 across the Arctic Ocean. New multidisciplinary moorings were also deployed in the interior Arctic Ocean. The moorings cover the Atlantic

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[23] MOSAiC programme homepage. Last accessed June 2025. https://mosaic-expedition.org/

[24] NABOS programme homepage. Last accessed June 2025. University of Alaska Fairbanks. https://uaf-iarc.org/nabos/

[25] Beaufort Gyre Exploration Project homepage. Last accessed June 2025. Woods Hole Oceanographic Institute. https://www2.whoi.edu/site/beaufortgyre/

[26] Final Report. Last accessed June 2025. The Nansen Legacy project. https://arvenetternansen.com/final-report/

[27] The Nansen Legacy homepage. Last accessed June 2025. https://arvenetternansen.com/about-us/

water–influenced western Nansen Basin and the Transpolar Drift–dominated western Amundsen Basin. Through Arctic PASSION, an Atlantic–Arctic Distributed Biological Observational (A-DBO) network is being developed to coordinate existing time-series studies relevant to the CAO. The Atlantic DBO will be linked to the Pacific DBO (Moore and Grebmeier, 2019) and two new initiatives (Canada–Greenland and Eastern Eurasian Basin) for joint development of a Pan-Arctic Distributed Biological Observatory network. Ice-tethered observatories (ITOs), including ecosystem sensors, were deployed at the North Pole in July 2022 under Arctic PASSION. Further information can be found on the project website.[28]

6.1.7 HAUSGARTEN time-series

Since 1999, the Alfred-Wegener-Institute (AWI) in Germany has operated the Long-Term Ecological Research (LTER) observatory HAUSGARTEN in the Fram Strait (Soltwedel *et al.*, 2005, 2016). HAUSGARTEN is located in a region that is influenced by the marginal ice zone (MIZ) and constitutes a network of 21 sites that are sampled once a year using the German RV Polarstern and RV Maria S. Merian as well as the French RV L'Atalante. The stations are located along a bathymetric east–west transect between ~250 and 5 500 m water depth at about 79°N from Kongsfjorden (Svalbard) towards the Greenland continental margin. In addition, sampling takes place at three northern sites close to the ice edge and a southern, permanently ice-free station in the eastern part of Fram Strait. Multidisciplinary research activities include physical oceanography, remote sensing, biology, biogeochemistry, and sedimentology and cover all habitats from the ice to the seabed. Besides ship-based measurements, long-term moorings and bottom free-falling landers are deployed to measure hydrographical and biological parameters throughout the year while autonomous underwater and remotely operated vehicles are used to target specific research questions during cruises and to sample at the experimental central HAUSGARTEN site. Further information can be found on the time-series website.[29]

6.1.8 SUDARCO

Under the Sustainable Development of the Arctic Ocean (SUDARCO, 2023) project supported by the Norwegian Fram Center (2022–2026), two cruises revisited some of the 2021 Nansen Legacy sites in 2022 (Dodd *et al.*, 2022) and 2023 (Steen *et al.*, 2023) and 2024. SUDARCO focuses on the Fram Strait and Eurasian Arctic Basin area and aims to improve the knowledge base of the physical, chemical, and biological systems and their links to support future management decisions. Its contributing institutions are members of the Norwegian Fram Center. Further information can be found on the project website.[30]

6.1.9 Expeditions to special habitats

The following is a list of expeditions launched to investigate special habitats:

- Hot Vents in an Ice-Covered Ocean (HACON), 2019 and 2021. These two international HACON expeditions explored the Aurora vent field (Ramirez-Llodra *et al.*, 2024).

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[28] Arctic PASSION project homepage. Last accessed June 2025. Alfred Wegener Institute for Polar and Marine Research. https://arcticpassion.eu/

[29] HAUSGARTEN time-series homepage. Last accessed June 2025. Alfred Wegener Institute for Polar and Marine Research. https://www.awi.de/en/science/biosciences/deep-sea-ecology-and-technology/observatories/lter-observatory-hausgarten.html

[30] SUDARCO: Forskning for god forvaltning av Polhavet. Last accessed June 2025. Norwegian Polar Institute. https://framsenteret.no/forskning/forskning-for-god-forvaltning-av-polhavet-sudarco/

- The Arctic Lithosphere-Ocean Interaction Study (ALOIS), 2021 and 2022. This project focussed on the Gakkel Ridge, including the Aurora vent field and the Lena Trough (Schlindwein, 2023).
- The GoNorth 2022-2024 expeditions. These expeditions studied hydrothermal vents and various geological structures and their related ecosystems.[31] Further information is available on the GoNorth website.[32]
- Expeditions conducted by the autonomous drifting Russian Severny Polyus vessel.[33] Launched in 2022, the vessel has drifted during several missions across the CAO. Severny Polyus is a research vessel supported through the Russian Meteorology Service Roshydromet and can undertake geological, acoustic, geophysical, and marine research.[34]
- The North Pacific Research Board Arctic Integrated Ecosystem Research Program (IERP; 2016-2023)[35] had the mission to document anticipated shifts in the Pacific regions of the Arctic Ocean, including analyses of the abundance, assemblages, transport, seasonal composition, distribution, and production of phytoplankton, particulate matter, zooplankton, fishes, benthic invertebrates, and marine birds and mammals. Analyses also focused on the timing, magnitude and fate of the primary and secondary productivity, the flux between pelagic and benthic realms, and human interaction with the marine environment. Research cruises were conducted in the Chukchi Sea shelf and slope, extending into the Arctic Basin, including sediment grabs in continental slope margins and oceanographic and fisheries acoustics in the outer regions of the Chukchi and Beaufort seas and the margins of the Arctic Basin. All data are available online.[36] https://arctic-ierp.portal.axds.co/.

6.1.10 Upcoming field and planned monitoring activities in CAO

- Arctic Ocean 2050 (Polhavet 2050) is a 10-year Norwegian programme currently in its preparation phase and targeted to start in 2026 if funding can be secured. Eighteen universities and research institutes across Norway are participating in the programme, covering multiple disciplines in natural sciences as well as law and geopolitics. Further information is available on the Arctic Ocean 2050 website.[37]
- The GO-SHIP programme is part of both the Global Climate Observing System (GCOS) and Global Ocean Observing System (GOOS) programmes. In 2024, GO-SHIP planned a two-month (August–October 2024) oceanographic cruise across the CAO on the USCGC icebreaker Healy to investigate physical oceanography, carbon cycling, marine geochemistry, and ecosystem components via hydrographic

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[31] Daglige rapporter fra toktet 2023. Last accessed June 2025. GoNorth. https://gonortharctic.no/category/tok-tet-2023/

[32] GoNorth website. Last accessed June 2025. https://gonortharctic.no/

[33] Polar station "Severny Polyus" has completed its work. Last accessed November 2025. Polar Journal. https://polarjournal.net/polar-station-north-pole-41-has-completed-its-work/

[34] Russia's North Pole platform starts ice drift towards Greenland Sea. 2022. The Barents Observer. https://www.thebarentsobserver.com/arctic/russias-north-pole-platform-starts-ice-drift-towards-greenland-sea/118229

[35] North Pacific Research Board Arctic Integrated Ecosystem Research Program website. Last accessed November 2025. https://nprb.org/arctic-program/

[36] Arctic IERP Data Portal. Last accessed November 2025. North Pacific Research Board Arctic Program. https://arctic-ierp.portal.axds.co/

[37] Arctic Ocean 2050 website. Last accessed June 2025. https://uit.no/arcticocean2050

measurements using standard techniques. Unfortunately, the cruise was cancelled in 2024 because of vessel engine problems. These data would provide valuable results for comparison with previous CAO ship sampling, including the recent SAS activities in the Eurasian and Amerasian basins. Further information is available on the GO-SHIP website.[38]

6.1.11 International agreement requiring international and collaborative field activities

6.1.11.1 The Central Arctic Ocean Fisheries Agreement (CAOFA)

The International Agreement to Prevent Unregulated Fishing in the High Seas of the Central Arctic Ocean (CAOFA) with its Joint Program of Scientific Research and Monitoring (JPSRM) under CAOFA's Scientific Coordinating Group has developed a monitoring programme. The draft monitoring plan was evaluated at a June 2024 meeting of the Conference of Parties (COP); once approved, the plan will be made public for coordination with ongoing CAO research activities. Specific to developing fisheries, the programme will evaluate key ecological linkages between potentially harvestable fish stocks of the CAO and the adjacent shelf ecosystems. A linkage between understanding fish populations and key ecosystem components will need to leverage ongoing and planned scientific programmes by international partners. Further information can be found on the CAOFA website.[39]

6.1.11.2 Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ)

The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ) was adopted in March 2023 and will enter into force in January 2026. The agreement establishes a pathway for the creation of strongly protected marine protected areas in ABNJ, will require that certain human activities in ABNJ undergo rigorous environmental impact assessment, will provide for capacity building and technology transfer, and will set up a process for sharing of benefits from marine genetic resources derived from ABNJ.


Polar bear. Image credit: Jon Rønning, IMR

[38] GO-SHIP website. Last accessed June 2025. https://www.go-ship.org/

[39] Central Arctic Ocean Fisheries Agreement. Last accessed June 2025. National Oceanic and Atmospheric Administration, USA. https://vlab.noaa.gov/web/caofa

6.2 Spatial coverage of science activity

The primary season for science activities in the CAO is in late summer to autumn (August–October) when sea ice coverage is at a minimum. The exception was during 2020–2021 when RV Polarstern was locked in the drifting sea ice as part of the MOSAiC programme (see Section 6.1.2). Figure 6.1 provides a schematic of many of the science activities and associated countries as leads for the programmes outlined previously in Section 2.5.1 (note: some programmes include shelf activities, while this chapter focuses on their CAO contributions).

6.3 Temporal occurrences of science activity

Scientific activity can occur year-round through icebreakers that are frozen in the sea ice, such as was the case with the MOSAiC expedition (Section 6.1.2). However, most scientific activities usually take place during late summer and fall (August–October) at the maximum ice retreat into the Arctic Basin. Coordinating a network of these activities in an international framework would facilitate opportunities to share data from different Arctic regions at different times of the year. In the Pacific sector, the multinational Distributed Biological Observatory (DBO) observation programme allows seasonal comparisons on shelf-to-slope systems on standard transects with post-cruise data sharing (Moore and Grebmeier, 2019). The developing pan-Arctic DBO in the Pacific, Atlantic, Davis Strait/Baffin Bay, and East Siberian Sea will allow for data sharing of field results across the Arctic.[40] A similar network of deep Arctic transects, as planned for the SAS2 during 2030–2032 activities, could provide an opportunity to network and share datasets to compare and contrast ecosystem components.

6.4 Future CAO activities

There is a need for multidisciplinary, international time-series stations from the outer shelf slope and into the basin of the CAO, for field studies aimed at evaluating the status and trends of biological components and key environmental drivers within polar ecosystems. Emerging observations indicate that physical changes (such as warming seawater and declining sea ice) are driving shifts in marine species composition and habitat suitability at variable trophic levels. Environmental changes have the potential to influence carbon cycling that may signal ecosystem reorganization. Ship sampling, moorings (including water sampling and biological sensors) satellite observations, autonomous vehicles, and new biological and chemical sensors to moorings will all require new technologies for increased real-time data streams. Key parameters for study include ship-based core water column and sediment measurements, utilization of new genomic studies, including biological sensors and mammal passive acoustics on moorings, enhanced satellite observations for polar regions, and imaging capabilities for plankton and benthos. International collaboration is needed for an agreed set of standardized measurements in different regions of the Arctic for broader-scale comparisons, including developing national-led transects into deep basins that are coordinated in a pan-Arctic network for shared data evaluation. There is also a need to expand ecosystem modelling capabilities for evaluating and forecasting polar ecosystem change.

[40] Pan-Arctic Distibuted Biological Obsevatory (DBO) website. Last accessed June 2025. https://dbo.cbl.umces.edu/about_Pan-ArcticDBO.html

Planning has begun for the upcoming next international polar year (the Fifth International Polar Year [IPY-5] 2032–2033). This large, coordinated effort has the potential to move the knowledge base substantially along, while the ongoing geopolitical challenges remain a hindrance.

Future perspectives

As the Central Arctic Ocean (CAO) opens with reduced sea-ice extent and thickness, there is an increase in science activities both by icebreakers and ice-strengthened vessels, and eventually regular vessels, to understand the impacts of these changes on climate dynamics and associated ecosystems, both regionally and globally. Due to international agreements, such as the Central Arctic Ocean Fisheries Agreement (CAOFA) and its developing monitoring plan, international science activities are required by nations to investigate the potential impacts of exploratory fishing operations and before any commercial fishing would be allowed. In addition, the developing agreement within the United Nations Convention on the Law of the Sea (UNCLOS) on the "Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ) is directly pertinent to biological impacts through any activity, including science, commercial, and military, and associated infrastructure. Science activities and their impact on the high Arctic environment and surrounding marginal seas that connect the CAO to the world should be evaluated in the composite of all the ongoing and planned activities in the region.

7 Fishery vessels in the vicinity of the CAO

Kevin Hedges, Harald Gjøsæter, Edda Johannesen, and Lis Jørgensen

7.1 Fishery activity

Commercial vessel–based fisheries use a variety of gears to catch fishes within a certain size range, targeting one or more species. Bottom trawls, longlines, gillnets, and traps can all be used to catch demersal fishes; pelagic trawls, longlines, and gillnets can be used to catch fish throughout the water column, from a few meters above the seabed to the sea surface. Active fishing gear such as trawls are pulled by a vessel through the water; bottom trawls are pulled across the seabed and catch animals that are herded and swept into the net. The size of the trawl, size of the mesh in the trawl, and speed at which the trawl is towed all affect how well the trawl fishes and the amount and composition of the catch. Passive fishing gears, such as longlines, gillnets, and traps, are set and left in place to fish. Animals can be attracted to such gear by bait, as with longlines and traps, or they can be snared as they swim through the area where the gear is deployed, as with gillnets. The hook size and type of bait used in longlines and the mesh size used in pots and gillnets all affect the composition of passive gear catch.

7.2 Spatial coverage of fishery activities

Commercial fisheries in the high seas in the CAO (figures 7.1 and 7.2) are presently prohibited by the Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean (CAOFA), which was ratified by ten parties [Canada, the People's Republic of China, the Kingdom of Denmark (in respect of the Faroe Islands and Greenland), the European Union, Iceland, Japan, the Kingdom of Norway, the Republic of Korea, the Russian Federation, and the United States of America] and is valid until 2037. The agreement was signed in Ilulisaat, Greenland, on 03 October 2018. On 25 June 2021, the last of the parties ratified the agreement, bringing it into force. According to the CAOFA, no fishing shall take place unless a joint programme of research and monitoring, developed by the parties, has demonstrated that sustainable fishing can take place and until an agreed management regime is in place (Rayfuse, 2019).

While the CAOFA presently prohibits commercial fishing, it does permit scientific surveys and exploratory fishing. Exploratory fishing is intended to collect data to assess the sustainability and feasibility of future commercial fisheries and to contribute to collecting scientific data relating to potential fisheries. Under the CAOFA, exploratory fishing can only be authorized if it adheres to conservation and management measures that are established by the parties. Following timelines established by the CAOFA, the conservation and management measures for exploratory fishing are to be established by June 2024, within three years of the CAOFA coming into force. Given that timeframe, exploratory fishing could begin in the CAO high seas (Figure 7.1) any time after June 2024.

Parts of the CAO LME surrounding the CAO high seas, consisting of shelf and slope areas, are under national jurisdictions. These areas include the northern Barents Sea (Norway and Russia), Kara and Laptev seas (Russia), and the shelf north of Canada and Greenland (Figure 7.1). During 2014, 2015, 2018, and 2020, fishing vessels operating in areas adjacent to or within the CAO LME were mainly found in the northern Barents Sea and the Chukchi Sea, and to a lesser degree in the Kara Sea, the East Siberian Sea, the Laptev Sea, and the Beaufort Sea. No fishing activities were recorded in the CAO basin or the North Canadian Archipelago (Figure 7.2).

In the CAO LME and adjacent seas, most fishery activity has occurred in the Atlantic gateway to the Arctic Ocean: the northern Barents Sea, the eastern parts of the Fram Strait, and the areas to the west and north of Svalbard (Figure 7.2; see also Silber and Adams, 2019). Here, bottom trawl fisheries for northern shrimp (*Pandalus borealis*), Greenland halibut (*Reinhardtius hippoglossoides*), Atlantic cod (*Gadus morhua*), and haddock (*Melanogrammus aeglefinus*) have been ongoing for many years, taking place when ice melts in the summer. Since all ongoing fishing in these areas is connected to the continental shelf and upper slope and targets mainly shelf-associated species, bottom trawl fishing effort is not expected to expand northwards from the Atlantic gateway into the CAO basin even when more northern areas become accessible because of increased ice melt (Haug *et al.*, 2017). It is, however, likely that fishing effort will increase in intensity in established fishing areas if fish and shellfish concentrations increase in response to increased temperatures.

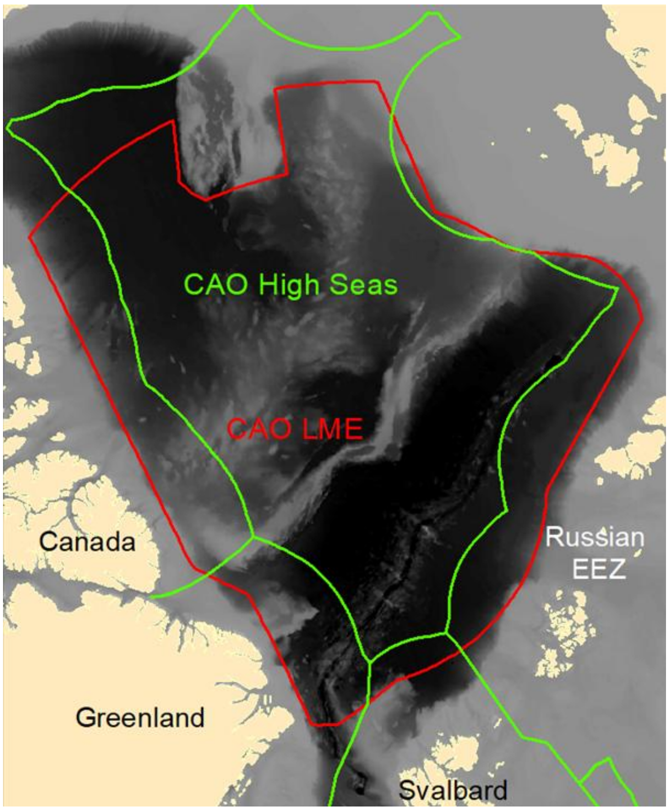

Figure 7.1. The Central Arctic Ocean (CAO) large marine ecosystem (LME; red) and national exclusive economic zones (EEZs; green) delimiting the CAO high seas.

In Canada, Greenland halibut is found in the Beaufort Sea, which is directly adjacent to the CAO LME, but the stock has not been sufficient to garner interest in the development of a commercial fishery. Commercial harvest of Greenland halibut occurs in Baffin Bay, which is more removed from the CAO LME. These regional differences within Canadian waters demonstrate that the presence of a commercially recognized species is not sufficient to lead to fishery development. Interest in fishery development is also driven by remoteness from ports and markets in the context of potential harvest levels and prices.

Overall, fisheries within the CAO LME represent a minor human impact because of the long distance to ports, which increases the costs of catching fish and bringing them to market, restrictions in accessibility because of ice, and overall low biomass of fish (Snoeijs-Leijonmalm *et al.*, 2020). Only four out of 154 unique ships that were registered in the CAO during 2012–2022 were fishing vessels (Table 3.2). These were registered in 2013, 2018, and 2020, respectively.

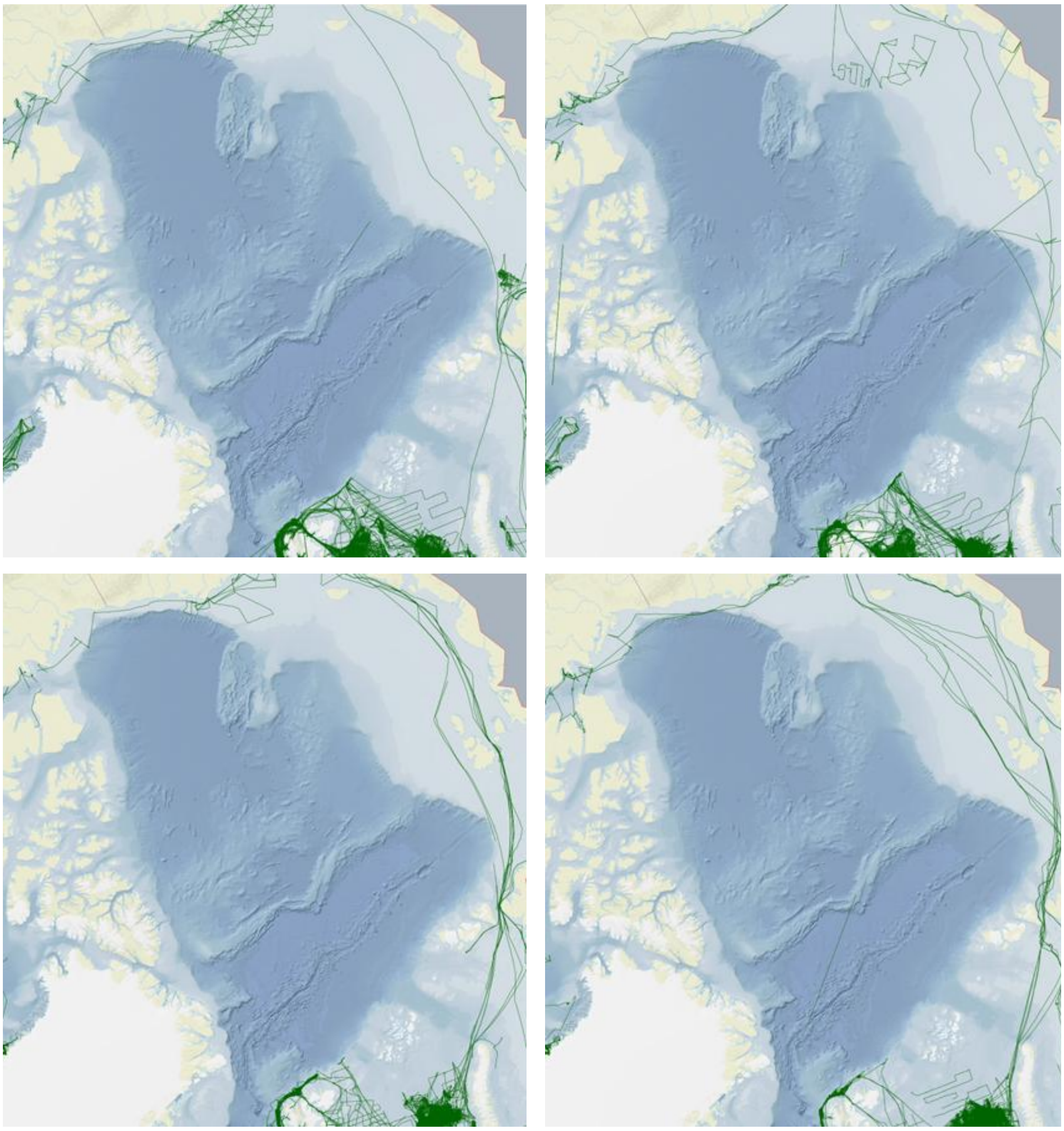

Figure 7.2. Sailing routes (green lines) of fishing vessels in 2017 (upper left panel), 2018 (upper right panel), and in 2022 (lower left panel) and 2023 (lower right panel) around the Central Arctic Ocean (CAO). The figures may indicate that fisheries only happen outside the WGICA study area even though some fisheries happen close to the Chuckie Sea.

The development of pelagic fisheries further north in areas under national jurisdiction is possible if pelagic stocks move into these areas during feeding migrations. Candidate species for northward expansion include capelin (*Mallotus villosus*), polar cod, herring (*Clupea harengus*), blue whiting (*Micromesistius poutassou*), and redfish (*Sebastes spp*.). However, even if one or more of these stocks that presently forage further south should move into northern areas, fishery development is not likely because the stocks would be more accessible further south, closer to fishing ports and with lower fuel consumption and other associated costs. In addition, national restrictions might limit a northward expansion of fisheries. For example, the fishery on the

Barents Sea stock of capelin is restricted to early spring, just before spawning, in spawning grounds and spawning migrations in the southern Barents Sea, so that if spawning areas do not shift north to new areas, the fishery will not shift either (Alrabeei *et al.*, 2021).

To conclude, fisheries in the CAO LME are limited and are expected to continue to be so in the foreseeable future. It should be noted, however, that this expectation of low interest of the fishing industry to future expansion in the CAO is founded on the assumption that sufficient harvestable resources remain available in more accessible areas and that the agreement to prevent unregulated fisheries also remains in force after 2037.

Commercial fisheries can affect the supporting ecosystem in many ways. Bottom-contact fishing gear can remove corals, sponges, and other structure-forming elements that provide habitat for small fishes and invertebrates, thereby affecting recruitment and forage availability [see Collie *et al.* (2017) for a discussion of impacts of bottom trawling on fish productivity]. Biological removals of target species result in the extraction of energy from the system. Predator populations that compete with fisheries for a target species can experience loss of forage resources or increased foraging costs to obtain less abundant food resources [see Engelhard *et al.* (2014) for a discussion of interactions between fisheries, forage fishes, and predators]. Non-target species encountered as bycatch suffer increased mortality, often without the benefit of direct population assessments and management regimes that target maintaining population sustainability. The collective impacts on habitat, predator–prey interactions, and increased mortality interact with other stressors in the environment, making direct causal links between fishing activities and changes in animal populations or ecosystems difficult to identify.

8 Pressures from ships and humans in the CAO and regulations

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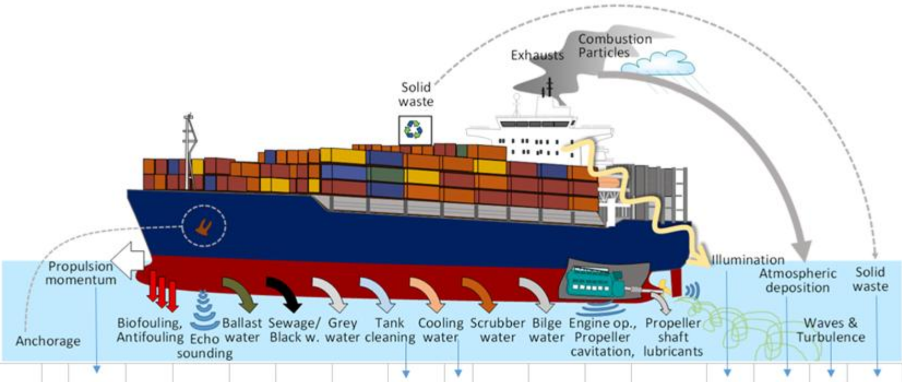
Human activities in the Arctic are regulated at different levels of governance. Instruments of global application, such as the comprehensive UNCLOS (1982), sector-specific fish stocks agreement (FSA; UN, 1995), or MARPOL (IMO, 1973), apply to the whole of the marine Arctic, including the CAO LME. These instruments provide the framework for a more refined regional approach. By way of example, the CAOFA[41] is anchored in the context of UNCLOS and the FSA; the International Code for Ships Operating in Polar Waters (Polar Code; IMO, 2014) has been made effective by amending globally applicable IMO instruments: primarily MARPOL and SOLAS (IMO, 1974), which are, in turn, well integrated with UNCLOS through the mechanism of rules of reference.

The five Arctic coastal states lack jurisdiction over activities on the high seas, except for their flag state jurisdiction, which applies to ships registered in those states. However, they do possess authority to regulate certain activities within their EEZs, in accordance with the jurisdiction, rights, and obligations, as allocated by UNCLOS. In the EEZ, coastal states have exclusive rights to regulate the exploration and exploitation of resources, jurisdiction for the protection and preservation of the marine environment, and limited jurisdiction over international shipping. As an exception to the general rule, UNCLOS Article 234 allows coastal states to adopt special measures to prevent pollution from vessels in ice covered areas.

The absence of an instrument dedicated to addressing a specific pressure from a human activity should not be misconstrued as an absence of regulation altogether. UNCLOS provides a regulatory framework that can be applied to activities both within and outside national jurisdictions. The recently adopted BBNJ Agreement is expected to strengthen this framework.

Sections 8.1–8.10 define and describe the 11 pressures relevant for the CAO that are anticipated to come from ship traffic (science activities, tourist activities, and military activities), (Figure 8.1). Each pressure described below is defined according to the Options for Delivering Ecosystem-Based Marine Management (ODEMM) project (ICES 2021c,d; Pedreschi et al., 2023; Roux and Pedreschi 2024).

[41] The Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean (CAO). https://eur-lex.europa.eu/EN/legal-content/summary/agreement-to-prevent-unregulated-high-seas-fisheries-in-the-central-arctic-ocean.html



Pressure	Anchorage	Propulsion momentum	Biofouling, Antifouling	Echo sounding	Ballast water	Sewage/ Black w.	Grey water	Tank cleaning	Cooling water	Scrubber water	Bilge water	Engine op., Propeller cavitation,	Propeller shaft lubricants	Illumination	Atmospheric deposition	Waves & Turbulence	Solid waste
Collision (birds, mammals, ice habitats)		X															
Non-indigenous species (NIS)			X		X	X	X										X
Contaminating compounds					X	X	X	X	X	X	X		X		X		
Nutrient and organic enrichment						X	X	X		X					X		X
Acidiphying compounds								X		X					X		
Marine litter (incl. microplastics)			X			X	X				X				X		X
Artificial light pollution														X			
Noise and energy pollution	X	X		X								X					
Physical Seabed Disturbance	X															X	
Shipping regulatory framework			*AFS*		BWMC	MARPOL Annex IV	*MARPOL Annex IV*	MARPOL Annex I		*MARPOL Annex VI*	MARPOL Annex I		MARPOL Annex I		MARPOL Annex VI		MARPOL Annex V

Figure 8.1. Ship operations give rise to different environmental pressures. The arrows are not proportional in size; atmospheric deposition and scrubber water are the primary sources of contaminating compounds, along with antifouling paints. Most ships are equipped with marine growth protection systems in their cooling systems, and preliminary results indicate that cooling water may contribute as much as antifouling paints to copper load from ships (modified with permission from Jalkanen *et al.*, 2021).

8.1 Contaminants

Definition: Introduction of pesticides, antifoulants, pharmaceuticals, heavy metals, and hydrocarbons into marine waters.

Regulation: The primary instrument designed to prevent pollution from ships is MARPOL. The Polar Code amended MARPOL to address specific regional challenges, such the prohibition of discharges into the sea of oil or oily mixtures, noxious liquid substances or mixtures containing noxious liquid substances, cargo residuals, and cleaning agents or additives in hold washing water. Although Arctic ports often lack adequate reception facilities, the Polar Code establishes a de facto special area under MARPOL Annex I. A few years after the entry into force of the Polar Code, the IMO introduced a ban on the use and transportation of heavy fuel oil (HFO) in the Arctic. This ban includes provisions for waivers and exceptions. With respect to air pollution sourced from ships, MARPOL Annex VI sets limits on sulphur oxide and nitrogen oxide emissions from ship exhausts. It prohibits deliberate emissions of ozone-depleting substances and introduced regulations on vessel energy efficiency. Black carbon emissions remain an area where additional actions are needed. MARPOL Annex VI allows for the establishment of emission control areas (ECAs), but the prospects for such an ECA in the Arctic are uncertain. The International Convention on the Control of Harmful Anti-fouling Systems on Ships (IMO, 2001) prohibits the use of harmful organotin compounds in antifouling paints used on ships and has established a mechanism to prevent the potential future use of other harmful substances in antifouling systems.

Beside the pressures from global sources described in Section 2, one of the largest contributions of contaminating compounds in the CAO originates from atmospheric deposition from ships. Scrubber discharge water is one source of emissions, caused by ships that are equipped with exhaust-cleaning systems; antifouling paints are another source. Particulate matter and black carbon in exhausts are also deposited on ice or sea surfaces. Emissions of sulphur oxides cause acidification either through atmospheric deposition or through scrubber discharge waters. Oil leaks from propeller shaft lubrication and oily residues enter the marine environment from bilge water. Atmospheric deposition of nitrogen oxides is a primary pathway for the introduction of nitrogen species from ships, in addition to black-, grey-, and scrubber water that also contain nitrogenous compounds. Black- and grey water are also the primary sources of phosphorus from ships.

Science activities in the high Arctic are limited because of sea-ice conditions, although they have increased in recent years as a result of climate warming and sea-ice reduction. Research vessels have internationally agreed controls on the release of contaminants. As outlined in Section 2.2, research vessels, primarily icebreakers, are the dominant vessel type used in science activities in the CAO (ASTD System[42]), although their relative impact in terms of introducing contaminants is low compared to increasing commercial ship traffic (see sections 2.2 and 3.2).

8.1.1 Metals

Antifouling paints have been identified as the main source of both copper (Cu) and zinc (Zn) from shipping, and scrubber discharge water is another significant source (Ytreberg *et al.*, 2022). Globally, cuprous oxide is the dominating biocide in antifouling paint, often in combination with zinc oxide, which increases the overall toxicity and controls the leaching process (Amara *et al.*, 2018). The use of antifouling paints has been shown to cause elevated concentrations in marinas and natural harbours in the Baltic Sea (Kylin and Haglund, 2010; Egardt *et al.*, 2017; Lagerström *et al.*, 2020a). According to a recent compilation of 145 commercially available antifouling paints for the shipping and leisure boat sector, the release rate of Cu can vary from 2 to 66 µg cm^{-2} d^{-1} between antifouling products (Jalkanen *et al.*, 2021). Typically, a higher release rate is needed to protect the hull surface from biological fouling in areas with high fouling pressure, while a lower release rate is needed in low-fouling areas such as the Baltic Sea. Recent studies suggest that a release rate of between 2.2 µg cm^{-2} d^{-1} and 5 µg cm^{-2} d^{-1} could be sufficient to prevent macrofouling (e.g. barnacles and macroalgae) in the Baltic Sea and Kattegat, respectively (Lagerström *et al.*, 2020b), indicating that most antifouling coatings for the shipping sector are excessively toxic when used on ships in the Baltic Sea. Due to the low growth rates of Arctic organisms in even lower temperatures than in the Baltic Sea, the same can be assumed for the CAO. Beside Cu and Zn, scrubber discharge water is also recognized as contributing to the load of vanadium and nickel to the marine environment (Ytreberg *et al.*, 2022).

8.1.2 Oil

Oil leakage from machinery can reach 6 l d^{-1} and can increase with ice coverage in the area of operation and with distance of the operation from the shore.[43] On average, 2.6 l d^{-1} of oil leak out from the stern tube of a ship and risk entering the marine environment (Lundberg, 2021). The factors that could influence the leakage rate are design related, such as vibrations, the rotational speed of the propeller shaft, and radial and axial movements of the propeller shaft; external factors include the quality of water and foreign materials.

8.1.3 Chemicals

Aside from the use of weapons systems during a war, possible military pressures include contaminant impacts dispersed from coastal areas, such as radioactive waste from decommissioned nuclear submarines, as described with the Arctic Military Environmental

[42] Arctic Ship Traffic Data (ASTD). Last accessed June 2025. https://www.astd.is

[43] Stort og usynlig oljesøl vokser – mottrekk haster. 2022. SINTEF. https://www.sintef.no/siste-nytt/2022/stort-og-usynlig-oljesol-vokser-mottrekk-haster/

Cooperation (AMEC) programme that began in 1996 (Ortman, 2009; Sawhill, 2000). Other contaminating compounds from military activities could include oil, gas, chemicals, nutrients, microplastics, and litter. However, there is no separate information about compounds derived from military pressures occurring in the CAO. It is anticipated that pollution from military activities (vehicles in the air, on the ice, and in the water; humans walking on the icecap) activity within the CAO high seas or in the surrounding areas may enter the CAO ecosystem.

8.1.4 Scrubbers

An increasing number of ships use exhaust gas cleaning systems or "scrubbers" to remove SO_X from their exhausts to meet stricter global regulations that entered into force in 2020 limiting the maximum sulphur content in marine fuels. A ship equipped with a scrubber can continue to use the cheaper, high-sulphur, residual heavy fuel oil (HFO) and still comply with the regulations in MARPOL Annex VI with respect to the emission of SO_X into the air. However, the scrubber wash water, which is most often discharged back into the sea, is heavily acidified (typically 500–1000 $m^3 h^{-1}$, pH 3) leading to acidification of the water. Scrubber discharge water also contains high concentrations of toxic polycyclic aromatic hydrocarbons (PAHs) and heavy metals (Lunde Hermansson *et al.*, 2021; ICES, 2021b).

8.1.5 Emissions and atmospheric deposition

One of the main environmental impacts of marine transportation is air pollution generated by engine fuel combustion (Eyring *et al.*, 2010; Cullinane and Cullinane, 2013). Ships contribute to emission of carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_X), sulphur oxides (SO_X), carbon monoxide (CO), and various species of particulate matter (PM) including organic carbon (OC) and black carbon (BC) (Derwent *et al.*, 2005; Eyring *et al.*, 2005). Sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) are important air pollutants and are recognized as the key polluting components of ship emissions (Eyring *et al.*, 2010; Matthias *et al.*, 2010). Both gases are implicated in atmospheric chemical reactions that produce aerosols and acid rain (Seinfeld and Pandis, 2006). High levels of SO_X and NO_X are involved in the generation of tropospheric ozone and other air pollution components and, when combined with other atmospheric chemicals, form PM (Walker *et al.*, 2019). Black carbon emissions from heavy oil combustion (Figure 8.2) contribute to a reduction in the albedo of ice and snow surfaces and introduce pollutants from the atmosphere into the ocean (Mayer *et al.*, 2024). The volume of pollutants released depends on the environmental conditions that ships meet during operation (Fuglestvedt *et al.*, 2009; Gencarelli *et al.*, 2014; Schröder *et al.*, 2017; Ytreberg *et al.*, 2021). Greenhouse gas emissions consisting of CO_2, CH_4, and nitrous oxide (N_2O) from marine transportation are a significant contributor to global anthropogenic air pollution. Increased CO_2 absorption by the oceans from marine transportation will exacerbate environmental extremes caused by climate change (Walker *et al.*, 2019).

It is noteworthy that naval vessels usually operate covertly and do not deliberately leave unnecessary traces of their presence, including pollution. Despite this, the use of ammunition and expendable sensor and weapon countermeasures such as sonar buoys, XBTs, and flares leads to emissions of Cu, other heavy metals, batteries, and explosives, all of which are toxic compounds in the marine environment. Atmospheric emissions from ships (Figure 8.2) are mainly generated by engine fuel combustion, which reached a record value in the CAO in 2020 for icebreakers (mainly research ships). Cruise ships reached a maximum fuel consumption volume in 2022 of 899 km^3. Fuel consumption within the CAO LME in the maximum year 2020 was 5 122 km^3, compared to volumes in the Barents Sea of 596 648 km^3 during 2020.

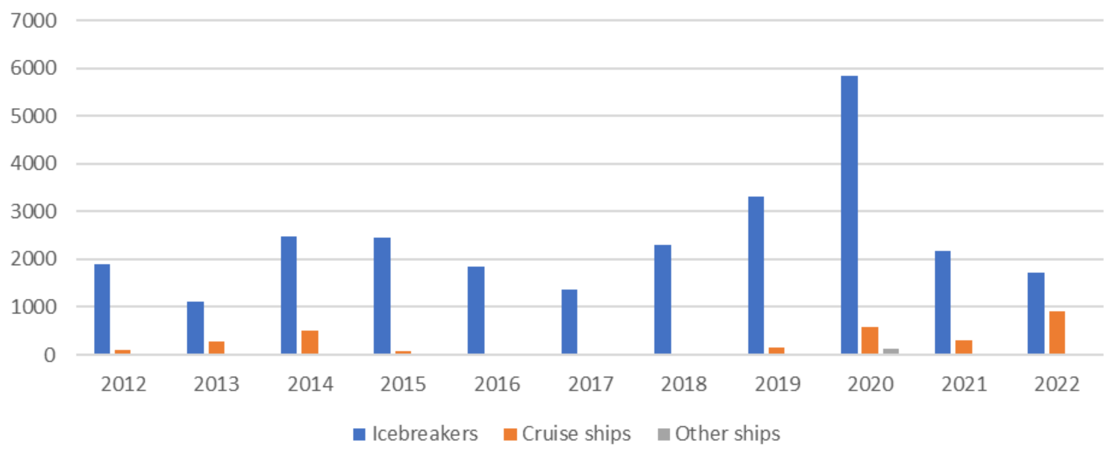


Figure 8.2. Fuel consumption (km³) per ship type (icebreakers are mostly research vessels) per year during 2012–2022 for the CAO LME.

On 01 January 2020, a new global cap on sulphur content in marine fuels was implemented by the IMO to reduce the air pollution created by the shipping industry (IMO, 2020). The "IMO 2020" rule limits the sulphur in fuel oil used on board ships operating outside designated emission control areas to 0.50% m/m (mass by mass), a significant reduction from the previous limit of 3.5%. Present knowledge gaps concerning the composition and variability of the fuel used by ships makes the emission calculation of PM, NO_X, SO_X, and, to some extent, CO uncertain in the Arctic Ship Traffic Data system (ASTD) since 1 January 2020. With this uncertainty in mind, the CAO likely reached a high value in 2020 for emissions of NOx (Figure 8.3, left panel), SO_2 (Figure 8.3 right panel), CO_2 (Figure 8.4, left panel), CO (Figure 8.4, left panel), and aerosols (i.e. PM; Figure 8.4, right panel) in metric tonnes.

Aircraft also add atmospheric emissions to- the CAO. During landing, take-off, and taxiing, aircraft generate pollutant plumes including particulate matter (PM), especially ultrafine particles (UFPs) from jet engines, volatile organic compounds, oxides of sulphur, and oxides of nitrogen (Carslaw *et al.*, 2006; Valotto and Varin, 2016). Ecosystems are impacted by air pollution, particularly sulphur and nitrogen emissions, and ground-level ozone as it affects their ability to function and grow.

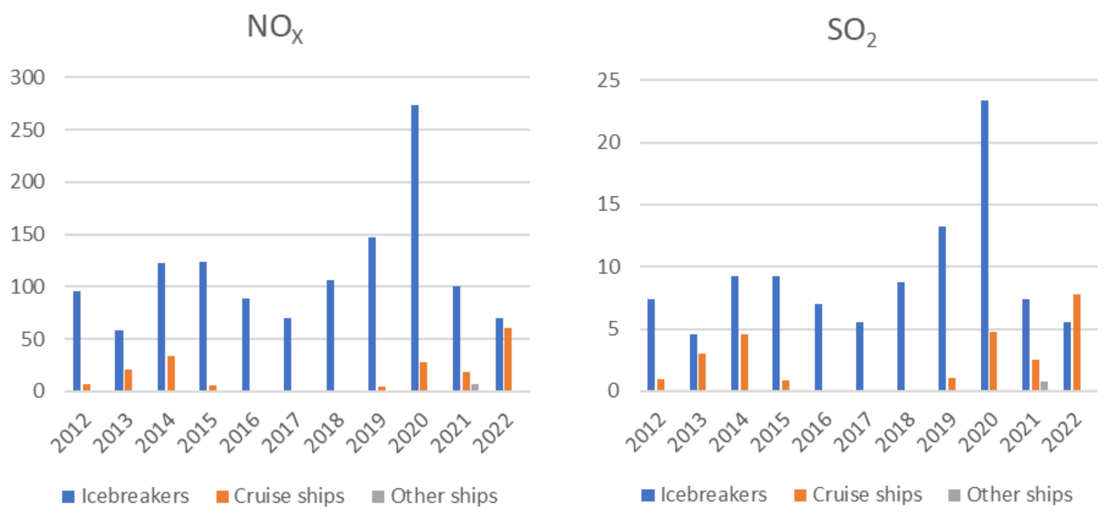


Figure 8.3. The nitrogen oxides (NO_X, left panel) and sulphur oxide (SO_2, right panel) emission in metric ton per ship-type per year during 2012–2022 in the CAO large marine ecosystem (LME).

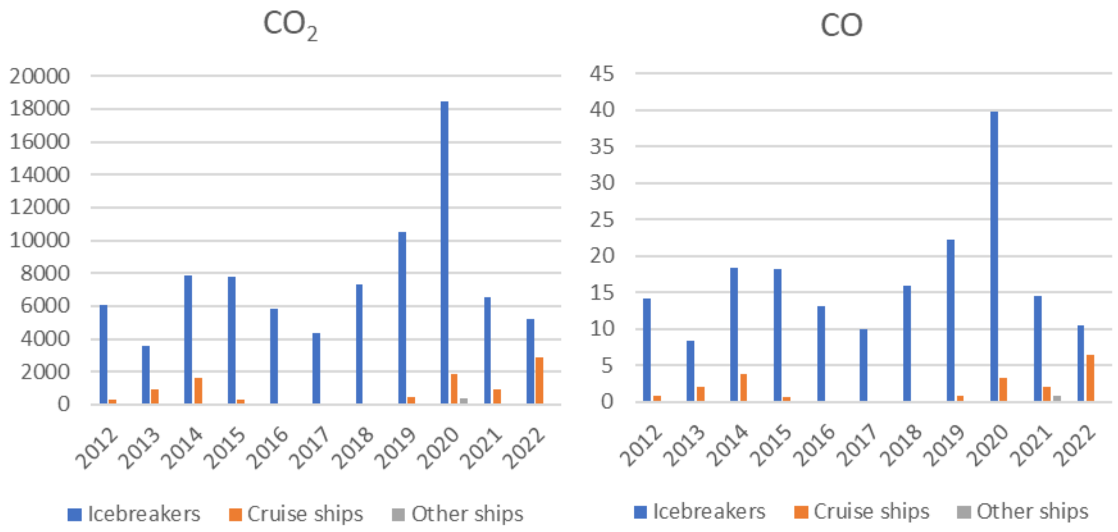


Figure 8.4. Carbon dioxide (CO2, left panel) and carbon monoxide (CO, right panel) emissions in metric tonnes per ship-type during 2012–2022 in the CAO large marine ecosystem (LME).

8.2 Non-indigenous species

Definition: Introduction of non-indigenous species (NIS) and translocations of species by the activities of a particular sector (e.g. through shipping)

Regulations: The International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM; IMO, 2004) is the main international instrument addressing the introduction of NIS (IMO, 2024). All ships in international traffic are required to manage their ballast water and sediments according to a ship-specific ballast water management plan. All ships will also have to carry a ballast water record book and an international ballast water management certificate. The ballast water management standards will be phased in gradually. As an intermediate solution, ships should exchange ballast water mid-ocean. However, most ships will need to install an on-board ballast water treatment system.

Studies from other ice-covered marine areas: Baltic and Barents seas.

Besides the spreading of NIS via global sources, as described in Section 2, NIS primarily spread through ballast water discharge (not expected to be happening in the CAO), biofouling on hulls, hitchhiking among trade goods (Drake *et al.*, 2007; Boltovskoy *et al.*, 2011), as well as through black- and grey water and food waste.

The risk of introduction of NIS is related to the number of ships, and the risk of species' establishment is tied to climate similarities between the source location and the location to which they are introduced (Nong *et al.*, 2019).

Ballast water release during research cruises is most likely to occur when ships approach ports in the marginal seas to refuel, with minimal input in the CAO. For antifouling needs, a self-polishing paint is used, and the potential contaminant from this source is because of the regular contact of ships with sea ice. Additional corrosion protection and antifouling paint are also used inside tubes and cooling systems on the ship. See Section 2.2 for further information.

Presently, the number of NIS introduced in the Arctic is low (Holbech and Pedersen, 2018), and the Arctic Ocean has been presumed to be a lower risk region for biological invasions due to limited access, harsh environmental conditions, and inadequate food resources that hinder dispersal, survival, growth, and/or reproduction for many species (Ruiz and Hewitt, 2009).

Growth on ship hulls is generally low because of scraping by ice and the use of self-polishing paint. Again, modern vessel technology can be used as an example. The Norwegian scientific Icebreaker "Kronprins Håkon" uses cathodic and corrosion protection and antifouling for growth/corrosion inside tubes and cooling systems.

Despite the perception that the threat of invasive species is low, a contrasting view is that the Arctic is increasingly under threat of biological invasions because of climate warming and increased human activity (Matishov *et al.*, 2011). Shipping on a global scale has resulted in the translocation of species attached via biofouling, i.e. the accumulation of aquatic species (Drake *et al.*, 2007). Ballast water, which is used to stabilize vessels at sea, contains suspended matter that can create sediments within the ballast tanks. These sediments and the actual ballast water can contain microscopic cysts and eggs for fish of 30 cm or longer (Carlton, 2001; HELCOM, 2018). Shipping may introduce NIS that have high dispersion capacity and the ability to survive in ballast tanks (Riccardi, 2006).

Increase in NIS can be mitigated by the international Convention for the Control and Management of Ships' Ballast Water and Sediment (BWM Convention), which was globally ratified in 2017 and fully implemented by 2024 (IMO, 2017).

8.3 Marine litter, including micro plastics

Definition: Marine litter originates from numerous sources and consists of different materials including metal, glass, rubber, wood, cloth, and plastics (including microparticles of plastics).

Regulations: MARPOL Annex V on Regulation for the Prevention of Pollution by Garbage from Ships generally prohibits the discharge of all garbage into the sea, subject to some exceptions. The Polar Code imposes more stringent additional requirements on the discharge of various substances, including a total prohibition on the discharge of garbage other than food waste.

Studies on litter from CAO: Kühn *et al.* (2018) on microplastics in polar cod; Peeken *et al.* (2018) on microplastics in sea ice.

Studies from other ice-covered marine areas: Barents Sea, Hausgarten, and Bering Sea.

Investigations have shown a correlation between increasing shipping activity and increasing densities of macroplastics and microplastics found in Arctic waters (Parga Martínez *et al.*, 2020). Ships are conveyors and potential dischargers of plastics in various forms, including cargo straps, packaging, sheeting, crates, single-use containers of consumables, clothing, and even cargo itself (e.g. plastic pellets or nurdles for industrial production). Accidental discharge of plastics can occur through collisions, grounding, or extreme weather conditions, but avoidable ship-generated plastic waste also enters the sea via illegal dumping, improper handling, inadequate procedures and storage facilities on board, unfiltered wastewater discharge, and lack of plastic waste reception facilities in ports (Osmundsen, 2023). The thermal insulation and varnish used for ship protection can also be a local source of microplastics (e.g. Tekman *et al.*, 2017; Grøsvik *et al.*, 2018; Herzke *et al.*, 2021).

Plastics and synthetic fibers enter the Arctic seas mainly as a result of shipping and commercial fishing (Grøsvik *et al.*, 2018; Novikov *et al.*, 2021). With increasing industrial and shipping activity in the resource-rich Arctic, expectations are that marine litter, notably plastic pollution, will increase (Provencher *et al.*, 2010; Smith and Stephenson, 2013).

Paints applied to commercial ships have been identified as a source of microplastics because polymers are used as binding agents in all anticorrosive and antifouling marine coatings.

Furthermore, the release of microplastics from coatings may be amplified by in-water cleaning operations to remove biofouling (Tamburri *et al.*, 2022).

Marine litter has been found in diverse Arctic regions and environmental compartments, notably in sea ice (Peeken *et al.*, 2018), snow (Bergmann *et al.*, 2019), and water (Lusher *et al.*, 2015; Bergmann *et al.*, 2016). Plastics and other floating marine debris can be transported to high latitudes by currents along the coast and in the open sea for hundreds and thousands of miles (Novikov *et al.*, 2021; Vesman *et al.*, 2020), and the Arctic is a very likely potential reservoir for the accumulation of marine litter (van Sebille *et al.*, 2012).

In one study, the central Atlantic and Barents Sea appeared to have more microplastics, mostly of terrestrial origin, in terms of weight concentration (7–7.5 $\mu g\ m^{-3}$) than the North Atlantic and Siberian Arctic (0.6 $\mu g\ m^{-3}$; Pakhomova *et al.*, 2022).

Despite the challenges of plastic disposal, practical solutions are within reach. For example, on board the Norwegian scientific icebreaker Kronprins Haakon, waste streams are separated with the use of a shredder and multichamber compactor. Refuse is collected in big tanks and delivered for disposal on land.

From the tourist activities on the sea ice, undocumented sources estimate that more than 20 bulldozers, one aircraft, and tons of other gear could be spread around the Arctic seabed from Russia's ice base Barneo when left on the ice at the end of the season (Nilsen, 2020a,b).

Science activities primarily retain their equipment and supplies on board, although mooring deployments and gliders are potential deployments that could release microplastics with dissolution over time. Moreover, long-term deployments always bear the risks of not being recovered due to heavy ice conditions, or malfunctioning releasers and gear that is deployed during expeditions can be lost. However, all scientific activities seek minimal losses, not only because the material would contribute to marine litter, but because valuable equipment, data, and samples would be lost. Thus, precautionary measures are taken to avoid accidental losses, e.g. adjusting sampling programmes to ambient weather conditions, and, in case of lost moorings or landers, intensive efforts are made to search for and recover the equipment using e.g. remotely operated vehicles. See Section 2.2 for further information.

8.4 Artificial noise pollution

There is growing recognition that commercial shipping contributes to underwater noise, which has detrimental effects on the critical life functions of a wide range of marine species, including mammals, fish, and invertebrates. This is of particular interest in ice-covered seas because icebreaking ship platforms are greater sources of significant noise than open-water shipping. To date, the international response at the IMO has been limited to drafting a set of voluntary Guidelines for the Reduction of Underwater Noise from Commercial Shipping in 2014. The Guidelines address ship design, propellers, hull design, and on-board machinery. They offer recommendations for noise reduction technologies, primarily relating to ship design, but also operational and maintenance considerations. In 2023, a revised set of guidelines was agreed upon and is currently awaiting approval.

Underwater noise pollution is related to quiet natural areas decline and biodiversity loss (Laiolo, 2010; Iglesias-Merchan *et al.*, 2015). Energy-related pollution, including noise, is caused by engine operation, propeller cavitation, echo sounding, waves, and turbulent mixing from the propulsion and for some ships that are also icebreaking.

Ship noise (from e.g. engines, ice crushing, and the use of scientific equipment such as echosounders) is the biggest contributor to underwater anthropogenic noise (PAME, 2021b). It is substantially higher than the noise that occurs in the natural acoustic environment of the polar regions, where ice melting, pressure cracking, and iceberg calving dominate the soundscapes (Dziak *et al.*, 2015, PAME, 2019b). Noise from earthquakes, undersea volcanoes, and hydrothermal vent activity, and other geophonic components produce sound over different frequencies and spatial and temporal scales (Tolstoy *et al.*, 2004). Vessels are known to generate high levels of low frequency noise from their propulsion systems that can transmit over vast areas far from ship traffic lanes. At present, the primary source of anthropogenic noise in the CAO is from icebreaking vessels that seasonally visit the region (Stevenson *et al.*, 2019).

The most important pressures from peace-time military activities are probably noise. However, naval vessels such as submarines usually operate covertly and are, therefore, built to be silent. However, naval ships typically use long-range, low-frequency active sonar systems to detect submarines, and this intense noise pollution has been associated with whale strandings and is known to cause injury, stress, and habitat avoidance in marine mammals (Kvadsheim *et al.*, 2020). Similarly, use of explosions from tests of underwater ammunition are very loud noise sources which can lead to injury in fish, marine mammals, and birds (Kvadsheim *et al.*, 2020). Demolition of war remnants such as bombs and mines also happens in the Arctic seas and likely kills and injures hundreds of marine mammals every year (von Benda-Beckmann *et al.*, 2015). Underwater noise may have more severe impacts in the Arctic compared with nonpolar regions due to a combination of lower ambient sound levels and increased sensitivity of Arctic marine animals to underwater noise (Halliday *et al.*, 2020; Miller *et al.*, 2022).

Scientific expeditions (both nuclear and fossil-fuelled icebreakers and research conducted from submarines) collect multiple types of data including seismic data, sub-bottom profiler data, geological sampling with the use of special equipment, borehole drilling, gravity and magnetic anomalies, offshore geodetic data, multibeam bathymetry surveys, fish echo sounding, and general field surveys (e.g. Nikishin *et al.*, 2021). All of these activities are associated with noise production.

As ice retreats, shipping activity will increase, with concurrent excess noise levels as high as 30 dB μPa^{-2} (over a week-long average). In the CAO, excess noise levels of 3 dB account for a reduction by 50% of acoustic communication ranges for marine mammals (PAME, 2021b).

In the eastern Canadian Arctic, icebreaker and tankers (during July–October) had the highest sound levels, followed by general cargo and bulk carriers (Jones, 2021). In July and October, the sea-surface temperature is colder and the water column more mixed, which increases propagation of radiated sound from ships (Jensen *et al.*, 1994).

In the East Siberian Sea, which is a relatively quiet sea during the ice cover period compared to other places in the Arctic Ocean, ambient noise level shows a clear seasonal variability, largely determined by sea ice conditions. During the open water season, ambient noise level increases, reaching 16 dB higher than the annual average (Han *et al.*, 2021).

An increased inflow of shallow “tongues” of warm Pacific and Atlantic waters into the Arctic Ocean is also altering the acoustic environment by creating a local maximum in the sound-speed profile at depths of between 100 and 200 m. This water layer acts as a strong acoustic duct, channelling sound across distances of 80–100 km (Poulsen and Schmidt, 2016).

However, because the Arctic environment is poorly sampled (including seabed topology, sediment characteristics, and oceanography), there is uncertainty for acoustic propagation. Sea-ice morphology parametrization needs to be addressed, soundscape modelling needs to be validated with observations, and the need exists to include ice, wind, biological, and anthropogenic sources (PAME, 2021c).

Sound propagates relatively fast and far under water, carrying information over greater spatial scales than most other sensory cues such as light or chemicals (Urick, 1983). Natural ambient underwater sound levels in the Arctic vary on a timescale of hours to months, likely due to the combined effects of sea-ice cover and sea-surface wind patterns, and sound levels are generally higher during open-water periods than when sea ice is present, consistent with other studies (Halliday *et al.*, 2021). The lower sound levels during ice cover are likely because of the scattering effects of sea ice on propagating sound and on the fact that sea ice acts as a barrier preventing sea surface waves from forming and generating noise (Jones, 2021). Sea ice is both a scatterer (by way of surface roughness) and an attenuator (through conversion to shear waves in the ice), so it reduces acoustic propagation when present, and this can lead to relatively quiet ambient sound levels (PAME, 2021b).

Sound speed is a function of water temperature, salinity, and pressure. In high latitudes, with colder sea-surface temperatures, the sound speed minimum moves to shallower depths (Kutschale, 1969). This causes sound to refract upward everywhere allowing sound generated near the surface, such as noise from ships, to propagate great distances. Changes in pH, temperature, upper-ocean stratification, and sea ice characteristics (including sea-ice age and cover) will also affect ambient sound levels and sound propagation (PAME, 2021b).

Ocean soundscapes are rapidly changing because of changing abundances of sound-producing animals (biophony), increases in anthropogenic (antrophony) noise, and altered contributions of geophysical (geophony) sources, such as sea ice and storms, owing to climate change (Duarte *et al.*, 2021).

The pervasive nature of shipping noise pollution has raised concern that it can cause widespread behavioural and physiological effects with consequences at the population level (Slabbekoorn *et al.*, 2010; Tyack, 2008). Most marine animals intentionally produce sounds ranging between 10 Hz and 20 kHz and are audible to a wide range of taxa. These sounds may be frequency or amplitude modulated and can be emitted as single pulses or occur in regular sequences or temporal patterns; examples include pulse trains of fish calls and melodic phrases of whale songs (Duarte *et al.*, 2021).

It is anticipated that noise from military activity in the air, on the icecap, and submerged in the water within the CAO may have an impact on the ecosystem. Movements of surface ships, submarines, and aircraft with personnel as well autonomously could create noise disturbances. Supersonic military jets, for example, may influence the behaviour of marine mammals (Laney and Cavanagh, 2000). In the context of the vast majority of ships that are non-military, including research icebreakers, it would be difficult to distinguish noise from “warships” or “enforcement” vessels. It also is noted that submarines are designed to be quiet. Although incidental, weapons explosions from the demolition of war remnants—including mines, bombs, and other “unexploded ordnance (UXO)”—can be a widespread source of hearing loss in marine mammals (von Benda-Beckmann *et al.*, 2015). Testing underwater ammunition also creates significant sound pulses (noting that sound travels 4.3-fold faster in water than air) that can injure fish, marine mammals, and birds (Kvadsheim *et al.*, 2020). Underwater demolition and noise generally may have more severe impacts in the Arctic Ocean compared with non-polar regions because of a combination of sea ice cover, also observed around Antarctica (Bohne *et al.*, 1985), as well as lower ambient sound levels from human activities and increased sensitivity of polar marine animals to underwater noise (Halliday *et al.*, 2020; Miller *et al.*, 2022).

Research vessels use sonar technologies to detect schools of fish or the morphology of the seabed. This type of activity, however, is expected to be a minor component in relation to underwater noise.

Table 8.1. Examples of natural and anthropogenic noise relevant for the Central Arctic Ocean (CAO) (from PAME, 2020 and Duarte *et al.*, 2021.

Sound creators	Acoustic frequency	Reference
Ice breaker ships	20 Hz to 20 kHz	Roth *et al.*, 2013
Ice breaker propellers	50–100 Hz	Roth *et al.*, 2013
Beluga whale	200 Hz to 20kHz;	Au *et al.*, 1985
Ice in Barents	1–20 kHz	De Vreese *et al.*, 2018
Multibeam echosounders and side-scan sonars	0.1–100 kHz?	Duarte *et al.*, 2021

8.5 Nutrient and organic enrichment

Definition: Organic enrichment, e.g. from industrial and sewage effluent input and/or fertilizers, and other nitrogen- and phosphorous-rich substances into rivers and coastal areas. Includes organic discards, e.g. aquaculture or fishing discards.

It is anticipated that nutrients and organic material from military activity within the CAO or in the surrounding areas may enter the ecosystem of the CAO. However, there is no separate information about nutrients derived from 'military pressures' occurring in the CAO.

Ships used for science, both icebreaking and non-icebreaking research vessels, release grey water periodically during their voyages, as do all ship activities at sea. Thus, the potential for nutrient and organic enrichment in the near-ship location occurs. All sewage treated by an approved sewage treatment system occurs prior to discharge of grey water (holding tanks in operation, drainage, and discharge when landing).

8.6 Extraction of species

Definition: Targeted extraction of species.

Regulations: Extraction of living resources is regulated based on the provisions of UNCLOS and FSA. At the regional level, other relevant agreements are the 1980 Convention on Future Multilateral Co-operation in North-East Atlantic Fisheries (NEAFC, 1980; which subsequently established the North East Atlantic Fisheries Commission [NEAFC]), the CAOFA, introducing a moratorium on fishing in the CAO, and the Russian–Norwegian Fisheries Commission, which potentially plays a role in regulating fisheries in the relevant area. The hunting of polar bears is strictly regulated as a result of the 1976 agreement on the Conservation of Polar Bears that prohibits the taking of polar bears, subject to specific exceptions, including takings for scientific or conservation purposes and by local people exercising their traditional rights. On a broader scale, the 1992 Agreement on Cooperation in Research, Conservation and Management of Marine Mammals in the North Atlantic (which subsequently established the North Atlantic Marine Mammal Commission [NAMMCO]) contributes to conservation, management, and study of marine mammals in the North Atlantic.

No commercial fishing is allowed in the CAO, and most hunting is strictly regulated. This is due to the Agreement to Prevent Unregulated Fishing in the High Seas Portion of the Central Arctic Ocean that came into force in 2021, the agreement from 1976 on the Conservation of Polar Bears, and the 1992 NAMMCO Agreement that contributes to the conservation, management, and study of marine mammals in the North Atlantic (read more in Section 5).

Research and scientific operations have sampled in the CAO for decades (see Section 6) using grabs, cores, nets, and, in the ice-free areas, trawls on the slopes. Such equipment samples vertebrates and invertebrates for scientific purposes.

Extraction of living resources, such as exploratory scientific fishing planned under the CAOFA (CAOFA, 2021), will naturally have a negative impact on those species extracted if unregulated. In the water column, this issue would be the pelagic community large enough to be caught in a pelagic trawl. If test bottom-trawling activities are undertaken, it will disturb deep-sea benthic communities through damage to organisms living on the seabed. During commercial trawling, the size of nets (10–100s of metres in length) to cover very large spatial areas (10s of metre openings and of kms in length) that can contact the seabed have a much greater impact spatially compared to the limited seabed disturbance from the scientific pelagic or epibenthic trawling that normally uses much smaller nets (nets of up to 10 m in length and with openings of up to 3 m). See Section 2.2 for further information. Current extraction of microbes and marine invertebrates and fishes in research expeditions is limited to sampling areas mostly < 1 m^2.

8.7 Physical seabed or sea ice disturbance

Definition: Physical interaction of human activities with the seabed and with seabed fauna/flora causing physical damage and/or mortality (e.g. from trawling or anchoring). The definition excludes death or injury due to collision. Abrasion may cause damage to spawning grounds.

Adaption of definition to CAO: Physical damage can also be made to ice cover when ice breaker ships break through the ice.

Scientific expeditions conduct geological and biological sampling from the seabed (abrasion, smothering, substrate loss) with the use of special equipment for borehole drilling, trawls, sledges, grabs, and sediment cores (see e.g. Nikishin *et al.*, 2021; GoNorth[44]). This equipment impacts the seabed through abrasion, smothering, and substrate loss, and can have a negative impact for long-lived species attached to hard substrates or in surrounding soft sediments during the extraction process. Damage to hydrothermal vent chimneys and other seabed structures, that can take thousands of years to build up, along the ridges and cliffs of spreading ridges should be evaluated before deep-sea mining proceeds to commercial extraction levels. Today, there is no deep-sea mining in the CAO. However, currently, Norway has approved exploratory mining in an area south of the Fram Strait and this will be the test case on impacts of this activity on the biodiversity of deep-sea organisms. This impact should be tracked on appropriate timescales of years to decades and evaluated to determine the impacts before a large opening of deep-sea mining should occur.

The impact of scientific icebreaker activities on, in, and under ice habitats is considered small because of the limited time the ships spend transiting the ice and the small spatial extent compared to the overall sea ice coverage. Human presence on the ice (e.g. walking on the ice) can dislodge under-ice habitats and associated biological communities, yet because of the brief time and space of these activities, such activities have a small impact.

There is concern among indigenous human populations that both habit change and the noise impacts of icebreakers have negative impacts on subsistence hunting.

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[44] Geosciences in the northern Arctic. 2018. GoNorth. https://www.npd.no/globalassets/2-force/2019/documents/archive-2010-2018/joining-forces-2018/gonorth---forwick.pdf

8.8 Artificial light pollution

Regulations: There are no international standards developed to regulate artificial light pollution from human activities. Some regionally developed recommendations have been prepared for the southern hemisphere. It is likely that artificial light pollution will qualify as "pollution" under UNCLOS Article 1 and thus become part of the general obligations on all states to prevent, reduce, and control such pollution.

Studies from other ice-covered marine areas: Berge *et al.*, 2020a (Arctic Ocean, but not CAO)

Globally, light pollution is a growing concern. The ecological impacts of this form of pollution will most likely be greatest in regions where biological communities have not evolved in conjunction with nighttime artificial light (Davies and Smyth, 2018; Marangoni *et al.*, 2022). Many species use natural light cues (sun, moon, stars, and aurora borealis) to migrate vertically in the water column or navigate across regions. The recent occurrence of artificial light sources can interfere with these cycles, as well as animal foraging and breeding activities [review in Davies and Smyth (2018); Marangoni *et al.* (2022)]. The increase in vessel traffic and other developments in the CAO and adjacent waters will lead to an increase in artificial light, which will increase local impacts on marine taxa.

Artificial light from fishing vessels and stationary platforms is known to influence invertebrates, fishes (McConnell *et al.*, 2010; Berge *et al.*, 2020a), and marine birds (Merkel and Johansen, 2011), but less is known about its impact on marine mammals. Large vessels that radiate more light, such as cargo ships and tankers, increase artificial light emissions in the CAO and adjacent shelves, particularly in gateway areas. Due to the high sensitivity of marine animals to changes in light intensity, increased artificial light can locally affect the vertical distribution of zooplankton and fish, leading to reduced prey availability for surface-feeding predators such as polar cod and seabirds (Hobbs *et al.*, 2021; Flores *et al.*, 2023). The impact of artificial light on research vessels can lead to false estimations of pelagic biomass and the vertical distribution of animals during ecosystem surveys (Berge *et al.*, 2020a). Artificial lights attract and cause injury and death to marine birds, which become disoriented by lights and then fly into coastal buildings, stationary and moving vessels, and offshore platforms. The numbers of affected birds per incident ranges from several to hundreds. Common factors associated with these events include the time of year (newly fledged birds tend to be more susceptible), hours of darkness (especially with little or no moonlight), poor visibility (stormy or foggy weather), high winds, and high light radiance emanating from the associated vessel or platform (Merkel and Johansen, 2011; Rodriguez *et al.*, 2014; Gjerdrum *et al.*, 2021). The species affected by light pollution depend on the region, but commonly affected species groups include eiders, fulmars, shearwaters, storm petrels, and auklets, all of which occur in or near the CAO (ICES, 2020).

Changes in seabird distribution as a result of loss of sea ice and shifts in prey distribution may exacerbate the impacts from light pollution in the CAO and adjacent shelf waters. For example, some seabirds in the Bering Strait region, such as short-tailed shearwaters (*Puffinus tenuirostris*) and thick-billed murres (*Uria lomvia*), have shifted their distribution farther north on the Chukchi Shelf, near the edge of the CAO (Kuletz *et al.*, 2020), even though they must still return south through the Bering Strait. Other marine birds, such as eiders (*Somateria* sp.), maintain the timing of their post-breeding southward migration from the Arctic coast through the Bering Strait region. Due to lack of sea ice, these southward migration patterns now overlap with increased vessel traffic during months of nighttime darkness, potentially resulting in higher risk of vessel–bird collisions. The new overlap of human activities during the fall migration of marine birds could pose challenges to bird conservation and to management of vessel traffic lanes throughout the region.

Potential mitigation methods to reduce vessel–bird collisions have been identified These includes reduction in radiance, downward-directed lighting, slower vessel speeds, and avoidance of high-use areas during sensitive seasonal periods. These and other best practices have been promoted on limited regional levels but are not typically mandatory. Several projects are underway for the Arctic region that will identify areas of high risk and inform implementation of best practices and shipping lane design. These projects will overlay vessel traffic using AIS ship identifiers with data on seabird distribution (from at-sea surveys or tracking of individually tagged birds). Related projects using similar data are developing geofencing tools that will enable real-time identification of high-risk locations or situations.

Artificial light pollution from ship traffic is a major concern during the spring and fall shoulder months in the surrounding Arctic marginal seas of the CAO because of the increasing potential for migrating seabird and marine mammal species to strike ships. Since natural light is limited or non-existent above the Arctic Circle in marginal seas in winter, scientific vessels have strict limits for reducing or eliminating light use during transit in Arctic marginal seas, except during actual science operations. However, there is uncertainty around the protection of upper trophic level species in the CAO from commercial ship traffic. Although there are a limited number of both scientific ships that freeze into the Arctic Sea ice and of camps built on the ice, these activities have the potential to cause near-field light pollution.

It is anticipated that light pollution from military activity (in the air, on the ice cap, or submerged in water) within the CAO high seas or surrounding areas only has a local impact on the CAO ecosystem, in terms of e.g. local attraction of fish and zooplankton (Berge *et al.*, 2020a). However, light pollution and incidental ship strikes of migrating seabirds and marine mammals in surrounding Arctic seas is a seasonal issue and thus a potential stress factor as ships enter and leave the CAO, especially in autumn (September–October).

8.9 Unintended injury

Regulations: So far, there are no measures adopted to avoid unintended injury and mortalities on sea life caused by human activities for the CAO. There are, however, a number of available options for regulatory measures to be taken to avoid collisions with marine mammals, including traffic separation schemes (TSS), areas to be avoided (ATBA), and speed restrictions. These can be adopted through the IMO.

In the ocean, many species respond to nearby vessels with surface-active (i.e. present at the surface for breathing or basking) or avoidance behaviours (New *et al.*, 2015). Fast and silent naval vessels are likely to also result in whale ship strikes, and anecdotes exist of torpedoes hitting whales.[45] Military exercises can also lead to accidents such as ship or aircraft collisions, with subsequent contamination of the marine environment (Rossland *et al.*, 2018).

Ship strikes on marine megafauna in the CAO from new and existing trade routes (Yang *et al.*, 2018) can threaten both the megafauna and their habitats (van Waerebeek *et al.*, 2007).

A major consideration for all marine transportation is the possibility of impacts with marine animals. Recorded ship strikes are likely underestimated, or go unreported, and often are not recognized until reaching port, with the whale draped over a ship's bulbous bow bulb (Félix and van Waerebeek, 2005). At present, the probability of vessels colliding with marine

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[45] British Navy mistook whales for submarines and torpedoed them, killing three, during Falklands War. 2013. News Corp Australia Network. https://www.news.com.au/world/british-navy-mistakes-whales-for-submarines-and-torpedoes-them-killing-three-during-falklands-war/news-story/92e895efd40db654fa41a62a3312f4c0

mammals in the CAO is low (Stevenson *et al.*, 2019). In the Bering–Chukchi–Beaufort area, scars on marine mammals from ship strikes are infrequent, occurring on ~2% of all harvested bowheads (*Balaena mysticetus*).

A common step to reduce ship strikes is to alter shipping routes in different areas or at different times when whale concentrations are high (Panigada *et al.*, 2006). But as the numbers of vessels in the CAO is supposed to increase as sea ice retreats, it is unclear how marine mammals will respond to these changes. There is some evidence indicating ice-associated cetaceans may not be as reliant on sea ice as previously thought (Hauser *et al.*, 2018), but it is difficult to say with certainty if species like bowhead, narwhal, and beluga will shift toward the CAO as sea ice retreats and water temperatures increase. If these shifts occur, concerns about vessel collisions with marine mammals will presumably increase (Stevenson *et al.*, 2019).

The use of military weapons within the CAO high seas is thought to have an impact on the ecosystem. This can be local or pan-Arctic, depending on the type of weapon used. Also, as noted above, the potential for marine mammal strikes could be an increased issue seasonally through the gateways and surrounding shelf seas during their migrations.

Human activities via vessels, submarines, aircraft, or drones always have the potential for injuries and mortalities to the living components of the ecosystem, including humans. Multiple scientific studies require instrumentation on sea ice that necessitates increased safety precautions for scientists, both during their operations and for protection from polar bears. These activities have minimal impacts on sea ice dynamics spatially and temporally as these studies are limited in scope and extent.

8.10 Human presence on ice

Definition: Humans that have left a ship, aircraft, or submarine and are moving freely on the floating sea-ice cap. The category of "human presence" therefore covers only tourists and people who actually set foot on the ice; it does not include any ships themselves. It is anticipated that military personnel moving on the ice cap or submerged in the water within the CAO high seas may have a local impact on the ecosystem.

Regulations: The International Law of the Sea primarily governs actions of states rather than individuals directly. It specifies the rights and duties of states, who are then required to translate (implement) these rights and duties into domestic legislation. The domestic legislation is what ultimately regulates the conduct of individuals. Furthermore, under international law, there are several grounds upon which a state can exercise jurisdiction. For example, if an individual disembarks from a ship to walk on ice, their actions are subject to the jurisdiction and legislation of the flag state, which is the state where the ship is registered.

8.11 Summary of pressures from human activities

Table 8.2 summarizes the relevance of the pressures (more information in sections 8.1-8.10) from the defined human activities scientific icebreakers, tourist vessels, military activities, and global sources.

Table 8.2. Human activities and pressures relevant for the Central Arctic Ocean (CAO).

	Contaminants	Non-indigenous species	Marine litter, incl. micro plastics	Artificial noise pollution	Nutrient and organic enrichment	Extraction of species	Extraction of non-living resources	Physical seabed and sea-ice disturbance	Artificial light pollution	Unintended injury and mortality in open water	Human presence on ice
Science icebreakers and research activity	Yes	Maybe	Yes	Yes	Maybe	Yes	Yes	Yes	Yes	Yes	Yes
Tourist vessels and activity on the ice/camps	Yes	Maybe	Yes	Yes	Yes	Not relevant	Not relevant	Yes	Yes	Yes	Yes
Military ships and activity	Yes	Maybe	Yes	Yes	No	Not relevant	Not relevant	Yes	No	Yes	Maybe
Global sources drifting into the CAO	Yes	Maybe	Yes	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant

Pressure relevance:

- **Yes, it is relevant** (black)
- **Maybe it is relevant** (dark grey)
- **No, it is not relevant** (light grey)
- **Not relevant to consider at all** (white)

9 Existing international management frameworks

Alf Håkon Hoel and David Fluharty.

9.1 Background

The CAO is under the jurisdiction of the five coastal states to the Arctic Ocean: The Russian Federation, USA, Canada, Denmark/Greenland, and Norway. There is also a 2.8 million km^2 high seas area in the middle of the ecoregion, which does not fall under the jurisdiction of any state. The WGICA area (Figure 1.1) is in the high seas area and in the northernmost parts of the maritime zones of Canada, Greenland, Norway, and the Russian Federation. This chapter addresses the international governance mechanisms for the WGICA area, with an emphasis on legally binding instruments.

The international governance framework consists of global and regional agreements, the cornerstone of which is UNCLOS. The global framework applies to the Arctic Ocean in the same way as it applies elsewhere in the world. The implementation of this framework is largely carried out by states through their respective domestic legislation and in cooperation with other states.

This section is organized as follows: an introductory description of the Law of the Sea Convention (UNCLOS) and its associated agreements, followed by an account of the international governance frameworks for living marine resources, shipping, marine environment, marine scientific research, and oil and gas, addressing both global and regional frameworks. It concludes by briefly describing the role and functions of the Arctic Council in relation to the CAO LME.

9.2 The global framework: The United Nations Convention on the Law of the Sea (UNCLOS)

9.2.1 Overview

The 1982 Law of the Sea Convention ("the Convention") was negotiated in 1973–1982 and entered into force in 1994. Currently, the Convention has 171 parties (as of October 2025) and is ratified by four of the CAO coastal states. US is not party to the Convention but considers it customary international law. The Convention has an important position in international law, providing a global order for the oceans, widely regarded as the "Constitution of the oceans". It provides the legally binding rights and obligations for states in the seas.

The Convention establishes specific governance mechanisms for continental shelf delimitation, deep seabed mineral resources, and dispute resolution. It also specifically mentions "competent international organizations", including the IMO, regional organizations for the protection of the marine environment, marine science organizations, and regional fisheries management organizations and arrangements (RFMOs/As).

9.2.2 Maritime zones

UNCLOS defines maritime zones. In the territorial sea, the seaward limit of which may extend to 12 nmi (22.2 km) from the baselines (lines drawn along the coast), the coastal state has sovereignty over the water column, seabed, and air space. In their respective 200 nmi (370 km) EEZs, coastal states have extensive powers, including jurisdiction over the natural resources.

Other states must comply with the coastal state's regulations regarding exploring and exploiting resources but also enjoy rights, notably freedom of navigation. Where the distance between opposing coasts of coastal states is less than 400 nmi, states are to seek to establish bilateral boundaries.

In the high seas, beyond the EEZs, states exercise the freedom of the high seas, including fishing, scientific research, navigation and overflight, and the laying of submarine cables and pipelines. Flag states are responsible for the vessels flying their flag.

The continental shelf of a coastal state is the seabed and subsoil that are a natural prolongation of that state's land territory. The continental shelf extends to a minimum 200 nmi or farther from shore, as defined by legal and geological criteria in the Convention. The coastal state has sovereign rights to explore and exploit the natural resources of the continental shelf, and these rights do not depend on any express proclamation. Where the continental shelves extend beyond the 200-mile EEZ limit, states are to submit information on their claims to the Convention on the Limits of the Continenal Shelf (CLCS), which provides recommendations on the final extended limits that the state is to establish. The Arctic states that are parties to the Convention have submitted claims to the extended continental shelves in the Arctic Ocean to the Commission on the Limits of the Continental Shelf established by the Convention. Norway received recommendations from the Commission in 2009. The other submissions are under consideration by the commission.

Furthermore, the Convention provides that the seabed and ocean floor beyond the limits of national jurisdiction (the "Area") and its mineral resources constitutes the common heritage of mankind.

9.2.3 The implementing agreements of the United Nations Convention of the Law of the Sea (UNCLOS)

The 1994 Agreement Relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982 (Overview, 1994) forms an integral part of the Convention. It deals mainly with procedural aspects and has an extensive annex modifying the effect of the deep seabed mining provisions (Part XI) of the Convention. The 1995 United Nations Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (UNFSA) entered into force in 2001. The objective of the UNFSA Agreement is to ensure the long-term conservation and sustainable use of straddling fish stocks and highly migratory fish stocks.

Since 2004, discussions on marine biodiversity in areas beyond national jurisdiction (BBNJ) have taken place under the auspices of the UN General Assembly (UNGA). Negotiations on a treaty were initiated in 2018, and an agreement was concluded in 2023, addressing area-based management tools, marine genetic resources, environmental impact assessments, and assistance to developing countries. It will enter into force in 2026.

9.2.4 Processes to follow up on the Convention

The United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea (the Consultative Process, 1997) facilitates the annual review by the General Assembly in annual resolutions on oceans and the Law of the Sea. The UN General Assembly has also initiated processes for specific issues, such as the BBNJ discussions noted above and Regular Process for Global Reporting and Assessment of the State of the Marine Environment. To date, two such assessments have been produced.

9.3 Living marine resources

9.3.1 The United Nations' Convention of the Law of the Sea (UNCLOS) and Fish Stocks Agreement (UNFSA)

At the global level, UNCLOS and the UNFSA set out the legal framework for the conservation and management of fish stocks. A number of other treaties and arrangements are also important in this respect.

In the establishment of EEZs, the Convention codifies a coastal state´s sovereign rights for the purpose of exploring, exploiting, conserving, and managing the fish stocks. These rights are subject to certain duties, among them considering the best scientific evidence available to ensure that the maintenance of the living resources is not endangered by overexploitation, and to promote the objective of optimum utilization of the living resources. The Convention also contains provisions regarding enforcement of laws and regulations of the coastal state.

On the high seas, the flag states of the fishing vessels shall take measures for their respective nationals, as may be necessary, and cooperate with other states in the conservation and management of living resources. The UNFSA applies to the conservation and management of straddling fish stocks and highly migratory fish species, notably by requiring the implementation of a precautionary approach and an ecosystem approach. The Agreement strengthens regional and subregional fisheries agreements and enforcement arrangements.

9.3.2 Other global instruments

Over the last decades, the global governance framework for living marine resources has been significantly expanded, based on the UNCLOS-UNFSA framework.

The 1993 Agreement to promote compliance with international conservation and management measures by fishing vessels on the high seas (FAO Compliance Agreement, in force 2003; FAO, 1993). The objective is to promote flag state compliance with international conservation measures on the high seas, ensuring that fishing vessels entitled to fly their flags do not undermine international conservation and management measures.

The 2009 Agreement on port state measures to prevent, deter and eliminate illegal, unreported and unregulated fishing (FAO Port State Agreement, in force 2016; FAO, 2016). The objective of the agreement is to prevent, deter, and eliminate such fishing through the implementation of effective port state measures.

The FAO Code of Conduct for Responsible Fisheries was concluded in 1995 (FAO, 1995) as a voluntary instrument (soft law). It contains principles that states should make use of, including ecosystem-based management, international cooperation, and the precautionary approach. FAO has developed a series of technical guidelines for the implementation of the Code, as well as International Guidelines for the Management of Deep-sea Fisheries in the High Seas (2008) and International Guidelines on Bycatch Management and Reduction of Discards (2011).

The 1946 International Convention for the Regulation of Whaling established an International Whaling Commission (IWC). It was concluded to provide for the proper conservation and management of whale stocks and thus make possible the orderly development of the whaling industry.

The 1979 Convention on the Conservation of Migratory Species of Wild Animals (into force in 1983). The objective of the CMS (1979) is to conserve species of wild animals that migrate across national boundaries. It works by listing species in one of two appendices and establishing obligations for their protection.

The 1973 Convention on International Trade in Endangered Species of Wild Fauna and Flora, (CITES, 2024; in force 1975) regulates international trade in plant and animal species that are or may become threatened with extinction. It lists species in categories according to the degree of protection they need.

9.3.3 Regional agreements relevant to WGICA

The subarctic seas in the North Atlantic and the North Pacific have globally significant fisheries taking place mainly in the waters of, and managed by, coastal states. Large fish stocks are often transboundary, and bilateral and regional fisheries arrangements are important in these regions. Some of these are important also in the CAO.

The NEAFC convention (in force 1982) aims to ensure the long-term conservation and optimum utilization of the fishery resources in the Convention Area. NEAFC's regulations apply to the high seas in its Regulatory Area, which includes the high seas areas of a part of the CAO (the Atlantic wedge). NEAFC has adopted a significant number of regulations, including to prevent adverse impacts from bottom fishing on vulnerable marine ecosystems (VMEs).

The NAMMCO Agreement (in force 1992) has the objective to contribute, through regional cooperation, to conservation, management, and study of marine mammals in the North Atlantic. NAMMCO has functions in relation to research, regulations of economic activities, and enforcement of regulations, and it provides management advice for walrus and toothed whales.

In 2015, the five coastal states to the CAO agreed to a declaration where they undertook to not let their vessels start fishing in the ecoregion's high seas in the absence of a regulatory arrangement. They also decided to establish a Joint Program of Research and Monitoring, and to invite potential distant-water fishing nations to discussions on an expanded agreement. Following negotiations which also included Japan, China, the Republic of Korea, Iceland, and the EU, the Agreement to Prevent Unregulated Fishing in the High Seas Portion of the Central Arctic Ocean was signed in 2018 (in force 2021). This agreement establishes that the parties will not let their vessels start commercial fishing in the high seas until 2037 at the earliest, should commercially viable resources be discovered there. The moratorium will be continued in five-year increments until objected to. The agreement also establishes a joint program of scientific research and monitoring.

The 1973 Agreement on the Conservation of Polar Bears (in force in 1976) aims for the conservation of polar bears. It provides for prohibition on the taking of polar bears, subject to specific exceptions, including takings for scientific or conservation purposes and by local people using traditional methods in the exercise of their traditional rights.

9.3.4 Other fishery agreements

In addition to those listed above, there are a number of fisheries arrangements of a more limited nature. In the Northeast Atlantic, there are a number of coastal state agreements on fisheries management. These are often complex, consisting of annually reviewed multilateral and bilateral agreements. There is also an annual North Atlantic Fisheries Ministers´ Conference and a Nordic cooperation at the ministerial level.

9.4 Shipping

9.4.1 UNCLOS

In relation to shipping, the main rights and obligations for the protection and preservation of the environment of both coastal and flag states are established by the Convention. The global regulatory regime on maritime traffic, safety at sea, and vessel source pollution is contained in other instruments.

9.4.2 The International Maritime Organization (IMO)

The competent international organization for issues related to shipping is the IMO, which is the body primarily responsible for developing regulations on navigation, safety at sea, and vessel source pollution.

UNCLOS requires flag states to adopt laws and regulations for the prevention, reduction, and control of pollution in the marine environment from vessels flying their flag. Coastal states have wide discretion to adopt regulations on shipping within their territorial sea to protect the marine environment. In their respective EEZ, coastal states have jurisdiction over the protection of the marine environment, but in exercising these rights, they must have due regard for the rights and duties of other states. Special rules apply in ice-covered areas. Whereas the prescriptive jurisdiction of coastal states is limited, that of port states is, in principle, unlimited.

A number of legally binding and non-legally binding instruments on maritime safety and vessel source pollution have been adopted by the IMO. The most important are

- The 1974 International Convention for the Safety of Life at Sea (SOLAS; in force 1980; IMO, 1974). The SOLAS Convention and its protocols include regulations on construction, equipment, and operation of vessels.
- The 1973 International Convention for the Prevention of Pollution from Ships, as modified by the Protocol of 1978 relating thereto (MARPOL73 /78) and 1997 Protocol. The MARPOL Convention is aimed at preventing pollution from ships. It covers pollution by oil, noxious liquid substances in bulk, harmful substances carried by sea in packaged form, sewage, garbage, and air pollution. Certain areas may be designated Special Areas in which stricter regimes for prevention of discharges are adopted.
- The 1972 Convention on International Regulations for Preventing Collisions at Sea (COLREG; in force 1977). The COLREG Convention addresses regulation of navigation, including traffic separation schemes.
- The 2004 International Convention for the Control and Management of Ships` Ballast Water and Sediments (BWMC; in force 2017). The BWMC is aimed at preventing the transfer of harmful aquatic organisms and pathogens through ship ballast water and sediments.
- IMO also has a number of non-binding instruments, including General Provisions on Ships' Routing (1985) and PSSA Guidelines (Particularly Sensitive Sea Area).

9.4.3 Regional agreements relevant to WGICA

Building on earlier non-binding agreements (Polar Shipping Guidelines, 2002), IMO has developed a legally binding International Code for Navigation in Polar Waters (Polar Code; in force 2017) to address shipping risks that are specific to operations in polar waters. It covers matters relating to design, construction, equipment, training, operation, search and rescue, and protection of the environment.

The 2011 Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic came into force in 2013. The objective of the agreement is to strengthen aeronautical and maritime search-and-rescue cooperation and coordination in the Arctic. It specifies the parties´ competent authorities and agencies, establishes rules for the conduct of search-and-rescue operations, and details the content of cooperation.

9.5 The environment

9.5.1 UNCLOS

UNCLOS provides the international legal framework for the protection and preservation of the marine environment. There is a general obligation for all states to protect and preserve the marine environment and to take measures necessary to prevent, reduce, and control pollution from any source.

There is also an obligation for states to cooperate in formulating and elaborating further rules and standards at global and regional levels, as well as provisions regarding enforcement rights and obligations on the part of flag states, coastal states, and port states. A coastal state's sovereign rights to exploit its natural resources is to be done in accordance with the duty to protect and preserve the marine environment. States' measures to prevent, reduce, and control pollution must include those necessary to protect and preserve rare or fragile ecosystems and habitats of depleted, threatened, or endangered species.

9.5.2 Other global agreements

Numerous global and regional agreements build on the environmental provisions of the Convention, notably IMO conventions and the regional seas agreements developed under the UN Environment Program (UNEP).

The 1992 Convention on Biological Diversity (CBD, in force in 1993) addresses the conservation of biological diversity, the sustainable use of ecosystem components, and the fair and equitable sharing of the benefits arising from the utilization of genetic resources. CBD apply in areas under the parties′ jurisdiction and to processes and activities of a party's nationals. The Conference of the Parties (COP) keeps the implementation of the Convention under review. Its non-legally binding decisions include the 2011 Aichi targets and the 2022 Kunming-Montreal Biodiversity Framework.

The 2001 Stockholm Convention on Persistent Organic Pollutants (in force 2004) aims to protect human health and the environment from persistent organic pollutants (POPs), substances defined as such because of their persistence, bioaccumulation, long-range transport, and adverse effects. The Convention requires parties to prohibit the production and use, and to restrict the trade, of certain listed POPs. Substances defined as POPs can be added to the lists in the convention.

The 1989 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (the Basel Convention, in force 1992) addresses the transboundary movement of hazardous wastes though the establishment of a prior informed consent procedure in respect of the import of such wastes (Basil Convention, 1989).

The 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, London (The London Convention, in force 1975) and the 1996 Protocol (in force 2006) is the primary international agreement controlling the deliberate dumping of non-ship-generated waste at sea. Its objective is the effective control of all sources of marine pollution and to promote steps to prevent pollution of the sea.

The 1992 United Nations Framework Convention on Climate Change (UNFCCC, 2024; in force 1994) has the objective to achieve stabilization of the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Parties must develop national inventories of their greenhouse gas emissions and removals, implement programmes to mitigate climate change, and cooperate in the development, diffusion, and application of technologies, practices, and processes that control, reduce, or prevent emissions. The 2015 Paris Agreement (UNFCCC, 2015; in force 2016) seeks to enhance the implementation of the UNFCCC *inter alia* by holding the increase in global average temperatures well below 2°C above pre-industrial levels and increasing the ability to adapt.

The 1987 Vienna Convention on the Protection of the Ozone Layer and the Montreal Protocol on Substances that Deplete the Ozone Layer (in force 1989) aim to protect human health and the environment against adverse effects from human activities that modify or are likely to modify the ozone layer. The ultimate objective is the elimination of ozone-depleting substances.

In addition to these legally binding agreements, global non-legally binding arrangements are relevant to the conservation and use of the marine environment:

- The 1995 Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA) seeks to prevent the degradation of the marine environment from land-based activities.
- The 1992 United Nations Conference on the Environment and Development (UNCED) produced the global action plan for the environment (Agenda 21), which promotes new approaches to managing human uses of ocean resources.
- The 2002 World Summit of Sustainable Development produced the Johannesburg Plan of Implementation which, among other things, calls for the application of the ecosystem approach and the promotion of integrated oceans management.
- The 2012 UN Conference on Sustainable Development (Rio+20) produced a political outcome document, The Future We Want (2012), renewed past commitments, and addressed a number of thematic issues, including oceans and seas.
- Non-binding agreements, but of considerable political importance, are the 17 Sustainable Development Goals (SDGs) including SDG 14 "Life below water" adopted by UNGA in 2015.

Polar cod. Image credit: Erling Svensen, IMR

9.5.3 Regional instruments of relevance to WGICA

Regional environmental instruments that pertain to the Arctic marine environment are most numerous for the North Atlantic.

The 1979 Convention on Long-range Transboundary Air Pollution (LRTAP, in force 1983) aims to protect human beings and their environment against air pollution and to limit and, as far as possible, gradually reduce and prevent air pollution including long-range transboundary air pollution. Protocols to the Convention address specific pollutants such as ozone, sulphur, and nitrogen oxides, heavy metals, persistent organic pollutants, and volatile organic compounds.

The 1992 Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR, in force 1998) aims to prevent and eliminate marine pollution, achieve sustainable management, and sustain legitimate uses of the sea to meet the needs of present and future generations. The Convention concerns the marine environment of the Northeast Atlantic and covers all sources of marine pollution and includes all human activities except fishing.

9.6 Marine scientific research

9.6.1 UNCLOS

The Law of the Sea Convention addresses the rights and obligations of coastal states with respect to the conduct of marine scientific research in the different maritime zones. Marine scientific research is a freedom of the high seas, and states have a duty to promote and facilitate the development and conduct of such research.

Coastal states have the exclusive right to regulate, authorize, and conduct marine scientific research in their respective territorial sea. They also have jurisdiction with regard to research in their EEZ and on the continental shelf, but their competence is more limited than in the territorial sea. They have the right to regulate, authorize, and conduct marine scientific research. Other states wishing to conduct research in the coastal state's EEZ and continental shelf must obtain the consent of the coastal state.

9.6.2 The Intergovernmental Oceanographic Commission (IOC)

The IOC is recognized as the competent international organization for marine scientific research under the Convention. It promotes international cooperation and coordinates programmes in marine research, services, observation systems, hazard mitigation, and capacity development. While it does not have a regulatory mandate, the IOC plans, coordinates, and supports global and regional programmes.

The Decade of Ocean Science for Sustainable Development, which runs from 2021 to 2030, was initiated by the IOC and endorsed by the UN General Assembly. It aims at "the science we need for the ocean we want" through a number of activities and initiatives, including for the Arctic.

9.6.3 Regional agreements of relevance to WGICA

Science is a significant human activity in the Arctic, as well as critical in the sustainable management of the Arctic marine environment. As already described, the Law of the Sea Convention contains general provisions regarding marine scientific research. In addition, there are also regional binding and non-legally binding instruments and institutions that play an important role.

The 1992 Convention for a North Pacific Marine Science Organization (establishing the North Pacific Marine Science Organization (PICES; in force 1995). PICES was established to advance scientific knowledge about the ocean environment, global climate change, living resources and their ecosystems, and the impacts of human activities, and to promote the collection and rapid exchange of scientific information on these issues. The PICES area is northwards of 30°N in the Pacific Ocean.

The 1964 Convention for the International Council for the Exploration of the Sea (ICES) builds on the ICES organization established in 1902 (ICES, 1964). ICES has 20 Member Countries from the North Atlantic. ICES promotes, coordinates, and disseminates research on the physical, chemical, and biological systems in the North Atlantic and adjacent seas such as the Arctic Ocean, and provides advice on human impacts on its environment, and advice on fisheries management. In support of this, ICES Data Centre facilitates the exchange of oceanographic, environmental, and fisheries data and information.

The 2017 Agreement on Enhancing International Arctic Scientific Cooperation (in force 2018) seeks to enhance cooperation in scientific activities to increase the effectiveness of and efficiency in the development of scientific knowledge in the Arctic. The agreement addresses matters such as entry and exit of persons and equipment, access to research infrastructure and areas, and access to data.

The International Arctic Science Committee (IASC, 2022) and the International Arctic Social Sciences Association (IASSA, 2025) are non-governmental organizations based on non-binding agreements. The mission of IASC (1990) is to encourage, facilitate, and promote research to foster greater scientific understanding of the Arctic and its role in the Earth system. The International Arctic Social Sciences Association aims to promote international cooperation and increase the participation of social scientists in Arctic research.

The Polar Years (most recently 2007–2009) have mobilized resources for and interest in Arctic marine research.

9.7 Oil and gas

9.7.1 UNCLOS

Coastal states have sovereign rights over their continental shelf, within and outside 200 nmi, for the purpose of exploring and exploiting its natural resources, including oil and gas. There are a number of international instruments that address issues related to the exploration and exploitation of oil and gas resources.

The general obligations of the Law of the Sea Convention to protect and preserve the marine environment are of significance when states engage in oil and gas activities. The Convention also contains an obligation to prevent pollution from seabed activities. Coastal states are required to adopt laws and regulations to prevent, reduce, and control pollution of the marine environment arising from seabed activities.

9.7.2 Other global instruments

The MARPOL Convention and the London Dumping Convention (Section 9.5.2) also include regulations that are relevant for oil and gas activities, as they cover operational pollution from continental shelf installations.

Furthermore, the International Convention on Oil Preparedness, Response and Co-operation (the OPRC Convention) requires states to prepare for and respond to an oil pollution incident nationally or in cooperation with other states. The Convention covers oil pollution incidents involving ships, offshore units, seaports, and oil handling facilities.

UNEP has developed non-binding guidelines for state practice with regard to offshore mining and drilling.

9.7.3 Regional instruments of relevance to WGICA

The OSPAR Convention (1992). Decisions and recommendations of OSPAR are of significance for oil and gas activities in the Northeast Atlantic (OSPAR, 2017). These regulations are more extensive and specific than the obligations to prevent pollution in UNCLOS. OSPAR covers all sources of marine pollution, including from oil- and gas-related activities. It prohibits dumping of wastes and other matter from offshore installations and includes obligations to protect and conserve ecosystems and the biological diversity of the maritime area.

The 1993 Agreement Between Denmark, Finland, Iceland, Norway and Sweden Concerning Cooperation in Measures to Deal with Pollution of the Sea by Oil or Other Harmful Substances (in force 1998). The parties undertake to cooperate in the protection of the marine environment against pollution of the sea by oil or other harmful substances.

The 2013 Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic (in force 2016) aims to strengthen cooperation, coordination, and mutual assistance among the parties on oil pollution preparedness and response to protect the marine environment from pollution by oil. It requires the parties to have national systems to respond to incidents, lists authorities and contact points, and have rules on notification and monitoring, requests for assistance, and movement and removal of resources across borders.

9.8 Other instruments

Some regional instruments are important in other respects than those previously addressed. Environmental impact assessments are addressed both by the UN Economic Commission for Europe (ECE; and is, therefore, open to all Arctic countries) and by Arctic Council guidelines.

The 1991 ESPOO Convention on Environmental Impact Assessments (in force 1997) sets out an obligation to assess the environmental impacts at an early stage of planning and before decisions are made. Parties to the Convention must have a system for EIAs and carry out an EIA before the decision is taken to authorize or undertake proposed activities.

9.9 The Arctic Council

The mandate and activities of the Arctic Council span environmental protection and sustainable use of Arctic resources, but it does not have a mandate to manage human activities in this regard. The non-binding Ottawa Declaration of 1996 established the Arctic Council (1996) as a high-level intergovernmental forum to promote cooperation, coordination, and interaction among the Arctic states, particularly in issues of sustainable development and environmental protection in the Arctic. The member states of the Arctic Council are Canada, Denmark (including Greenland and the Faroe Islands), Finland, Iceland, Norway, the Russian Federation, Sweden, and USA. Six indigenous groups have status as permanent participants.

There are six working groups of the Arctic Council: Arctic Contaminants Action Program (ACAP), Arctic Monitoring and Assessment Programme (AMAP), Conservation of Arctic Flora and Fauna (CAFF), Emergency Prevention, Preparedness and Response (EPPR), Protection of the Arctic Marine Environment (PAME), and Sustainable Development Working Group (SDWG). Each working group has a specific mandate, a chair, and a management board or steering committee and is supported by a secretariat. These groups execute the programmes and projects mandated by Arctic Council ministers as stated in the Ministerial Declarations that result from biannual ministerial meetings. All decisions of the Arctic Council and its subsidiary bodies are by consensus of the eight member states.

The ministerial declarations contain broad instructions for the development of the work programmes of the working groups. Among the important accomplishments of the Arctic Council to date are the various assessments that have been performed for the Arctic Environment (1998), the Arctic Climate Impact Assessment (ACIA, 2004), the Arctic Human Development Report (2004), the Oil and Gas Assessment (2008), and the Arctic Marine Shipping Assessment (2009). In addition to the assessments, which are major undertakings, the working groups run a large number of projects. These may result in strategic initiatives, e.g. the Arctic Marine Strategic Plan, or project reports on issues of concern, e.g. ecosystem-based oceans management.

9.10 Conclusions

The CAO governance regime has been amplified considerably over the last decades through numerous legally binding international and regional agreements. Regional agreements of particular importance are those on international scientific cooperation (2016), oil spill prevention (2013), search and rescue (2011), the IMO Polar Code (2017), and to prevent unregulated fishing in the CAO (2018) among the five coastal states as well as the EU and five distant-water fishing countries. The scientific cooperation agreement and prevention of unregulated fishing agreement bring new arenas and opportunities for strengthened research and monitoring in the ecoregion.

In addition, there are a large number of international agreements besides those mentioned above that pertain to the CAO (Arctic Ocean Review, 2011).

10 The vulnerability of CAO ecosystem components toward pressures

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This chapter describes the ecosystem components of the CAO, their distribution, seasonality and vulnerability to pressures stemming from local human activities, when combined with those related to the introduction of various types of pollution and invasive species from sources outside the region. Climate change effects are summarized and factored into the scoring of risks posed by local and global pressures. In assessing the vulnerability of different ecosystem components to different pressures, we include consideration of the combined effects of locally and globally generated pressures.

Twelve pressures have been identified from human activities (scientific research, tourism, and military activity) and global sources (see sections 1–7):

1. Climate Change
2. Contaminants
3. Non-indigenous species
4. Marine litter, incl. micro plastics
5. Artificial noise pollution
6. Nutrient and organic enrichment
7. Extraction of species
8. Extraction of non-living resources
9. Physical seabed/sea-ice disturbance
10. Artificial light pollution
11. Unintended injury and mortality in open water
12. Human presence on ice

10.1 Climate-related effects on the ecosystem of the CAO

This section provides an overview of the climate-related changes underway in the Arctic. These changes affect virtually every aspect of the CAO ecosystem and must be taken into account when considering the additional impacts related to existing and proposed human activities inside and outside the region.

10.1.1 Climate-related effects on physical and chemical ecosystem characteristics

Climate-related effects on the physical and chemical characteristics of the CAO that are most significant for the biota of the region include the following:

Rising ocean temperatures

Temperatures are increasing two–three times as fast in the Arctic as in the mid-latitudes, although there are regional differences (IPCC, 2018; Jahn *et al.*, 2024). A rise in seawater temperature of up to 4°C is expected in parts of the Arctic Ocean (IPCC, 2021). The surface velocities of the North Atlantic current, which transports most of the ocean heat as well as nutrients and planktonic organisms toward the Arctic Ocean, have increased up to twofold over the last 24 years (Oziel *et al.*, 2020).

Decline in Arctic Sea ice

Annual and multiyear ice in the Arctic Ocean, including the CAO, is decreasing in volume and extent at an accelerating rate (CAFF, 2013) and in all months of the year (Richter-Menge *et al.*, 2017). Some projections indicate that the CAO could be largely ice-free in summer by the 2030s (AMAP, 2017b), as actual declines in extent have outpaced modelled declines (Meltofte *et al.*, 2013). In addition to reductions in volume and extent, warming is influencing the age, timing (freeze-up and thawing), location, and physical characteristics of ice.

Changes in precipitation

Models predict a substantial increase in precipitation over the next century, much of which is likely to be rain (Bintanja and Andry, 2017). The Arctic experienced an overall decrease in Arctic snow-cover extent (snow that covers the Arctic at the end of spring) from 1967 to 2012 (Derksen and Brown, 2012). Snow-cover duration has continued to decline, with its annual duration decreasing by 2–4 days per decade (AMAP, 2017b). However, the general increase in precipitation may result in more snow on sea ice in some regions and times of the year (von Quillfeldt, pers. comm. Oct 1, 2018).

Changes in light availability

Shifts in timing, location, and type of ice and snow cover change the availability of light for primary producers, resulting in spatial and temporal changes in ice-associated algal and phytoplankton blooms described in Section 13 (CAFF, 2017). In addition, sea ice reduces light penetration into the underlying water by up to 99%. The loss of ice, combined with the increase in light-generating human activity in the Arctic Ocean and the sensitivity of some Arctic species to small variations in solar and lunar illumination, may mean these species are extremely vulnerable to light pollution, which is at its extreme in the high Arctic (Ludvigsen *et al.*, 2018).

Changes in salinity

Increased river run-off and melting sea ice are resulting in significantly elevated freshwater inputs into the ocean. This freshwater is changing ocean salinity levels, particularly in the top 45 m (CAFF, 2017). Compared with the 1980–2000 average, the volume of freshwater in the upper layer of the Arctic Ocean has increased by 8 000 km^3, or more than 11%. This volume equals the combined annual discharge of the Amazon and Ganges rivers (AMAP, 2017b).

Changes in circulation and stratification

The freshwater flux together with the influx of increasingly warm Atlantic water has modified Arctic Ocean circulation and increased stratification (Yang *et al.*, 2016). These trends are likely to continue to accelerate. Changes in the locations of frontal boundaries are likely to shift as the ocean warms, stratifies, and freshens (CAFF, 2017).

Ocean acidification

Rising concentrations of CO_2 in the atmosphere are taken up in part by the ocean, which leads to ocean acidification, a phenomenon that is amplified in the Arctic as colder water absorbs more CO_2 than warmer water. Simulation models show that the Arctic Ocean may experience the greatest acidification within the global ocean, with the largest simulated pH changes worldwide occurring in Arctic surface waters (Steinhacher *et al.*, 2009; Wassman *et al.*, 2011). Simulations for the CAO indicate that acidification will increase with decreasing sea-ice cover, which will permit greater CO_2 uptake and accelerate freshwater input (AMAP, 2018a). Freshening of surface seawater lowers the concentration of calcium ions (AMAP, 2018a), which a large and diverse group of marine organisms require to build shells or skeletons (Michel *et al.*, 2013).

Declining oxygen levels

Levels of dissolved oxygen, essential to life in the ocean, are declining throughout the world's oceans, the result of a combination of warming-induced decline in the solubility of oxygen in seawater and reduced ventilation. In a 2017 study of global oceanic oxygen declines over the last 50 years, the sharpest decline by percentage was found in the Arctic Ocean (Schmidtko, 2017), likely the result of stratification-induced reductions in ventilation.

Cumulative and synergistic effects

It is important to note that these climate-related effects may combine to have cumulative or synergistic effects. For example, increased atmosphere–ocean gas exchange and meltwater release resulting from sea ice decline significantly enhances ocean acidification (Yamamoto-Kawai *et al.*, 2009).

10.2 Climate impacts on the living ecosystem

10.2.1 Microbial processes

While no direct effects of temperature increases on microbes have been reported, ongoing large-scale changes in salinity (through the seasonal thawing of the sea ice) and nutrient distribution (through water currents) may influence microbial community composition and metabolic functions (e.g. Polyakov *et al.*, 2017; Fernández-Gómez *et al.*, 2019; Charette *et al.*, 2020; Nöthig *et al.*, 2020; Terhaar *et al.*, 2021). Modelling the impacts of climate change is hindered by enormous gaps in knowledge of the dynamics, activity patterns, and metabolic potential of key microbes (e.g. Royo-Llonch *et al.*, 2021).

10.2.2 Primary producers

A suite of environmental variables (e.g. sea ice, nutrients, light, water stratification, salinity, and temperature) determine the abundance, biomass, primary production, and taxonomic composition of primary producers (Poulin *et al.*, 2011). Changes in these variables are already having effects on biodiversity and production of primary producers in the Arctic Ocean (Hop *et al.*, 2020; Castellani *et al.*, 2022; Hegseth and von Quillfeldt, 2022; Melnikov *et al.*, 2022; Brandt *et al.*, 2023). There is also a shift from light-limited to nutrient-limited growth of ice algae earlier in the spring (Duarte *et al.*, 2022).

For example, sea ice drives the taxonomic structure of protist communities under the ice and the epipelagic habitats of the CAO (Flores *et al.*, 2019). Declining multi-year ice (MYI) has already resulted in a decrease in sea-ice protist diversity in the Arctic Ocean (Hop *et al.*, 2020).

Hardge *et al.* (2017) suggest that the continued reduction in sea-ice extent, and particularly in MYI, may reduce species diversity in all habitats of the CAO. The increasing proportion of first-year ice (FYI) may, however, offer better growth conditions for ice algae during the shorter ice-covered period (Leu *et al.*, 2015).

Because of thinning of the ice (and the shift from MYI to FYI) and, therefore, enhanced light availability, bottom communities may develop earlier in the season (Lim *et al.*, 2022; Stroeve *et al.*, 2024; van Leeuwe *et al.*, 2018) and reach higher biomass, though more condensed in time (Leu *et al.*, 2015). Also, a declining snow cover is likely to have increasing importance for primary production (Selz *et al.*, 2018), as will an increase in meld pond formation (Hancke *et al.*, 2022). However, it has been suggested that nutritional content of key algae taxa will vary in response to shifts in under-ice light conditions, which may result in a net loss in nutritional output (Duncan *et al.*, 2024). Thinner ice and more open water may lead to an increase in light transmission and may, therefore, also lead to under-ice blooms of phytoplankton (Arrigo *et al.*, 2012; Leu *et al.*, 2015; Assmy *et al.*, 2017; Clement Kinney *et al.*, 2023).

Changes in the thickness and structure of sea ice, the amount of snow on top of the ice, and longer seasons of open water, particularly on Arctic shelves, have shifted the production from ice algae to phytoplankton in water masses (Wassmann and Reigstad, 2011; Barber *et al.*, 2015; Melnikov, 2018; Kvernvik *et al.*, 2020) and moved open-water production northwards (Renaut *et al.*, 2018). Earlier thawing and later freeze-up provides a longer growth season for phytoplankton, which may result in increased total primary production (Arrigo and van Dijken, 2015; Brandt *et al.*, 2023).

Due to the close connectivity between sea ice and the pelagic and benthic food webs, changes in sea-ice coverage and ice algal production will likely have important consequences for food web functioning and carbon dynamics of the pelagic and benthic system (Kohlbach *et al.*, 2016; Brown *et al.*, 2017; Flores *et al.*, 2019; Hegseth and von Quillfeldt, 2022; Koch *et al.*, 2023), e.g. reduced efficiency of pelagic benthic coupling in the Arctic deep sea during lower ice cover (Zhulay *et al.*, 2023).

These changes are compounded by the influx of warmer Atlantic water transporting more boreal species into the Arctic. This "borealization" may result in the replacement of cold-water phytoplankton with more temperate species (Hegseth and Sundfjord, 2008; Harrison *et al.*, 2013). The total effect of replacing cold-water phytoplankton with more temperate species for the CAO is uncertain, but a shift in phytoplankton community structure will have consequences for carbon cycling and trophic transfer (Wassmann and Reigstad, 2011). Increased freshening and warming of the surface ocean might also amplify the permanent halocline and favour a regenerating community and small species, e.g. flagellates over diatoms (Li *et al.*, 2009; Tremblay *et al.*, 2012). The winter silicate concentration in Atlantic water entering the Arctic has declined during the last 20 years (Rey, 2012), which may have significant consequences, e.g. a change in the spring bloom phytoplankton community structure because of a decrease in diatoms.

Among the species being transported into the Arctic through the Bering Strait is *Alexandrium catenella*, a cyst-forming dinoflagellate that causes paralytic shellfish poisoning. Massive deposits of *A. catenella* resting cysts in bottom sediments of the Alaskan Arctic, as well as abundant vegetative cells in the water column during summer months, have been reported (Anderson *et al.*, 2021a). So far, 36 potentially harmful or toxic marine unicellular eukaryote taxa have been recorded in phytoplankton across the Arctic (Poulin *et al.*, 2011). The potential risk of fish and aquatic bird kills, lowered fitness in marine mammals, and public health threats attributable to these taxa is uncertain. The presence of algal toxins in Arctic marine mammals, however, has been reported (Lefebvre *et al.*, 2016).

If strong algal blooms become increasingly common in Arctic waters, this could lead to impacts on seabirds and fish because of either toxic effects or increased turbidity affecting foraging for visual predators (Frederiksen, 2017). For example, a coccolithophore bloom is associated with opaque blue water that may affect seabird foraging or prey distribution (Baduini *et al.*, 2001).

10.2.3 Sea ice fauna and zooplankton

Sea ice provides habitat for numerous ice-associated animal species, ranging from unicellular organisms to large crustaceans (amphipods), fishes, and mammals [reviewed by Steiner *et al.* (2021)]. The ongoing rapid decline in overall areal extent and thickness of sea ice, as well as lengthening ice-free periods, the demise of multiyear ice, and increasing dynamic mobility and deformation [reviewed by Meredith *et al.* (2019)] are profoundly affecting habitat distribution, food availability, and life-cycle dynamics of ice-associated (sympagic) fauna.

There is evidence of decreasing abundance of protists and sympagic crustaceans related to the loss of multiyear ice (Melnikov, 2018; Hop *et al.*, 2021a). In pelagic zooplankton, the changing phenology of ice algal blooms has increased the risk of recruitment failure because of a mismatch of life cycles and bloom phenology, as described for the ecologically important copepod *Calanus glacialis* (Søreide *et al.*, 2010).

The already observed changes in the magnitude, timing, and phenology of ice algae and phytoplankton production described in this section have yielded both positive and negative impacts on the ability of the Arctic ecosystem to support invertebrate communities. Sympagic fauna cover a large (> 50%) part of their carbon demand from ice algae (Budge *et al.*, 2008; Kohlbach *et al.*, 2016). The increasing variability in ice algae production, therefore, likely has impacted standing stocks and the reproductive success of species that are dependent on ice algae, such as the widely distributed ice amphipod *Apherusa glacialis* (Barber *et al.*, 2015).

In the CAO, the seasonal change in light intensity controls both the seasonal vertical migration and the spring and autumn diel vertical migration of zooplankton. Notably, light levels as weak as the light from the moon or ships affect the vertical distribution of zooplankton (Last *et al.*, 2016; Berge *et al.*, 2020a). Model projections indicate that the ongoing thinning of sea ice and prolongation of the ice-free season can lead to reduced access of zooplankton to the under-ice habitat during the polar night, impacting their winter survival (Flores *et al.*, 2023). While it is certain that the decline in ice during the past decades has impacted the light regime and hence the seasonal and diel/lunar change in the vertical distribution of zooplankton, it is not known how strongly this has impacted the standing stock biomass or the community structure.

Recent studies of the effects of ocean acidification imply both neutral and negative impacts of acidification on early life stages of zooplankton and predominantly negative effects on calciferous zooplankton (Lischka *et al.*, 2011; Lischka and Riebesell, 2012; Arnberg *et al.*, 2013; Bailey *et al.*, 2017).

Advection of more boreal zooplankton into the CAO (Bluhm *et al.*, 2020) has resulted in significant changes in the zooplankton community structure and foodwebs, progressing from the marginal shelf seas towards the slopes of the Arctic Basin. This borealization reflects the northward expansion of abundant zooplankton species such as the Atlantic copepod *Calanus finmarchicus* (e.g. Dalpadado *et al.*, 2020) and also predators such as lion's mane jellyfish (*Cynaea capillata*; Crawford, 2016). Borealization increases competitive pressure on Arctic communities, often leading to a northward retreat of endemic Arctic fauna and a shift in quality and amount of available prey.

10.2.4 Benthos

Weakened pelagic–benthic coupling in the Chukchi Borderland/Canada Basin region (Zhulay *et al.*, 2023), the Laptev Sea slope into the Nansen Basin (Boetius and Bienhold, 2024), and in the Fram Strait of the Atlantic Arctic gateway (Dannheim *et al.*, submitted; Soltwedel, unpub. HAUSGARTEN data; Taylor *et al.*, 2017 and references therein) indicates changes in food supply that can affect benthic biota.

In the deep Arctic (LTER HAUSGARTEN observatory in Fram Strait), there has been significant and consistent declines in benthic biodiversity and stocks over the past 25 years. The decline in organic input has been accompanied by reductions in the abundance and diversity of benthic organisms across all size classes—meiofauna, macrofauna, and megafauna. Macrobenthic abundance, single species, and single functional traits significantly changed between 2010 and 2021 but without significant long-term trends in community structure or diversity (Dannheim *et al.*, submitted).

Nematode abundance at depths of 1 300 m, 2 500 m, and 4 000 m significantly decreased between 2000 and 2014 (Soltwedel *et al.*, 2020) with a following downward trend (Schnier *et al.*, submitted) and pronounced and progressive shifts in species composition over time (Schnier *et al.*, submitted).

Megafaunal densities declined around 50% from 2004–2015 to 2016–2021 (Boehringer *et al.*, submitted; Taylor *et al.*, 2017) with some spatial heterogeneity in ecological responses. An increase in Arctic primary production does, therefore, not always translate into increased food supply to the deep Arctic seabed. In contrast, evidence from benthic organism abundance, biodiversity metrics, and trophic structure highlight what can perhaps be interpreted as a trend toward ecosystem impoverishment, with potential consequences for the structure and function of Arctic benthic communities.

Intermittent years with differing conditions and spatial heterogeneity, including vicinity to the shelf break, appear to add variability to the emerging pattern, as shown for Fram Strait (Taylor *et al.*, 2017) and the Laptev Sea slope (Bienhold *et al.*, 2023) and evidenced in a mass occurrence event of mobile epifauna in the northern North Atlantic (Billet *et al.*, 2010).

Ocean acidification elicits varied responses in experiments involving benthic biota. A certain level of resilience to reduced pH was observed in Chukchi Sea clams (Goethel *et al.*, 2017), while reduced growth and metabolic rates and/or decreased calcification occurred in other bivalves [outside the Arctic, Gazeau *et al.* (2007)] and in sub-Arctic red king crab (*Paralithodes camtschaticus*) and tanner crab (*Chionoecetes bairdi*) juveniles (Long *et al.*, 2013). The opposite effect, of increased metabolic rate and calcification at the expense of other body functions, also occurred (Wood *et al.*, 2008). In deep Arctic waters and especially near the calcium-compensation depth, calcifiers with external shells such as bivalves and gastropods tend to already have thin shells (Bodil Bluhm pers. obs.), perhaps rendering them vulnerable to acidification.

10.2.5 Fish

As fish are generally ectothermic, changes in ambient temperature have a direct effect on their body temperature and metabolic rate. When fish experience increased ambient temperature within their tolerable range, their physiology adapts, e.g. by faster energy turnover rates, which often leads to increased growth rates. Such effects are not linear; when the temperature approaches the upper tolerance level, further increases may have negative effects, and individuals will increasingly demonstrate behavioural responses and use alternative habitats that provide thermal refuges. Changes in habitat use, while providing relief from high temperatures, can impose energetic costs through the need to move between habitats. This may result in increased use of habitats that have lower food availability or higher predation pressure as a trade-off to stressful ambient temperatures.

Sea-ice decline may also directly affect fish. Ice-associated production will vanish, directly affecting fish like young polar cod that prey on ice-associated species (Kolbach *et al.*, 2017; Geoffroy *et al.*, 2023). Without ice cover, more light will penetrate deeper into the sea, facilitating higher carbon production in the pelagic system and making it easier for visual feeders like fish to find food. At the same time, the loss of sea ice channels and structure reduce opportunities for prey fishes and invertebrates to escape predators. Overall, the shift from ice-associated to pelagic productivity will alter the composition of the algal and zooplankton communities, while the loss of structural complexity and increased light penetration will favour active visual predators and increase the exposure of fishes to avian predators.

Increased advection of water containing nutrients, plankton, and possibly fish eggs and fry into the CAO may boost the transport and early survival of boreal fishes into the ecoregion, which, in turn, may result in the displacement of native species further north. Increased forage for native species could also result in population growth, leading to higher population densities and larger distributions. The effects of advection will probably be most noticeable on the Atlantic side of the CAO, since the gateways between the Atlantic Ocean and the ecoregion through the Fram Strait and the Barents Sea are deep and allow for organisms to be advected at greater depths, while advection through the shallow Bering Strait only occurs in the upper water column. Several recent articles have discussed these processes on the Atlantic side (Aschan *et al.*, 2013; Hollowed *et al.*, 2013; Fossheim *et al.*, 2015; Kortsch *et al.*, 2015; Frainer *et al.*, 2017; Haug *et al.*, 2017; Johannesen *et al.*, 2016, 2017). The authors generally conclude that the changes observed so far have affected fishes on the borders of the CAO, while changes within the CAO are still to be documented. However, new reports of unexpected Atlantic fishes and squid in the ecoregion indicate that nektonic predators have been underestimated in the past and may be changing in species composition and abundance (Snoeijs-Leijonmalm *et al.*, 2022; Ingvaldsen *et al.*, 2023). Knowledge gaps on such key ecosystem components in combination with insufficient data on trends on animal abundance and diversity suggest that there is currently little confidence in identifying potential tipping points of the ecosystem or in detecting when such tipping points have been or will be passed.

Acidification is harmful to the egg and larval stages in some fishes. Stiasny *et al.* (2016) found that end-of-century levels of ocean acidification resulted in a doubling of daily mortality rates, compared to present-day CO_2 concentrations, during the first 25 days post hatching in Atlantic cod (*Gadus morhua*). Frommel *et al.* (2012) found that exposure to CO_2 resulted in severe-to-lethal tissue damage in many internal organs of Atlantic cod larvae in a mesocosm experiment, with the degree of damage increasing with CO_2 concentration. Kuntz *et al.* (2016, 2018) reported that swimming performance and metabolism were affected by increased temperatures and CO_2 levels in both Atlantic cod and polar cod, such that the competitive strength of polar cod was expected to decrease under future acidification and warming conditions. However, these experiments simulated conditions expected to occur many years into the future, and there is so far no evidence that the present conditions are causing problems for fish species already in the CAO. McElhany (2017) argues that even though laboratory studies show sensitivity to elevated CO_2 levels, they do not actually demonstrate an effect of ocean acidification and that, so far, there have been no unambiguous demonstrations of a population level effect.

To date, there are insufficient data on the effect of ocean acidification in the CAO on the species and community level over the past decades. In the boreal fish Atlantic cod, ocean acidification increased the sensitivity of embryo development to warming (Dahlke *et al.*, 2017). The combined stress of sea-ice decline, ocean warming, and ocean acidification could thus have a strong cumulative impact on early life stages of the ice-associated polar cod. Conversely, Steiner *et al.*

(2019) estimated the added negative impact of ocean acidification on the polar cod stock size at about 1% until the end of the 21st century, indicating that there is still large uncertainty regarding the cumulative impact of warming and ocean acidification at the population level.

10.2.6 Seabirds

At least 30 species of marine bird have been recorded in the CAO, eight of them regularly. Ivory gulls (*Pagophila eburnea*) have been documented to forage around the peripheral pack ice within the ecoregion in summer, and the ecoregion is particularly important during their late summer/autumn post-breeding staging and migration (Gilg *et al.*, 2010, 2016a; Fredriksen *et al.*, 2019). Similarly, the Ross's gull (*Rhodostethia rosea*) uses the Arctic Basin extensively for replenishment during its post-breeding migrations (Andreev, 2005; Gilg *et al.*, 2016b). In addition, portions of one Atlantic population of black-legged kittiwakes (*Rissa tridactyla*) regularly migrate across the CAO (Ezhov *et al.*, 2021). Other seabirds encountered in the ecoregion appear to be occasional visitors, most likely representing a small fraction of populations breeding and foraging farther onto the shelf and adjacent coastline.

The lives of Arctic seabirds and the patterns of sea-ice development and breakup are inextricably linked. Marine birds mainly use the marginal ice zone (MIZ) or pack ice with areas with open water, which allows access to areas where their food is concentrated. Changes in ice can affect marine birds indirectly through impacts on important ice-associated prey, such as polar cod and amphipods.

Ivory gulls make use of the MIZ throughout the Arctic (Gilg *et al.*, 2016a), but one of the most important feeding grounds is where the MIZ coincides with the shelf slope (Bluhm *et al.*, 2020; M. Gavrilo, unpubl. data). Therefore, with the sea ice retreating beyond the slope to the deeper Arctic Basin, the MIZ will not be located above the shelf or slope, i.e. the most productive areas, and likely will not serve as good feeding habitat for either the ivory gulls or other seabirds that use the MIZ.

The globally threatened ivory gull is also the seabird most affected by climate change and sea-ice loss (Loeng *et al.*, 2005; Gilg *et al.*, 2016a). It is also the Arctic seabird species most polluted by POPs and mercury (Bond *et al.*, 2015; Braune *et al.*, 2006; Lucia *et al.*, 2015; Miljeteig *et al.*, 2009, 2012). Levels of contaminants in the eggs, blood, and feathers of the gull are among the highest ever reported in Arctic seabirds and may have sublethal effects in combination with other stressors, i.e. climate warming (Strom *et al.*, 2019). Exposure to high levels of contaminants can act in concert with additional stress related to climate change to push ivory gull populations beyond their environmental tolerance limits (Miljeteig *et al.*, 2012).

Climate models predict that, by 2050, the Arctic Ocean will be free of sea ice in summer. The removal of this barrier between the Atlantic and the Pacific will modify a wide range of ecological processes, including bird distribution and migration within and along the margins of the CAO. A recent study by Clairbaux *et al.* (2019) identified 29 Arctic-breeding seabird species that currently migrate in the North Atlantic and could shift to a transarctic migration towards the North Pacific. The study also identified 24 Arctic-breeding seabird species which may shift from a migratory strategy to year-round residency in the high Arctic. There are also indications that Pacific seabirds may migrate into the Atlantic via the North Pole (Mckeon *et al.*, 2016).

Birds are responding to recent climate change in a variety of ways, including shifting their geographic ranges to cooler climates. There is evidence that northern temperate birds have shifted their breeding and non-breeding ranges to higher latitudes (i.e. La Sorte and Jetz, 2010), while some Arctic seabird shift polewards [see Section 9 in Skjoldal *et al.* (2022); Kuletz *et al.*, (2020)].

10.2.7 Marine mammals

Marine mammal species occurring in the CAO include narwhals, beluga whales, bowhead whales, polar bears, ringed seals, hooded seals (*Cystophora cristata*) and walruses (see ICES, 2021a). Generally, these species are believed to occur only seasonally, and for some species like walrus only a few individuals have been observed (Hamilton *et al.*, 2015a). The marine mammals most regularly occurring in the Pacific gateway area of the ecoregion are bowhead whales (Szesciorka *et al.*, 2024), beluga whales (Hauser *et al.*, 2018) and polar bears (Olson *et al.*, 2017). Beluga whales have also been recorded off the Siberian shelf (Belikov and Boltunov, 2002), but in the Atlantic gateway area, beluga whales stay mainly on the shelf (Vacquié-Garcia *et al.*, 2018). The most prominent marine mammal species in the Nansen Basin area are narwhals (Vacquié-Garcia *et al.*, 2017a), polar bears (Aars *et al.*, 2017) and ringed seals (Hamilton *et al.*, 2015b). Satellite tracking has shown that bowheads from the endangered and highly ice-affiliated East Greenland–Spitzbergen stock occasionally visit the Nansen Basin of the CAO (Kovacs *et al.*, 2020). Harp seals (*Pagophilus groenlandicus*) have not been reported in the WGICA area itself, but this ice-dependent Atlantic endemic species occurs in significant numbers in the shelf area north of Svalbard during summer (Hamilton *et al.*, 2021). Ice-dependent bearded seals (*Erignathus barbatus*), spotted seals (*Phoca largha*), and ribbon seals (*Histriophoca fasciata*) have sporadically been close to CAO, but their reliance on this area so far appears to be very limited (Boveng *et al.*, 2013; MacIntyre *et al.*, 2013; Citta *et al.*, 2018).

In adjacent ice-free areas, cosmopolitan species like minke (*Balaenoptera acutorostrata*), fin (*Balaenoptera physalus*), blue (*Balaenoptera musculus*), and humpback (*Megaptera novaeangliae*) whales have been increasingly observed during summer over the past decades (Moore *et al.*, 2019; Storrie *et al.*, 2018), particularly in the Atlantic gateway area. On the Pacific side, gray whales (*Eschrichtius robustus*) are increasingly observed in summer on the ice-free shelves (Moore *et al.*, 2019). This species has been a Pacific endemic since the extinction of gray whales in the Atlantic about 200 years ago (Alter *et al.*, 2015), but over the past 10 years, three gray whales are known to have entered the Atlantic Ocean (Scheinin *et al.*, 2011; Elwen and Gridley, 2013; AFP, 2021), most likely via increasingly ice-free passages in the Arctic Ocean, as also supported by a gray whale observation in the Laptev Sea (Shpak *et al.*, 2013). This is a clear indication of the potentially profound changes in species and population distribution and exchange rates that may occur during the current and projected future sea ice regimes in the Arctic Ocean, including the CAO.

Marine mammal climate change responses vary widely between and, in some cases, within species.

Polar bears

The effects of climate change differ among polar bear populations. So far, no overall declines in abundance, body condition, or reproductive output of polar bears have been observed in the area north of Svalbard (MOSJ, 2024). However, sea-ice reduction is believed to have reduced the carrying capacity of polar bears in the area (Aars *et al.*, 2017). A mitigated climate-change scenario (RCP 4.5) in a recent modelling study concluded that life history parameters of these polar bears are likely to be little affected by sea-ice retreat until after 2030 (Molnar *et al.*, 2020). More delayed responses are predicted for the East Greenland, Northern Beaufort, and Laptev Sea populations. According to this model, polar bears in the Southern Beaufort, Chukchi, and Kara seas are already negatively impacted by sea ice retreat. Only one small population in the northernmost Canadian Arctic Archipelago appears to remain unaffected by sea-ice changes by the end of the century.

Seals

There is some evidence of a ringed seal population within the CAO off the Chukchi shelf, but little associated data (von Duyke *et al.*, 2020). Most studies outside the CAO have so far not shown any negative responses to sea ice retreat among ice-associated seals in the Pacific gateway areas. Continued declines in sea ice and snow cover over the coming decades are, however, predicted to cause severe future declines in Beaufort Sea ringed seals (Reimer *et al.*, 2019). In the Atlantic gateway area, telemetry studies have shown that sea ice retreat forces young ringed seals to undertake much longer feeding migrations (Hamilton *et al.*, 2015b) and spend more time diving and less time resting. This is expected to constitute a significant deterioration of habitat quality. However, later analyses of growth, body condition, and reproductive rates have not shown any clear signs of this (Andersen *et al.*, 2021b).

Walruses

Sea ice reductions in the shallow Pacific gateway area have prompted more coastal habitat use among summering Pacific walruses (Jay *et al.*, 2012) and there are so far no signs of this subspecies utilizing the CAO. In contrast, male Atlantic walruses inhabiting the narrow shelf area to the north of Svalbard have been found to haul out on sea ice over very deep waters (Hamilton *et al.*, 2015a). These offshore walruses tended to dive deeper than walruses inhabiting coastal areas, particularly in winter (Lowther *et al.*, 2015). The capacity for deep diving and higher trophic level feeding indicates a potential for increased utilization of the CAO by Atlantic walruses (MOSJ, 2019).

Arctic whale species

Regional differences have been observed in the responses of bowhead whales to sea ice reductions. Atlantic gateway bowheads generally follow the retreating ice edge in summer (Vacquié-Garcia *et al.*, 2017a; Kovacs *et al.*, 2020), while Pacific gateway bowheads remain in the shelf areas even when sea ice has disappeared completely (Citta *et al.*, 2018; Moore *et al.*, 2019).

So far, sea ice reduction in the Chukchi and Beaufort Seas has been associated with increasing body condition (George *et al.*, 2015) and calf production of bowheads (Clarke *et al.*, 2016). This is likely partly driven by increased availability of bowhead prey species in response to enhanced primary productivity, caused by increased light availability and advection or wind-driven upwelling of nutrients (Pickart *et al.*, 2013; Tremblay *et al.*, 2011, 2014; Woodgate *et al.*, 2015). Bowhead whales in this area have made a spectacular recovery from overharvesting and are currently not considered endangered (Cooke and Reeves, 2018).

Abundance trend data for Atlantic gateway bowhead whales are uncertain, but recent estimates in the hundreds (Boertmann *et al.*, 2015; Vacquié-Garcia *et al.*, 2017a) have prompted a downlisting from critically endangered to endangered in the 2021 revision of the Norwegian redlist (Rødlista, 2021). Affiliation with sea ice is more pronounced in bowhead whales in the Atlantic gateway area, which has been attributed to particularly strong harvest-driven selection (bowheads may have been able to evade hunters by hiding in the ice) or avoidance of warmer waters for better thermoregulation (Chambault *et al.*, 2018; Kovacs *et al.*, 2020).

Increasing killer whale (*Orcinus orca*) presence in the Atlantic gateway (Storrie *et al.*, 2018; de Boer *et al.*, 2019) and the Pacific gateway area (Stafford, 2019) may also partially drive a preference for waters close to the sea ice (Breed *et al.*, 2017; Matthews *et al.*, 2020). With decreasing ice cover, direct and indirect effects of killer whale predation is likely to become an increasingly significant driver of habitat use and population trends in several arctic whale populations (e.g. Lefort *et al.*, 2020).

Narwhals

In summer 2015, unexpectedly high numbers of narwhals were observed in ice-covered areas over deep waters to the north of Svalbard (Vacquié-Garcia *et al.*, 2017). This is atypical since narwhals generally spend summer in ice-free coastal waters (Heide-Jørgensen *et al.*, 2015). Narwhals are generally not thought to feed much during summer, but some feeding behaviour has been observed in the small East Greenland narwhal population (Heide-Jørgensen *et al.*, 2020). Narwhals tagged in East Greenland actively selected water temperatures between 0.6 and 1.7°C, even though warmer waters were close by (Chambault *et al.*, 2018). A more detailed study showed increased foraging activity in the lower temperature range and suggested that prey catchability may be higher in the coldest water layers (Heide-Jørgensen *et al.*, 2020). As for bowhead whales, thermoregulatory problems at higher temperatures have also been suggested to drive preference for cold waters in narwhals. Both of these species lack a dorsal fin, which is inferred to hamper heat dissipation (Chambault *et al.*, 2018). This feature is, however, shared by several non-Arctic whale species like right whales (*Eubalaena glacialis*), right whale dolphins (*Lissodelphis borealis*), and finless porpoises (*Neophocaena* spp.), and the physiological evidence for thermoregulatory problems, therefore, currently must be considered weak. Within the known historic distribution area of narwhals, the warmest areas do, however, clearly have the lowest population sizes (Heide-Jørgensen *et al.*, 2020). These are all located to the east of Greenland, and the southernmost areas of East Greenland may already have lost their local narwhal population (NAMMCO, 2019). It is not known if these narwhals have shifted their distribution in response to prey distribution and/or prey catchability, killer whale avoidance, or a reduced ability to thermoregulate at higher temperatures (as suggested by Chambault *et al.*, 2018) or have simply gone extinct. Local hunting pressures may also have played a role in this catastrophic decline.

Beluga whales

Beluga whales are closely related to narwhals but are less consistently ice-affiliated. The habitat use of belugas in the Chukchi and Beaufort seas, for example, seems to be driven mainly by bathymetry and oceanographic features, and showed little change over a period of retreating ice cover (Hauser *et al.*, 2018). Longer ice-free seasons have, however, been associated with prolonged summer feeding in the western Beaufort Sea and changes in depth preferences. About 45 000 belugas summer in these areas, and some of them explore the deeper waters within the CAO (Hauser *et al.*, 2018; Lowry *et al.*, 2017). As previously mentioned, beluga whales in the Atlantic gateway area appear to exhibit a strictly coastal distribution pattern (Vacquié-Garcia *et al.*, 2018).

Beluga whale. Image credit: Jørgen Ree Wiig, Fishery Directory

10.2.8 Conclusion

The climate-related changes underway in the Arctic affect virtually every aspect of the CAO ecosystem. Climate-change related stress is occurring on top of existing stressors. These include the introduction of contaminants, plastics, invasive species, and pollution originating outside the Arctic, along with the impacts of human activities currently underway within the Arctic Ocean that affect the CAO, such as disturbance, pollution, and noise from shipping, icebreakers, military operations, and oil and gas operations, which can propagate over very long distances [noise from vessels has been detected > 100 km away, and noise from seismic airguns can be detected as far as 1300 km away (PAME, 2019b)]. All of these sources of stress —from climate change, the introduction of pollutants and invasive species from outside the Arctic, along with the effects of human activities already taking place in the Arctic that affect the CAO, must be taken into account when considering the additional impacts related to proposed new or expanded human activities in the region.

10.3 The spatial–temporal distribution of ecosystem components and vulnerability

In the following sections, we describe where the ecosystem components are distributed in the CAO, and when they are there. We also describe the ecosystem components vulnerability toward each of the relevant pressures coming from human activities or global sources.

11 Microbial communities

Pauline Snoeijs-Leijonmalm

11.1 The groups

Microbial communities consist of prokaryotes (bacteria and archaea), single-celled eukaryotes (protists: fungi, algae, and protozoa), and viruses. Millions of microbial cells and viruses, including thousands of species, are present in every litre of water, sea ice, and sediment in the marine environment (Gasol and Kirchman, 2018). Some members of microbial communities (algae, cyanobacteria, and other autotrophic bacteria) use light energy for photosynthesis and are known as primary producers (see Section 4.2), but the majority of microbial species are chemoautotrophs (using energy from the oxidation of inorganic molecules such as iron, sulphur, or magnesium), heterotrophs, or mixotrophs (capable of both autotrophic and heterotrophic metabolisms).

Microbes form the backbone of all ecological systems by controlling the cycling of elements essential for life—for themselves and for other organisms. The prominent ecological role of these organisms is not only based on their ubiquitous occurrence and fast generation times (the time it takes for a population to double in number) but also on their high diversity of metabolic pathways and symbioses with viruses and multicellular organisms. Key collective metabolic processes of microbial communities, such as carbon and nitrogen fixation and nitrogen, methane, and sulphur metabolism, effectively control global biogeochemical cycling. Over time, microbially driven processes have tangibly altered the chemical composition of the biosphere and its surrounding atmosphere, and thereby microbes have defined—and still define—the current living conditions on Earth.

The versatile microbial matter cycles driven by microbes allow other organisms to fulfil their life functions, often in symbiosis. However, in the form of parasites, microbes can also hamper other organisms and cause diseases. Microbial community composition strongly depends on habitat and responds instantly to environmental change because of high species diversity and short generation times that are, e.g. within the range of hours for wild bacteria. However, since the CAO is a cold, ultraoligotrophic ocean, productivity is extremely low at all levels, and microbial generation times may be slightly longer than elsewhere. In the CAO ecosystem, the three dominant microbial habitats are sea ice (sympagic), water column (pelagic), and deep-sea sediments (benthic). Each of these habitats has its own unique community composition (Skjoldal, 2022).

11.1.1 Sympagic microbial communities

Diverse communities dominated by cryophilic (cold-adapted) microbes and viruses live associated with the sea ice of the CAO (Bowman *et al.*, 2012; Rapp, 2014; Fernández-Gómez *et al.*, 2019). This high diversity is caused by high habitat diversity, such as different physical structures of snow and ice, interstitial water inside the ice (brine) that can vary from hypersaline in winter (salinity up to three–fourfold that of ocean water) to brackish in summer (down to one-tenth that of seawater) when the ice is partly melting, and melt ponds with fresh to slightly brackish water. From the ice surface down to the ice bottom (usually the sea ice is 2–3 m thick), there is a steep insolation gradient in summer from 100% at the ice surface to on average 9%

under the ice, which affects phototrophic microbes (Lund-Hansen *et al.*, 2015). Microalgal biomass is usually highest in the lower 5–10 cm of ice, where the ice is soft and porous and in contact with seawater, since seawater usually contains more nutrients than ice and snow. Not only microalgae thrive here, but also other microbes and viruses involved in versatile microbial metabolisms in association with the primary producers (including decomposition). These microbial communities reach their highest biomass in the Arctic summer. In winter, the ice habitat in the ecoregion experiences complete darkness, and photosynthesis is inhibited, while chemoautotrophic and heterotrophic microbial processes are active at low rates.

11.1.2 Pelagic microbial communities

The microbial communities in the water column immediately under the ice consist of a mixture of ice-associated and oceanic species and are highly diverse because the two groups meet here (Fernández-Gómez *et al.*, 2019). Oceanic species prevail further down the water column, and the purely water-column communities are less diverse (Bano and Hollibaugh, 2002; Galand *et al.*, 2010; Ghiglione *et al.*, 2012; Li *et al.*, 2016). Most of the microbial species that occur at greater depths in the CAO are the same as those elsewhere in the global ocean, since this is an interconnected environment with relatively uniform levels of structuring factors such as salinity and temperature.

11.1.3 Benthic microbial communities

Like in the deep-water column, the species of benthic microbes and viruses found in the CAO are mainly the same as those found in the global ocean at those depths. Their primary roles on the seabed are in decomposition-related processes (Dong *et al.*, 2015; Balmonte *et al.*, 2018; Wang *et al.*, 2018).

11.2 Spatial coverage in the CAO

Microbes and viruses are widespread in the oligotrophic CAO. They are everywhere in high numbers, but their abundances are generally lower than in more nutrient-rich seas. Patches of higher inorganic and organic nutrient availability can cause patchiness in microbe and virus distribution. A small patch of decaying algae captured inside the sea ice can create patchiness on a microscale; a piece of a tree transported with the transpolar drift from Siberia to the ecoregion can create patchiness at the metre scale; and at the marginal ice zone, larger patches of high productivity can be found at the km scale. The abundances of microbes and viruses also vary with ice depth; at the ice–seawater interface (the lower ca. 5 cm of sea ice), they are generally more numerous than in the sea ice above because of higher nutrient availability in seawater than in ice. The abundance of microbes and viruses varies also with water depth; in surface waters, they are more numerous than in deeper water, with the highest abundances at the chlorophyll maximum (in the CAO usually at depths of 10–40 m) and with slightly increased abundances in the Atlantic Water Layer (200–500 m) than in the layers above and below.

11.3 Temporal occurrence in the CAO

Microbes and viruses are persistent year-round. However, prominent seasonal variation in abundance and species composition does occur. Most seasonal variation occurs in the sea ice habitat, less in the water column, and least at the seabed. The most pronounced differences are between the half-year polar night and the half-year polar day because during the latter phototrophic processes occur in addition to all other metabolic pathways.

11.4 Vulnerability toward pressures from human activities

The two pressures "contaminating compounds" and "introduction of non-indigenous species" might negatively affect microbes and viruses in the microbial communities of the CAO.

For the other pressures considered in this report it is assumed that "artificial light pollution", "extraction of non-living material", "extraction of species", "human presence", "marine litter", "noise", "nutrients and organic enrichment", "physical seabed disturbance", and "unintended injury and mortality" have no adverse effects on microbes and viruses in the CAO at the population or community level. However, they might have local impacts on short timescales. For example, disturbances of microbial communities from vessels breaking the ice are local and short-term, and this human pressure is negligible compared to storms that create similar disturbances at much larger scales and much more frequently than ice-breaking ships.

Some of these pressures might have positive effects (not included in ODEMM) on the growth and diversity of microbial communities. One example is marine litter and microplastics, which could provide a physical substrate to sessile bacteria and viruses, thereby increasing their abundance and biodiversity. Marine litter and microplastics could also be degraded (used as nutrient substrate) by some bacteria, while nutrients and organic enrichment could directly stimulate the growth of microbes and viruses. Artificial light pollution from ships in winter could wake up hibernating photoautotrophic cells, causing them to start to photosynthesize. Although this is unnatural, it is not harmful.

11.4.1 Contaminants

Contaminating compounds may have negative effects on microbial communities. It cannot be excluded that contaminating compounds from global sources arriving in the CAO by air, ice drift, or water transport have direct negative effects on sea-ice and water-column microbes and viruses. Strongly toxic compounds such as Hg could be an example of this. The adverse effect would be widespread and occur persistently because contaminants arriving by the means mentioned above can spread over the entire ecoregion, and this could happen continuously. No direct negative effect of such compounds is expected on seabed microbes and viruses; because of the great depth of the CAO, contaminants are not likely to reach the seabed without becoming extremely diluted.

It can also not be excluded that contaminating compounds from ships in the ecoregion may directly harm microbes or viruses in the sea ice and water column. This could be e.g. pharmaceuticals. If so, the effect occurs only near the ship site, i.e. only when a ship that is discharging such compounds would pass by, which would be rare for tourism/recreation and military ships (less than one month per year) and occasionally for research vessels (between one and four months per year).

In all these cases, the degree of impact on microbial communities (including viruses) is expected to be low, i.e. not causing high mortality at the community level for the microbes because of their short generation times (dilution of the contaminants). However, bioaccumulation of the toxic compounds in higher trophic levels may be a larger problem.

In all these cases, the resilience of microbial communities (including viruses), i.e. the ability to withstand disturbances and maintain community functionality, would be high because of the short generation times and high diversity of microbes, which warrants fast recovery at the community level.

In all these cases, the persistence of the pressure would be low, i.e. after cessation of the pressure, the impact on the microbial communities disappears fast due to the short generation times and high diversity of microbes.

11.4.2 Non-indigenous species

It cannot be excluded that NIS that are pathogenic or compete for resources with native species of microbes or viruses (either free or embedded in other NIS) and are transported to the CAO by ship, could have direct negative effects on sea-ice and water-column microbes and viruses. If so, the effect occurs only near the (ship) site, i.e. only when a ship leaking NIS would pass by, and would be rare for tourism/recreation and military ships (less than 1 month per year) and occasional for research vessels (1–4 months per year).

Pathogenic species of microbes and viruses are not expected to arrive in the CAO from global sources by air, ice drift, or water transport, as they would likely die during transport. However, non-indigenous microbial and viral species that are pathogenic to or competing for resources with native microbial and viral species may arrive in the ecoregion with species of e.g. zooplankton, squid, fish, birds, and mammals, expanding their distributions northward in response to climate change.

In all these cases, the degree of impact on microbial communities (including viruses) is expected to be low, i.e. not causing high mortality at the community level for the microbes due to their short generation times (dilution of the contaminants). However, bioaccumulation of the toxic compounds in higher trophic levels may be a larger problem.

In all these cases, the resilience of microbial communities (including viruses), i.e. the ability to withstand disturbances and maintain functionality of the microbial communities, would be high due to the short generation times and high diversity of microbes, which warrants fast recovery at the community level.

In all these cases, the persistence of the pressure would be low, i.e. after cessation of the pressure, the impact on the microbial communities disappears fast due to the short generation times and high diversity of microbes.

12 Primary producers

Cecilie H. von Quillfeldt

12.1 The groups - Sea ice algae and phytoplankton

Sea-ice algae and phytoplankton are primarily regarded as photosynthesizing protists. However, protists are a diverse group of single-celled microbial eukaryotes which comprises photo-, mixo-, and heterotrophic taxa (Bluhm *et al.*, 2017; Hop *et al.*, 2020). Close to 1 276 sympagic algae and other protists (Bluhm *et al.*, 2017) and 2 241 phytoplankton taxa (Lovejoy *et al.*, 2017) have been recorded in the Arctic, with a dominance of large diatom and dinoflagellate cells that are relatively easy to identify through light microscopy. There are only a few studies with comprehensive species list from the CAO, and the total number of species recorded from sea ice in the area is less than 250 (Hop *et al.*, 2020).

The high variability in the number of single-celled algae across the Arctic can be related to sampling effort in time and space, but the knowledge on biodiversity is increasing as a result of improved sampling techniques, advanced microscopic and molecular methods, etc. (Poulin *et al.*, 2011; Daniëls *et al.*, 2013), as well as increased sampling in the central basins (e.g. Melnikov, 1997; Katsuki *et al.*, 2009; Joo *et al.*, 2012; Tonkes, 2012; Hop *et al.*, 2020).

12.2 Spatial coverage in the CAO

Although microscopic primary producers occur in patches, they are widely distributed across the CAO because they are transported by ocean currents and drifting ice (Abelmann, 1992; von Quillfeldt, 2000; Poulin *et al.*, 2011; Hop *et al.*, 2020; Hegseth and von Quillfeldt, 2022). Differences in distribution, however, occur on a smaller scale, often as a result of local environmental conditions (Cota *et al.*, 1991; von Quillfeldt, 2000). Furthermore, advection in addition to environmental filtering is important process that shapes plankton assemblages in the Arctic Ocean (Ibarbalz *et al.*, 2023).

There is also an ongoing northward range distribution shift, reflected in the geographic position of spring blooms and species composition (Brandt *et al.*, 2023). In addition, under-ice phytoplankton blooms have become more common (Arrigo *et al.*, 2012) and are likely to become more common and widespread with more frequent lead formation (Assmy *et al.*, 2017). There are, however, indications that different mechanisms (e.g. light conditions, nutrient availability, and advection) in different areas are driving under-ice phytoplankton blooms (Clement Kinney *et al.*, 2023).

A south–north spatial gradient similar to the seasonally dependent gradient in the species composition is often observed (Syvertsen, 1991). Furthermore, autotrophic flagellates characterize surface communities, interior communities consist of mixed microalgal populations, and pennate diatoms dominate bottom communities (van Leeuwe *et al.*, 2018). Higher phytoplankton biodiversity has been observed in the marginal ice zone compared to open water in some Arctic Seas (Ribeiro *et al.*, 2022). Large-scale patterns of net community production in the CAO are coupled to sea -ice coverage and nutrient supply (Ulfsbo *et al.*, 2014) although typically there is increased primary production at the ice edge (Sakshaug, 2004).

12.3 Temporal occurrence in the CAO

If there is sea ice, protists will usually be present in it. Such protists include both typical ice species and sometimes also resting stages of phytoplankton, especially in multiyear sea ice (Ambrose *et al.*, 2005; Hop *et al.*, 2020). Seasonality has a significant impact on species distribution, with a potentially greater role for flagellates in early spring (van Leeuwe *et al.*, 2018; Niemi *et al.*, 2011). Biodiversity may also increase over time as the communities develop, although this is also dependent on the type and origin of the ice (Hop *et al.*, 2020; Hegseth and von Quillfeldt, 2022). Furthermore, different ice communities reach their maximum biomass at different times. Melt-pond algal communities are assumed the last to reach their maximum biomass and may play an important role as a concentrated food source late in the season (Hancke *et al.*, 2022). The abundance of protists in winter assemblages is often greatly reduced (Niemi *et al.*, 2011) compared to spring and typical bloom situations, when there are sufficient light and nutrients, but this is also dependant on location (Leu *et al.*, 2015). Photosynthesis in sea ice is mainly controlled by environmental factors on a small scale and not by type of ice (van Leeuwe *et al.*, 2018).

A few cells will be present in the water column year-round, but higher biomasses like blooms occur during spring and summer. Dominant polar phytoplankton keep their photosynthetic apparatus functional over winter and have a high capacity to efficiently use the returning sunlight (Hoppe, 2022). As for primary producers in the sea ice, diversity and relative abundance are seasonally dependent, with flagellates dominating earlier in the season and centric diatoms becoming more important as the season advances (von Quillfeldt, 2000; Lovejoy *et al.*, 2002; Sukhanova *et al.*, 2009).

Changing freeze-up and thawing scenarios, as currently witnessed in the Central Arctic, might result in long-term changes in phenology and biodiversity of sea ice protists and pelagic species (Hop *et al.*, 2020; Brandt *et al.*, 2023).

12.4 Vulnerability toward pressures from human activities

Climate change, the most serious pressure of today, is dealt with in Section 10 of this report. Of the remaining identified pressures, only “contaminating compounds”, “microplastics”, and “introduction of non-indigenous species” have been considered. Some effects have been shown in culture, but the results may be biased since the studies are not accurately reproducing the current environmental concentrations (Nava and Leoni, 2021). So far, effects on population level remains to be documented, both in the CAO, but also at lower latitudes in the Arctic.

12.4.1 Contaminants

Increasing environmental pollution is an anthropogenic stress factor which may affect phytoplankton, but it is especially coastal areas and freshwater habitats that are affected (Häder and Gao, 2015). Pollution may affect phytoplankton communities at different levels — abundance, growth strategies, dominance, and succession patterns (D’Costa *et al.*, 2017). However, so far, most knowledge is obtained from experiments and observed at higher concentrations than those measured in the open ocean (Gioia *et al.*, 2011). Sensitiveness to the same chemicals may also differ notably amongst species (Broccoli *et al.*, 2021). Cell size has also been shown to be important in determining the sensitivity of marine phytoplankton (Echeveste *et al.*, 2011). Furthermore, pre-stressed with UV-B, natural phytoplankton communities have been shown to be more sensitive to pollutants such as atrazine, tributyltin, and crude oil, than those grown when UV is excluded (Echeveste *et al.*, 2011). Thus, synergistic interactions between several impact factors may be important, especially considering the ongoing climate change-induced effects in the CAO. In addition, potential effects will depend on the season, since biomass, species composition, and production of primary producers as well as the distribution and strength of pollutants are very variable throughout a year as well as between years.

Dissolved POPs may sorb to particles and organisms such as phytoplankton and can be removed from surface waters and delivered to the deep ocean by sinking particles and by zooplankton vertical migration (Gioia *et al.*, 2011). It has also been suggested that increased biomass and production in aquatic ecosystems, the result of the excess discharge of nutrients, causes a chain event that leads to reduced uptake of POPs in primary producers (Larsson *et al.*, 2000).

Even if no direct changes in phytoplankton communities are visible, pollutants may accumulate in phytoplankton and be passed on to other trophic levels in a cascading manner, resulting in biomagnification of certain pollutants (D'Costa *et al.*, 2017). However, altered primary production and food web lipid dynamics, which may influence pathways of e.g. lipophilic POPs, have been suggested but not tested in Arctic marine ecosystems (Dietz *et al.*, 2018).

12.4.2 Marine litter, including microplastics

Microplastics do interact with microalgae, but studies investigating the relationships between plastic debris and microalgae are still scarce and mainly experimental, and it remains difficult to predict how possible impacts may manifest themselves at the ecosystem level (Nava and Leoni, 2021). Possible effects on microalgae include growth inhibition, reduced photosynthetic efficiency, reduced movement, blockage of substance exchange, structural damage, and oxidative stress [Liu *et al.* (2021) and literature therein].

In addition, the interaction between ice algae and microplastics may influence the uptake of microplastics into sea ice (Hoffmann *et al.*, 2020). With sea ice present, significantly fewer algae cells were found in the ice when incubated together with microplastics compared to the incubation without microplastics (Hoffmann *et al.*, 2020). Furthermore, incorporation in sinking aggregates of ice algae or phytoplankton is likely to enhance the downward vertical flux of microplastics (Tekman *et al.*, 2020; Bergmann *et al.*, 2023) and may affect nutrient availability (Bergmann *et al.*, 2022).

Future studies are needed in order to clarify the differences in effects due to microalgae species and the properties of plastic materials (e.g. polymer type, chemical composition, weathering condition, surface charge, and size). This is because most studies have tested high concentrations of plastic particles, thus not accurately reproducing the current environmental concentrations reported in studies investigating the occurrence of plastics in marine and freshwater systems (Nava and Leoni, 2021). Most studies are also from areas or environments outside of or conducted on species not necessarily occurring in the Arctic.

12.4.3 Non-indigenous species

There are several factors which need to be in place for an introduced phytoplankton species to survive, but there are examples of successful establishments outside the Arctic. The non-indigenous diatom *Mediopyxis helysia* has dominated several spring blooms in the Wadden Sea after it was first observed in 2009, probably linked to its broad persistence under different resource conditions (Meier and Hillebrand, 2012; Meier *et al.*, 2015). Thus, the dominance in the plankton community has affected the diversity of the phytoplankton, and consequently it has been considered an invasive species (Fernandez *et al.*, 2014). The species has also been observed in Icelandic waters, and Fernandez *et al.* (2014) recommend that *M. helysia* should be given attention in the future as it has become invasive elsewhere. Furthermore, models shows that a shift from an ice-covered to an open-water Arctic Ocean could create favourable conditions for harmful dinoflagellate species that may arrive in the region, e.g. by ships (Goldsmit *et al.*, 2020), and thereby change the species composition of the phytoplankton community in certain areas (in addition to posing a potential threat to species at higher trophic levels). However, NIS are not considered a threat to the phytoplankton community of today's CAO.

13 Sea ice invertebrates and zooplankton

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13.1 The groups

13.1.1 Sea ice invertebrates

Sea ice–associated (sympagic) invertebrates are animals which either live in the network of brine channels within the sea ice matrix (sea-ice meiofauna) or are associated with the underside of sea ice, which they use as shelter from predators and as foraging ground (under-ice fauna). Sea-ice meiofauna are microscopically small, with most taxa not exceeding 1 mm in size. The dominant taxa are ciliates, dinoflagellates, harpacticoid copepods, and rotifers (Figure 13.1, panels A and B; Gradinger *et al.*, 2005; Ehrlich *et al.*, 2020). Nematodes and flatworms, which have been recorded as abundant in the past, have been rather scarce in recent years (Melnikov, 2018; Ehrlich *et al.*, 2020).

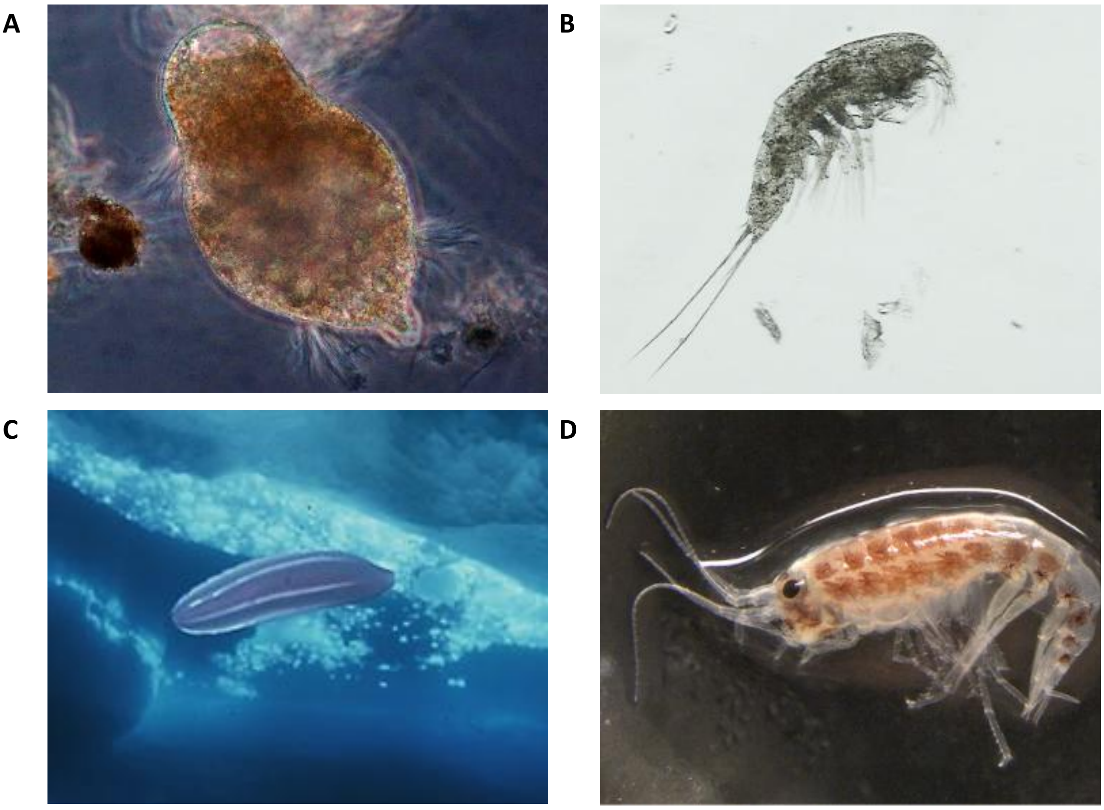


Figure 13.1. Sympagic invertebrates from the Central Arctic Ocean living inside (A, B) and underneath (C, D) of sea ice. Pictures not to scale. A) Ciliate; B) harpacticoid copepod; C) comb jelly *Beroe* sp.; D) ice amphipod *Apherusa glacialis*. Picture credits: Julia Ehrlich (A, B), Haakon Hop (C), Nicole Hildebrandt (D).

The under-ice fauna comprises permanently or temporarily ice-associated animals which are usually in the size range of millimetres to centimetres. A close association with sea ice is known for several sympagic amphipod species, including the ice-algal grazer *Apherusa glacialis*, the omnivores *Onisimus nanseni* and *Onisimus glacialis*, and the predatory *Gammarus wilkitzkii* and

Eusirus holmii (e.g. Hop *et al.*, 2021a). Several other invertebrate taxa using the under-ice habitat as a foraging ground include mysids, the ctenophores *Beroecucumis* and *Mertensia ovum*, the copepod *Calanus glacialis*, the pelagic amphipod *Themisto libellula*, and the chaetognath *Eukrohnia hamata* (Figure 13.1, panels C and D; David *et al.*, 2015; Ehrlich *et al.*, 2020; Hop *et al.*, 2021a).

13.1.2 Zooplankton

Zooplankton include animals that spend at least a part of their life hovering in the three-dimensional space of the water column. Zooplankton can move actively within certain limits (e.g. to avoid predators), but for large-scale transport (e.g. from one ocean basin to another), they depend on advection with ocean currents. In the vertical dimension, however, Arctic zooplankton participate in the largest mass movement on earth, a light-driven vertical migration in the water column (Berge *et al.*, 2020a). While vertical migration is usually tied to the diel cycle of the sun in lower latitudes, it becomes a seasonal vertical migration in the Arctic Ocean between the polar night and the polar day, with intermittent periods of diel vertical migration during twilight periods in autumn and spring (e.g. Flores *et al.*, 2023). Many Arctic zooplankton species exhibit the most abundant mode of vertical migration, i.e. dwelling near the surface during darkness (the polar night) and avoiding visual predators in deep waters during daylight (the polar day). Several species such as the ecologically important Arctic copepods *Calanus glacialis* (Figure 13.2, panel B) and *C. hyperboreus*, however, migrate to several hundred metres depth to survive the polar night in dormancy and return to the surface during the polar day to feed on ice algae and phytoplankton (Conover and Siferd, 1993; Falk-Petersen *et al.*, 2009; Daase *et al.*, 2013).

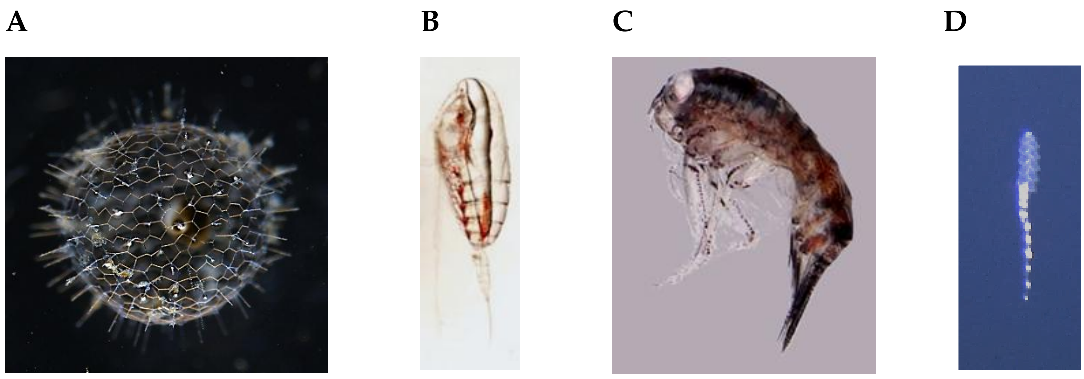


Figure 13.2. Arctic zooplankton species from different size classes. Microzooplankton: A) radiolarian; mesozooplankton: B) copepod *Calanus glacialis*; macrozooplankton: C) amphipod *Themisto libellula* and D) siphonophore *Rudjakovia plicata*. Pictures not to scale. Picture credit: Kim Vane (A), Carin Ashijan (B), Hauke Flores (C), EFICA consortium (D).

Zooplankton range in size from small, single-celled protists to large siphonophores several metres in length. Typically, they are divided according to their approximate size into the three categories: microzooplankton (< 0.01 mm), mesozooplankton (0.02–20 mm), and macrozooplankton (> 20 mm). The boundaries of these categories can vary between studies and taxa. Mesozooplankton communities in the CAO are usually dominated by copepods, among which are several genera that are considerably larger than in most copepods at lower latitudes, including *Calanus* spp., *Metridia* spp., and *Paraeuchaeta* spp. (Kosobokova and Hirche, 2000; Bluhm *et al.*, 2011a; Flores *et al.*, 2019). Microzooplankton (e.g. Lavrentyev *et al.*, 2019) and macrozooplankton (Snoeijs-Leijonmalm *et al.*, 2022; van Engeland *et al.*, 2023) are notoriously undersampled in the CAO in spite of their high ecological relevance at the base of the foodweb (microzooplankton) and for higher trophic levels, including fish, squid, and mammals. Among the most abundant microzooplankton taxa are the radiolarians (Figure 13.2, panel A) and copepods *Oithona similis*, *Oncaea borealis*, and *Microcalanus pygmaeus* (Hopcroft *et al.*, 2005; Hop *et al.*, 2021b).

Macrozooplankton in the CAO comprise amphipods (e.g. *Themisto* spp.), shrimp, chaetognaths, and jellyfish, including ctenophores, hydromedusae, and siphonophores, and larvaceans (Figure 13.2, panels C and D). Several primarily sympagic species can temporarily join the zooplankton, e.g. the ice amphipod *Apherusa glacialis* (Berge *et al.*, 2012; Kunisch *et al.*, 2020).

13.2 Spatial coverage in the CAO

13.2.1 Sea ice invertebrates

The State of the Arctic Marine Biodiversity Report (CAFF, 2017) compiled the results of 27 studies on sympagic meiofauna and 47 studies on under-ice amphipods over the pan-Arctic domain between 1977 and 2015. Updated versions of these compilations (Figure 13.1) were published in Bluhm *et al.* (2018) and Hop *et al.* (2021a). In sea ice meiofauna, the same higher taxonomic groups are present throughout the ice-covered Arctic Ocean (Bluhm *et al.*, 2018). However, the majority of studies were conducted in Arctic shelf seas, and information about the CAO is limited. In the Greenland/North American sector, the sympagic meiofauna community is often dominated by nematodes, whereas in the Eurasian sector, rotifers typically dominate. Rotifers are probably advected with the strong river influx along the Siberian coast (Bluhm *et al.*, 2018). In the CAO, this pattern is somewhat reflected by high relative abundance of rotifers in the Transpolar Drift domain vs. lower relative rotifer and higher nematode abundance in the Canada Basin and the Makarov Basin (Figure 13.3; Bluhm *et al.*, 2018). These general spatial patterns, however, must be considered with caution as the data compiled in CAFF (2017) and Bluhm *et al.* (2018) cover sparse sampling over several decades and include considerable interannual and seasonal variability, as well as variability due to different sampling protocols.

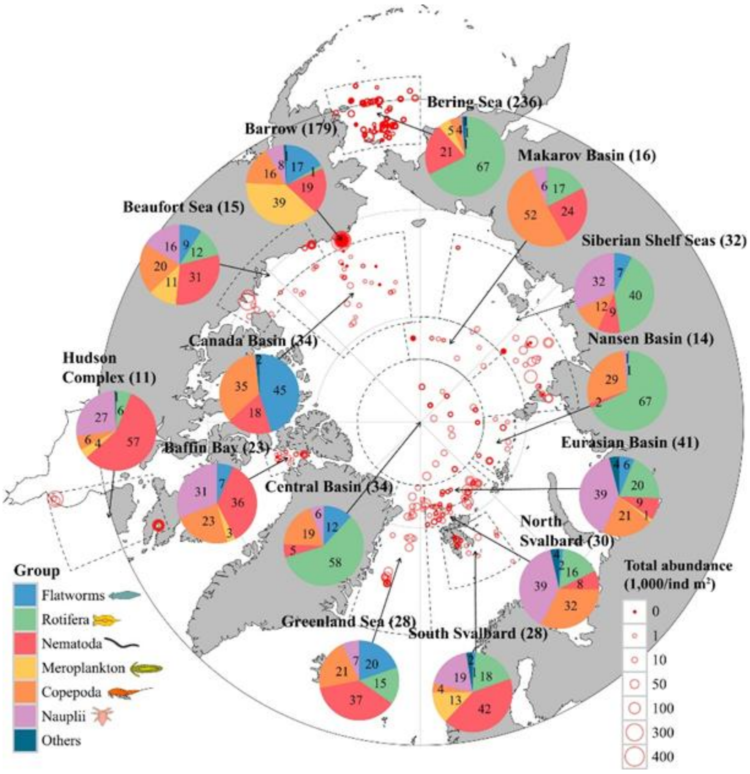


Figure 13.3. Taxonomic composition of sea ice meiofauna in different regions of the Arctic Ocean. Reproduced from Bluhm *et al.* (2018).

Due to the high technical effort necessary for sampling animals at the ice–water interface, data on under-ice fauna from the CAO are even more limited than data on sympagic meiofauna which can be studied from ice cores (Ehrlich *et al.*, 2020; Marquardt *et al.*, 2023). With regard to macrofauna, CAFF (2017) lists five Arctic sympagic amphipod species that are known to occur in the CAO, but the data are not sufficient to assemble general spatial distribution patterns (Figure 13.4). Several studies suggest that under-ice fauna distribution is related to under-ice topography and ice type (multiyear or first-year sea ice; e.g. Gradinger *et al.*, 2010; Hop *et al.*, 2000, 2021a). Hence, community composition is likely to be different between areas in the Greenland/Canadian sector of the CAO that are still covered by multiyear ice to a significant extent and areas dominated by first-year ice in the Eurasian sector of the CAO. Recent studies using standardized sampling with under-ice trawls indicated that the under-ice fauna community structure is related to gradients in sea ice and under-ice water properties, but also to nutrient concentrations in the water and the sea ice (David *et al.*, 2015; Flores *et al.*, 2019; Ehrlich *et al.*, 2020). This suggests that a spatial structure in under-ice fauna communities may exist in the CAO, but that it likely is dynamic and has been changing over the past decades due to the rapid transformation of the sea ice habitat.

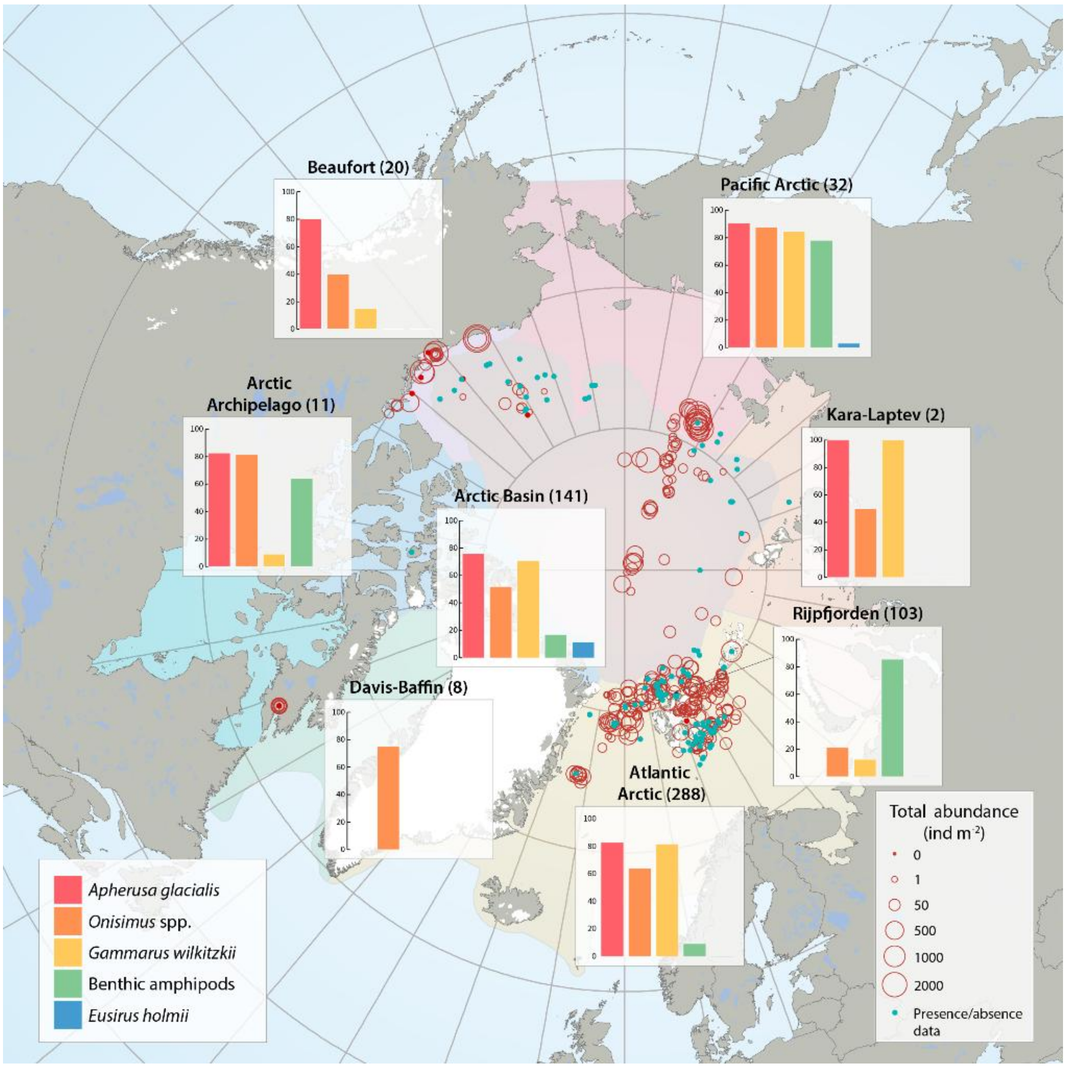


Figure 13.4. Occurrence of ice amphipods in different regions of the Arctic Ocean. Reproduced from CAFF (2017; can be accessed here: https://geo.abds.is/geonetwork/srv/api/records/4dc5ea32-fa8a-4c37-b875-9908bc8642f8/attachments/fig_3_1_6.png).

13.2.2 Zooplankton

The CAO exhibits distinct spatial variability in the distribution patterns of zooplankton. Factors such as ocean currents, bathymetry, sea ice coverage, and nutrient distribution contribute to the spatial variability of zooplankton communities. A strong vertical layering due to physical water column properties between Polar Surface Water in the top 100 m, intermediate Atlantic and Pacific Waters between roughly 100 and 1000 m, and deep water below results in vertically distinct communities which are, to some extent, connected through vertical migration (Kosobokova *et al.*, 1997, 2011; Bluhm *et al.*, 2015; Hop *et al.*, 2021b).

Horizontally, there are two major regimes in the CAO: the Eurasian Basin and the Amerasian Basin. The Eurasian Basin is strongly influenced by inflowing Atlantic water which advects heat, nutrients, and organisms deep into the CAO at intermediate depth (100–800 m; Wassmann *et al.*, 2015). Accordingly, the zooplankton community comprises considerable Atlantic components, such as the copepod *Calanus finmarchicus* and the amphipod *Themisto abyssorum*, as well as Arctic endemics, such as *Calanus hyperboreus* and *C. glacialis*. These are further distributed into the Arctic Ocean by the Atlantic Water Boundary Current north of Svalbard (Hop *et al.*, 2019) and the Transpolar Drift, which transports cold Polar Surface Water and sea ice from the Siberian shelf across the CAO towards Fram Strait (Bluhm *et al.*, 2015). In the Amerasian Basin, the Atlantic influence is much weaker, and Pacific water entering the Arctic Ocean through the Bering Strait forms an intermediate layer between the deeper Atlantic Water and the Polar Surface Water above (Wassmann *et al.*, 2020). A strong stratification of water layers of different origin inhibits nutrient replenishment to surface waters, resulting in an overall lower primary productivity which supports lower zooplankton biomass as compared to the Eurasian Basin. In the Amerasian Basin, Pacific species, such as *Neocalanus* spp. and *Metridia pacifica* contribute to the zooplankton community (Kosobokova and Hirche, 2000; Kosobokova, 2003; Bluhm *et al.*, 2015), while mesopelagic species may include carnivorous species, such as *Paraeuchaeta glacialis* and *Heterorhabdus norvegicus* (Yamaguchi *et al.*, 2022).

The communities in the two basins, however, share a high overlap in taxonomic composition as the Arctic Circumpolar Boundary Current advects significant amounts of zooplankton biomass from the Atlantic Ocean along the continental slopes of all basins (Bluhm *et al.*, 2015, 2020; Wassmann *et al.*, 2020). Accordingly, species composition can vary significantly at the edge of the CAO due to strong cross-slope gradients in community composition (Bluhm *et al.*, 2020; Hop *et al.*, 2019, 2021b). The epipelagic zooplankton community in the CAO responds strongly to variability in sea ice and surface-water properties, and changes in nutrient concentrations. This significantly impacts trophic structure, and ongoing environmental changes in the CAO have already affected spatial distribution patterns (Ashjian *et al.*, 2003; Flores *et al.*, 2019; Ehrlich *et al.*, 2020). Furthermore, accelerating sea ice decline and ocean warming are advancing the borealization of zooplankton communities from the periphery towards the CAO, making it difficult to predict if current distribution patterns will hold true in the future (Ershova *et al.*, 2021).

13.3 Temporal occurrence in the CAO

13.3.1 Sea ice invertebrates

The vast majority of studies on sympagic meiofauna have been conducted during the polar day, allowing only limited conclusions about the seasonal variability of the sympagic meiofauna community structure. Studies in land-fast pack ice (Utqiaġvik, USA) and in pack ice off Svalbard suggest that the abundance of several taxa (polychaetes, nematodes, copepods) in sea ice is very low during winter and peaks in spring and summer (Figure 13.5; Bluhm *et al.*, 2018). Seasonal studies on sympagic meiofauna from the CAO proper have so far not been conducted, but a similar seasonal pattern may be assumed.

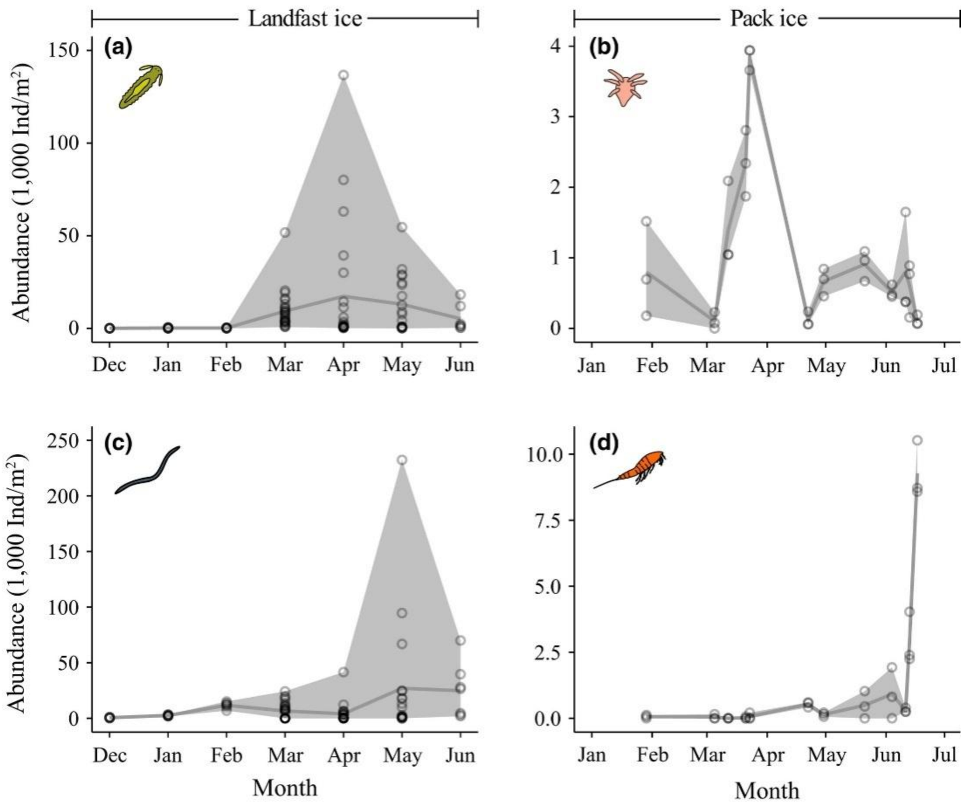


Figure 13.5. Seasonal variability in the abundance of key sympagic meiofauna taxa in sea ice. Reproduced from Bluhm *et al.* (2018).

The interannual variability of sympagic meiofauna is likely substantial, but difficult to gauge due to limited sampling effort and lack of time-series. A meta-analysis of sympagic protist communities gives strong indication that communities have significantly changed in parallel with the demise of multiyear sea ice and changing new ice formation patterns (Melnikov, 2018). It can be assumed that similar trends also apply to multicellular sympagic invertebrates. Recent studies suggest that the abundance of nematodes and flatworms in the Eurasian sector of the CAO has decreased further, possibly due to a disconnection of sea ice formation from the coastal habitats of these taxa off Siberia (Krumpen *et al.*, 2019; Ehrlich *et al.*, 2020).

Similar to the sympagic meiofauna, low sampling effort and lack of time-series data make it difficult to assess the inter-annual variability in the under-ice fauna composition. From a pan-Arctic perspective, most ice amphipods are generally more abundant under sea ice during summer than during winter (Hop *et al.*, 2021a). For example, it has been suggested that the ice amphipod *Apherusa glacialis* may spend the winter months in deeper waters (Berge *et al.*, 2012; Kunisch *et al.*, 2020). Likewise, *Calanus* spp., *Themisto* spp., chaetognaths, and jellyfish may only be attracted to the under-ice habitat during summer, when blooms of ice algae and phytoplankton nourish the foodweb under the sea ice (Ehrlich *et al.*, 2020).

A pan-Arctic meta-analysis of under-ice fauna suggested that the abundance of several ice amphipod species have shown negative trends (Hop *et al.* 2021a). In the pack ice north of Svalbard, the ice amphipod abundance declined substantially between the 1990s and the 2010s (CAFF, 2017). In recent years, unusually low abundances of the sea-ice amphipod *Apherusa glacialis* in this region may indicate increasing disconnection of sea-ice formation zones from recruitment areas for sea-ice macrofauna on the Siberian shelf within the Transpolar Drift (Krumpen *et al.* 2019; Ehrlich *et al.* 2020; Hop *et al.* 2021b).

13.3.2 Zooplankton

The seasonal variability of the zooplankton community structure in the CAO reflects the strong variability in irradiance, sea ice cover, and associated productivity pulses of ice algae and phytoplankton (CAFF, 2017). Overall, abundance and taxonomic diversity in surface waters peak during early summer when the sea ice breaks up and algal biomass reaches a short maximum (Leu *et al.*, 2015; Hop *et al.*, 2021b). During this period, filter-feeding appendicularians and other gelatinous zooplankton such as chaetognaths and comb jellies can reach high biomass, locally accounting for over 40% of the biomass of the epipelagic zooplankton community (Ehrlich *et al.*, 2020, 2021). The diversity of jellies is not well known, but over 50 different gelatinous taxa have been observed in Canada Basin, Northwind Ridge, and Chukchi Plateau (Raskoff *et al.*, 2010). A trans-seasonal analysis of copepod species composition and life cycles during the SHEBA drift study in the Amerasian Basin showed that the dominant copepod species follow two general seasonal strategies: (1) year-round activity with little change in depth distribution (e.g. *Metridia longa*) and (2) seasonally-pulsed reproductive activity and seasonal changes in activity and depth distribution of different life stages (e.g. *Calanus glacialis*, *C. hyperboreus*; Ashjian *et al.*, 2003). Although in a drift study like SHEBA it is difficult to distinguish seasonal changes from spatial patterns, it is evident that the seasonally migrating copepods cause pronounced abundance peaks during spring/early summer (Figure 13.6).

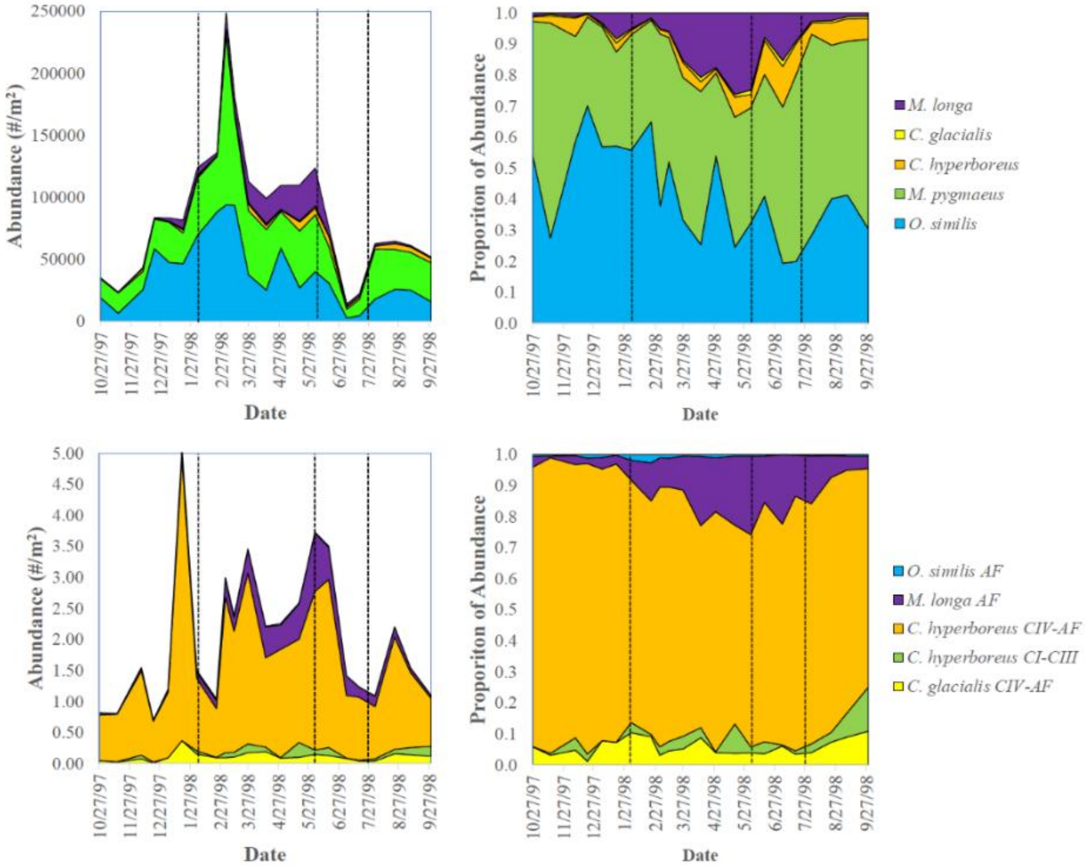


Figure 13.6. Seasonal changes in the abundance of abundant copepods in the Beaufort Gyre during the SHEBA drift (modified after Ashjian *et al.* (2003); figure provided directly by C. Ashijan).

A similar pattern during the winter–spring transition was found in the Eurasian Basin during the N-ICE expedition (Hop *et al.*, 2021b). The interannual variability in the zooplankton community in the CAO is largely influenced by drivers related to climate change, such as ocean warming, sea ice decline, and changing water mass distributions. These drivers promote the borealization of the Arctic zooplankton community, which progresses from the peripheral shelf seas into the CAO (Polyakov *et al.*, 2021). Strong borealization of the community composition along with significant biomass increases have been observed in the Barents Sea (Eriksen *et al.*, 2017) and the Chukchi Sea (Ershova *et al.*, 2015). The distribution and abundance of endemic Arctic zooplankton is also changing. For example, the abundances of the ecological key species *Calanus glacialis* and early life stages of *C. hyperboreus* have been shown to increase with lower sea ice concentration, suggesting that the core distribution of these species may shift towards the inner CAO as the sea ice deteriorates (Ershova *et al.*, 2021). Gelatinous zooplankton may also be increasing in Arctic waters, including large species such as the lion's mane jellyfish (*Cyanea capitata*) and helmet jelly (*Periphylla periphylla*; Crawford, 2016; Geoffroy *et al.*, 2018). However, the extent to which the zooplankton community has already changed in the ecoregion is difficult to assess because of a lack of (quasi-) time-series data.

13.4 Vulnerability toward pressures from human activities

A wide range of human pressures can affect the zooplankton in the CAO. This section focuses on the pressure that were assessed to have the most immediate impact on zooplankton and where the available knowledge allows at least a qualitative assessment. These include "contaminating compounds" (pollutants), "non-indigenous species", "marine litter", and "artificial light".

13.4.1 Contaminating compounds (pollution)

Exposure to contaminants may lead to uptake and bioaccumulation in zooplankton and sea ice fauna. This has been observed from crude oil in *Calanus hyperboreus* (Agersted *et al.*, 2018) and organochlorine contaminants in zooplankton from areas surrounding the CAO (Hoekstra *et al.*, 2002). Widespread distribution of mobile contaminants from global sources, such as Hg, PCBs, PBDEs, and PFASs may result in the chronic, long-term exposure of organisms to relatively low concentrations of these chemical compounds in water (Hallanger *et al.*, 2011a), which will most likely not result in detrimental effects in relatively short-lived Arctic zooplankton and sea ice fauna, with maximum lifespans of 5–7 years.

This may be different in case of an accidental release of high concentrations of chemicals, such as an oil spill. In an experimental set-up, exposure of the *Calanus glacialis* to the crude oil component pyrene during winter dormancy resulted in significant detrimental effects, including reduced egg production rate and increased mortality (Toxværd *et al.*, 2018). There is insufficient knowledge on the impact of oil spills on many rarely studied organisms at lower trophic levels in the Arctic Ocean. Slow degrading processes of a possible oil spill in Arctic waters may considerably increase the likelihood of living organisms getting in contact with toxic substances.

Indirect impacts on the whole food chain may also occur. For example, planktonic eggs may develop more slowly at low water temperatures and, therefore, may become exposed to toxic substances for longer periods than in temperate waters. The load of certain contaminants is enhanced at higher trophic levels of the marine foodweb through bioaccumulation, as has been demonstrated for Hg (Jæger *et al.*, 2009), PCBs (Sobek *et al.*, 2010), PBDEs (Hallanger *et al.*, 2011b), and PFASs (Kelly *et al.*, 2009) in the Arctic regions surrounding the CAO. Contaminants released from ships are expected to have only a local and temporary effect on zooplankton and sea ice fauna.

13.4.2 Non-indigenous species

The ongoing borealization of the Arctic Ocean promotes the introduction of Atlantic species, such as *Calanus finmarchicus*, *Themisto abyssorum* and species of euphausiids, and, to a lesser extent, Pacific species, such as *Metridia pacifica* into the CAO through the increasing influx of Atlantic and Pacific waters. The introduction of NIS from human activities acts on top of this large-scale borealization from global sources. The dominant source communities of NIS transported into the Arctic Ocean with ships originate from North Atlantic and North Pacific habitats (Chan *et al.*, 2019). Most taxa are benthic organisms from coastal habitats that are transported into shallow seas bordering the ecoregion. While these species are unlikely to find habitat in large parts of the ecoregion because of its great depth, there is significant potential for widespread establishment in shallower regions, such as the Chuckchi Borderland and the slopes of the Arctic shelf seas, including the Barents and Beaufort seas. New benthic filter feeders may increase predation pressure on zooplankton in some regions and could theoretically interfere with sea ice fauna in the shelf areas where sympagic organisms are entrained into the sea ice during autumn. Furthermore, there is increasing evidence that potentially toxic algae are transported into the Arctic Ocean with ballast water (Laget, 2017; Goldsmit *et al.*, 2020). A comparison of the dinoflagellate communities in four Canadian Arctic ports identified 12 potential NIS and seven potentially harmful species out of 49 dinoflagellate taxa (Dhifallah *et al.*, 2022). Arctic zooplankton may not be adapted to withstand the toxins of these newcomers when they are ingested, leading to increasing mortality. In a warming CAO, with less sea ice allowing more light to enter the water, conditions for potentially harmful algae species are becoming more favourable. In addition, predatory species from ballast water have the potential for mass population growth into the CAO. For example, increased abundances of planktivorous jellyfish may significantly impact the pelagic ecosystem of Arctic shelf seas (Eriksen, 2016), and such effects are likely to expand in the CAO if conditions become favourable for these tactile predators.

While the risks imposed by NIS can be considered minimal for sea ice fauna because NIS are not adapted to the extreme conditions of the sea ice habitat, the risk for Arctic zooplankton is likely to increase as a consequence of ocean warming and increasing human activities. Once NIS are established in the Arctic Ocean, their impact on the zooplankton community will likely be permanent for as long as the conditions that facilitated their arrival prevail. The effects of NIS on the ecosystem of the CAO, however, are barely understood. Due to the unique environmental conditions in the ecoregion, our ability to gauge the ecological impact of NIS based on experiences in other ecosystems is limited.

13.4.3 Marine litter, including microplastics

Large-sized marine litter (> 5 mm) is unlikely to affect sea ice invertebrates or zooplankton because the particles would be too large to be ingested, and the numbers of animals potentially entangled by large marine litter are too small compared to their numbers in the ocean to cause an effect on the population level. Microplastic particles (MP – marine litter particles between 1 µm and 5 mm in size), however, are in the size range of zooplankton prey and are, therefore, prone to ingestion (Figure 13.7). Due to its abundance in the ocean and sea ice, MP constitutes a widespread risk to zooplankton and sea ice fauna that are permanently present. Data from studies in regions bordering the CAO suggest that many taxa are potentially affected and that impact on their survival cannot be excluded. In laboratory experiments, MP have been shown to be both ingested and adhered to the body surface and appendages of various temperate zooplankton species (Cole *et al.*, 2013). Indeed, ingestion of MP by zooplankton has been reported from a wide variety of marine habitats, including the North Atlantic and the North Pacific (Desforges *et al.*, 2015; He *et al.*, 2022). Recently, a field study from the Fram Strait revealed high ingestion rates of such plastics in Arctic zooplankton (Botterell *et al.*, 2022). This study showed that between 0.01 and 1.8 MP were ingested per individual, and the majority of ingested MP were below 50 µm in size, which is a common size range of phytoplankton. Surface-dwelling and sea ice–associated amphipods (*Themisto* spp., *Apherusa glacialis*) had significantly higher MP ingestion rates than copepods (*Calanus* spp.). This difference may be related to a different feeding mode of amphipods compared to copepods, as well as to an enrichment of buoyant MP near the surface. Sea ice can contain relatively high amounts of MP, which are released during melting (Peeken *et al.*, 2018; Tekman *et al.*, 2020). Melting ice may, therefore, increase the exposure of sympagic fauna and surface-dwelling zooplankton to MP. The plastics can affect zooplankton in various ways, including intestinal damage, reduced ingestion of suitable food, slow or delayed growth, reduced spawning, shortened lifespan, and abnormal or even fatal gene expression (reviewed by He *et al.*, 2022). In combination with exposure to oil, microplastic particles can cause feeding suppressions in *C. hyperboreus* (Almeda *et al.*, 2021).

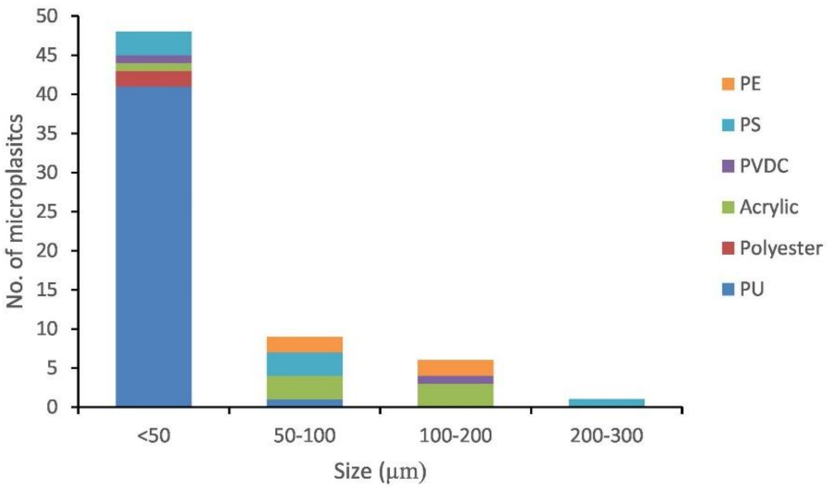


Figure 13.7. Polymer types within different size ranges found in zooplankton samples (PE: polyethylene; PS: polystyrene; PU: polyurethane; PVDC: polyvinylidene chloride). Reproduced from Botterell *et al.* (2022).

In the future, the impacts of increased emission of marine litter in the CAO on Arctic zooplankton and sea ice fauna are difficult to predict, but likely if no mitigation measures are taken.

13.4.4 Artificial light pollution

Light levels as weak as moonlight can affect the vertical distribution of Arctic zooplankton under the sea-ice cover (Last *et al.*, 2016; Berge *et al.*, 2020a), suggesting that the ongoing thinning of sea ice and prolongation of the ice-free season in lower latitudes have already had a significant impact on the vertical distribution of zooplankton. Recent studies have shown that light intensities as low as 10^{-7} µmol photons m^{-2} s^{-1} in ice-free waters (Hobbs *et al.*, 2021), and 10^{-6} µmol photons m^{-2} s^{-1} under the sea ice of the CAO (Flores *et al.*, 2023) are sufficient to trigger zooplankton migration. Research vessels, tourist vessels, and other ships emit light intensities far above these thresholds (Figure 13.8; Berge *et al.*, 2020b; Marangoni *et al.*, 2022). An experimental study using hydroacoustic measurements together with light measurements at different distances from a research vessel showed that zooplankton distribution was disturbed by artificial light down to 200 m depth (Berge *et al.*, 2020b). The area impacted, however, was quite small (0.125 km^2), indicating that artificial light has mostly a local effect, for as long as illuminated working platforms are present. The recent MOSAiC expedition (2019/2020), however, may serve as an example of local, but persistent, artificial light emission in the CAO. There is virtually no knowledge on the effect of (artificial) light on sympagic fauna. It is possible that artificial light causes disadvantageous behavioural responses at the wrong moment in their life cycle, as other marine invertebrates show similar behavioural ramifications [e.g. barnacles, amphipods, isopods; reviewed by Marangoni *et al.* (2022)]. To date, there are insufficient data on the response of Arctic under-ice fauna to a changing light field. However, ice amphipods may be more exposed to UV in thinner ice, which may deplete their antioxidant defences (Krapp *et al.*, 2009). Several Antarctic taxa of under-ice fauna show a distinct light-dependent diel vertical migration behaviour (Flores *et al.*, 2011), suggesting that also taxa in Arctic under-ice fauna may be susceptible to light disturbance.

While the effect of artificial light on sea-ice fauna and zooplankton in the CAO may be very local and transient, increasing ship traffic could alter the lightscape over larger areas in some regions in the future, with more widespread effects on zooplankton distribution, behaviour, and predator–prey interactions. Such large-scale effects on marine communities have been observed in various ecosystems at lower latitudes (Marangoni *et al.*, 2022).

Figure 13.8. Research vessel emitting light during the polar night. Reproduced from: Berge *et al.* (2020b).

14 Benthos

Amanda Ziegler, Bodil A. Bluhm, Jacqueline Grebmeier, and Lis Lindal Jørgensen

Deep-sea holothurian (sea cucumber) *Elpida* sp. Image credit: MAREANO.HI

14.1 The groups

Central Arctic Ocean benthos includes approximately 1 100 invertebrate species (Figure 14.1 from Bluhm *et al.*, 2011b; Ramirez-Llodra *et al.*, 2024) which have until now been affected only weakly by anthropogenic activities. However, the predicted ice-free summer in the Arctic in the near future may change that situation (Grebmeier and Jørgensen, 2022).

This section differentiates soft-bottom fauna, which covers the vast abyssal seabed and parts of other geomorphological features of the CAO (Bluhm *et al.*, 2011b, 2020), from hard-bottom communities, which are comprised of different fauna inhabiting parts of the ridges (with seamounts and vents) and slopes crossing through and surrounding the CAO, as well as irregularly distributed drop stones (Ramirez-Llodra *et al.*, 2024; Zhulay *et al.*, 2019).

14.1.1 Soft-bottom benthos

Soft-bottom benthos are represented in the thin benthic boundary layer by hyperbenthic and abyssopelagic taxa (Raskoff *et al.*, 2010; Zhulay *et al.*, 2019), with higher density and biomass associated with the overlying marginal ice zone (Rybakova *et al.*, 2019) and by the more 'typical' meio- and macrobenthos in soft sediments (Paul and Menzies, 1974; Kröncke, 1994; Schewe and Soltwedel, 1999; Kröncke *et al.*, 2000; Renaud *et al.*, 2006; Bluhm *et al.*, 2011b; Soltwedel *et al.*, 2020; Jorda Molina *et al.*, 2023). The soft-bottom benthos biomass in the Arctic basins is extremely low [largely < 0.5 g C m^{-2} deeper than 500 m and < 0.01 g C m^{-2} below 3000 m;

summary table in Bluhm *et al.* (2011b)] and, in a study from the Amerasian Basin, consists primarily of foraminifera (53%), bivalves (27%), sponges (7%), polychaetes (5%), and other groups (8%; Paul and Menzies, 1974). In addition, larger epifaunal megabenthic taxa including brittle stars, sea cucumbers, sea anemones and other cnidarians, and sponges inhabit soft-bottom areas of the CAO (MacDonald *et al.*, 2010; Rybakova *et al.*, 2019; Taylor *et al.*, 2018; Zhulay *et al.*, 2019). Among those, vulnerable species such as *Umbellula encrinus* have been recorded from soft sediments on slopes facing the CAO (Jørgensen *et al.*, 2016).

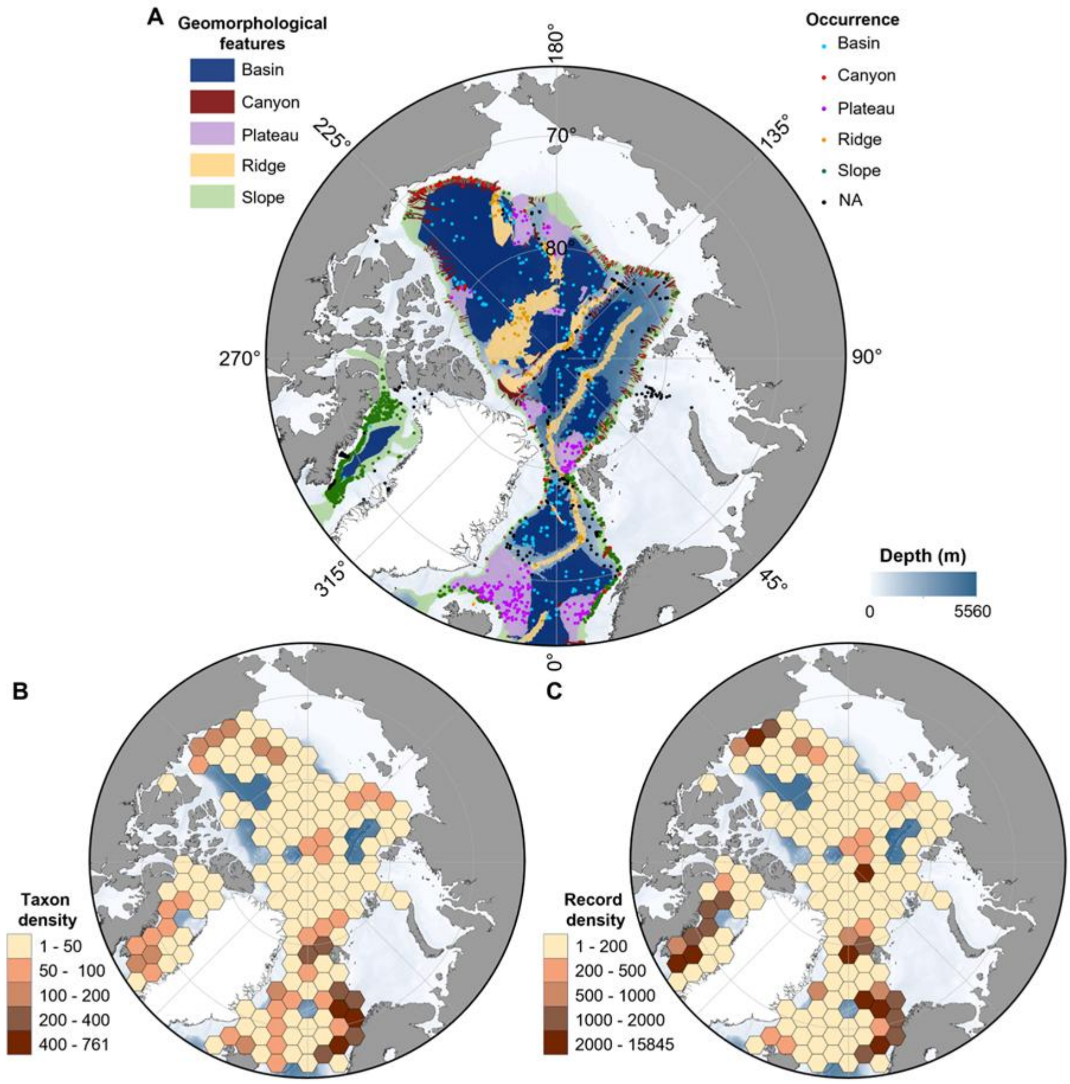
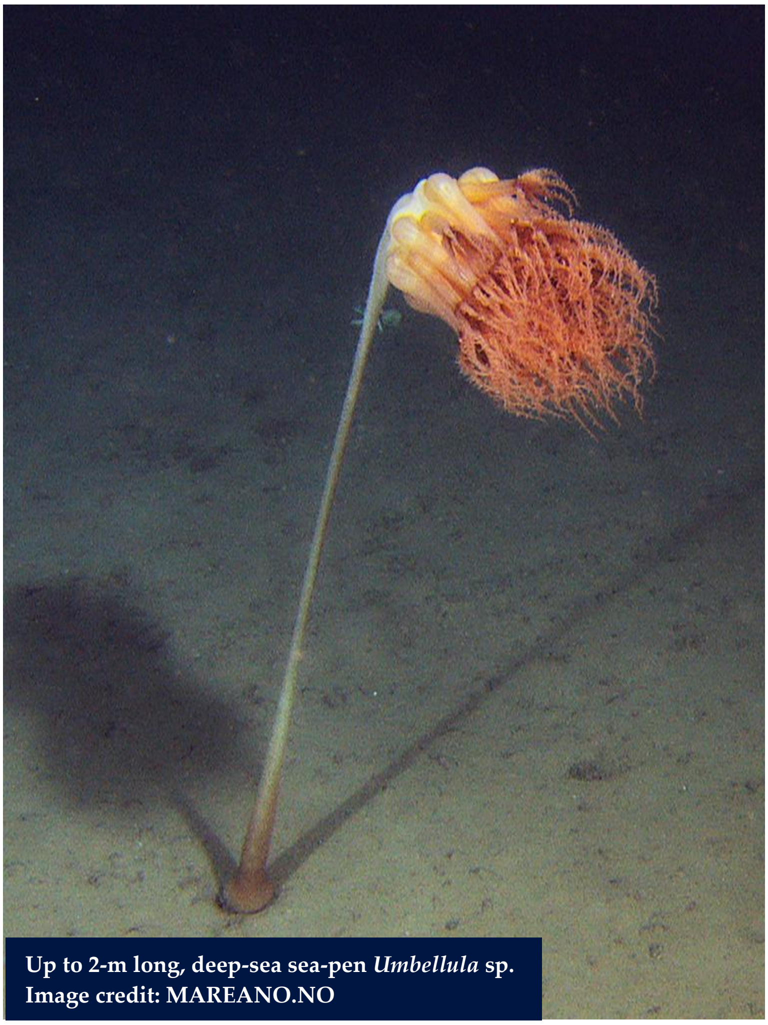


Figure 14.1. Taxon distribution records (circles) over seabed topography, showing the ridges (yellow), plateaus (pink) and slope areas (green) where benthos occurrences are comparatively shallow (yellow and green circles) and where hard-bottom benthos may be present. The deepest benthos occurrence records (blue circles) are on seabed (blue shades) dominated by softbottom fauna. Sea mounts and vent fields are concentrated on/along ridges (bottom panel). Reproduced with permission from Ramirez-Llodra *et al.* (2024).

These faunal taxa include a variety of feeding types, but as is common in the deep sea, many are detritivores, relying on the flux of organic matter from the surface (e.g. Degen *et al.*, 2015; Zhulay *et al.*, 2023). All other common feeding groups are also represented (Oleszczuk *et al.*, 2023; Zhulay *et al.*, 2021). The CAO comprises predominantly fine-grained sediments, namely clay, silt, and sand (Stein *et al.*, 1994). The soft-bottom benthos occupies a large area of the seabed, and although present in low densities and representing overall low biomass compared to shallow regions, it plays a key role in carbon and nutrient cycling (Klages *et al.*, 2004) and contributes to biodiversity including some endemic species (Bluhm *et al.*, 2011b).



Up to 2-m long, deep-sea sea-pen *Umbellula* sp.
Image credit: MAREANO.NO

14.1.2 Hard-bottom benthos

The hard-bottom benthos of the CAO is limited to regions with high erosion of surface sediments, ridges (including seamounts and hot vents, Figure 14.2), or where sporadic hard substrate including ice-rafted debris, wood, bones, and sponge stalks is present. Available studies show that hard-bottom benthos is dominated by sponges and anemones, but barnacles, crinoids, bryozoans, hydroids, and polychaetes also colonize hard substrates in the deep Arctic Ocean (Meyer-Kaiser *et al.*, 2022; Schulz *et al.*, 2010; Zhulay *et al.*, 2019). Because many hard-bottom benthos are suspension feeders, they contribute to the functional diversity of the CAO beyond enhancing taxonomic diversity. Due to the patchy nature of hard substrate in the ecoregion, comprehensive study of the hard-bottom benthos remains limited, and a complete understanding of spatial patterns in abundance, biomass, and community composition is not currently practical. However, it can be concluded that the patchy distribution of this substrate for recruitment makes the hard-bottom benthos susceptible to anthropogenic disturbances that remove or bury hard substrate, such as mining. Hard-bottom benthos include seamounts housing rich sponge beds and associated benthic biota (Boetius and Purser, 2017; Morganti *et al.*, 2022), fauna associated with hot vents in the spreading zone of the Gakkel Ridge including chemoautotrophic biota and new species (Edmonds *et al.*, 2003; Bünz *et al.*, 2020; Chen *et al.*, 2022; Ramirez-Llodra *et al.*, 2024), fauna on other ridges such as the Alpha Ridge (Schewe, 2001), and glacial-origin drop stones that constitute biodiversity islands (Mayer and Piepenburg, 1996; Zhulay *et al.*, 2019).

At submarine hydrothermal vent systems, chemosynthesis can play a large role in providing nutrients to deep-sea benthic communities (Sweetman *et al.*, 2013). Hydrothermal venting along mid-ocean ridges is an important contributor to ridge thermal structure, and the global distribution of such vents has implications for the biogeography of vent-endemic organisms. At vent sites on the Gakkel Ridge, which is a 1 100-km-long rift valley, abundant macrofauna were observed, with the composition of the chemosynthetic and associated faunal communities now in the process of being studied as the first Arctic vent field (Chen *et al.*, 2022; Ramirez-Llodra *et al.*, 2024). It is likely that even more new species of vent biota will be discovered at hydrothermal sites on the Gakkel Ridge, which have evolved in isolation from those in other oceans (Edmonds *et al.*, 2003; Ramirez-Llodra *et al.*, 2024). While these communities remain a knowledge gap for Arctic biodiversity, expeditions to hot vents on the Gakkel Ridge in 2019 (Bünz and Ramirez-Llodra, 2021), 2021 (Bünz and Ramirez-Llodra, 2021), and 2023 have begun to close this gap.

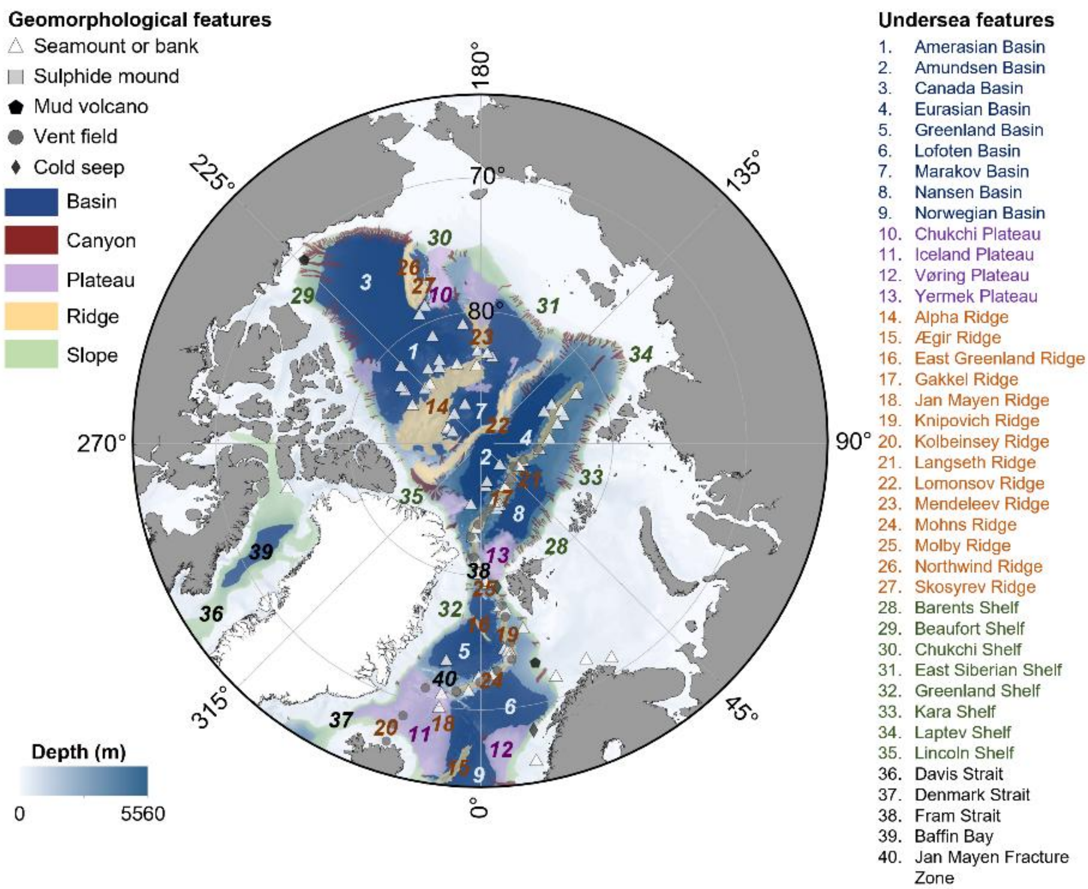


Figure 14.2. Map of the Arctic Ocean (66–90°N) showing geomorphological features and habitats. Habitats are indicated by symbols; colour-shaded geomorphological features were obtained from Harris *et al.* (2014), Beaulieu and Szafranski (2020), and GEBCO Undtyreersea Feature Names Gazetteer (https://www.ngdc.noaa.gov/gazetteer/). Bathymetry was obtained from Jakobsson *et al.* (2020). Reproduced with permission from Ramirez-Llodra *et al.* (2024).

14.2 Spatial coverage in the CAO

Soft-bottom benthos is widespread–patchy, because soft sediment covers the seabed of the basins making up the major area of the CAO.

Hard-bottom benthos is expected to be localized, because the ridges and slopes where hard bottom may be found are limited in areal extent and not well surveyed, meaning that distributions of the substrate are a knowledge gap.

Overall, benthic communities are similar within distinct depth bands across the slope and basin, with the maximum diversity of macrofauna at the shelf edge at depths of 100–300 m (Grebmeier and Barry, 2007; CAFF, 2017; Vedenin *et al.*, 2022). There is no clear mid-depth peak in diversity that is often found around 1 000–1 500 m in other word oceans (Bluhm *et al.*, 2011b, 2020). The lower slope and basin benthic community structure is distinct from the upper slopes based on taxonomic identity (Bluhm *et al.*, 2020; Vedenin *et al.*, 2018, 2022). Biogeographic affinity is dominated by Arctic–Atlantic and cosmopolitan fauna across all basins with more diverse affinities in shallower water (Mironov *et al.*, 2013; Zhulay *et al.*, 2019).

Soft-bottom benthos abundance and biomass decrease significantly with increasing depth as in the global ocean, with abundances in the CAO among the lowest recorded for the global deep sea (Wei *et al.*, 2010; Bluhm *et al.*, 2011b). For the CAO, these patterns were established and confirmed from meio- and macrobenthic studies. For example, a significant decrease in meiobenthic abundance with increasing water depth was detectable across the Alpha Ridge (Schewe, 2001) and for macrobenthos across the Eurasian Basin (Kröncke *et al.*, 2000). Soft-bottom benthic biomass, however, can be enhanced in proximity to topographic features. For example, meiobenthic biomass in the soft sediment areas of the Lomonosov Ridge was found to be higher than the biomass found in the nearby deep Makarov Basin (Schewe, 2001). Benthic communities of the deep Arctic Ocean reflect a distinct food web typical of food-limited oligotrophic systems, where deposit feeders consume highly reworked material and represent a high trophic level when assessed via stable isotope trophic markers (Iken *et al.*, 2005; Bergmann *et al.*, 2009; Zhulay *et al.*, 2023).

The hard-bottom benthos found deep in the CAO basins also has very low standing stocks. Benthic biomass, however, can be significantly higher on ridges and seamounts. For example, it was observed that suspension-feeding macrofauna increased both in abundance and species richness towards the Lomonosov Ridge, likely due to increased organic matter transport in currents affected by the ridge topography (Kröncke, 1994). Similarly, some seamounts in the CAO have been shown to harbor high densities of large sponges and other habitat-forming species (Boetius and Purser, 2017; Morganti *et al.*, 2022) which may be affected currents interacting with local topography. As mentioned in Section 4.4.1.2, hard-bottom species are also found on the hydrothermal vents along the mid-ocean ridges where faunal densities are locally much higher [e.g. at the Aurora vent site on the Gakkel Ridge, Ramirez-Llodra *et al.* (2023)].

14.3 Temporal occurrence in the CAO

Benthos as a group are long-lived species, and we consider them as present in CAO from common–persistent time-scales based on lifespans. However, time-series data from single locations are sparse for evaluating short-term changes in recruitment that affect biomass/abundance and community composition. As a whole, however, the soft- and hard-bottom benthos are likely to exist over common–persistent timescales.

14.4 Vulnerability toward pressures from human activities

Of the 11 pressures identified from human activities, four are considered relevant for CAO benthos and are described in this section: “contaminants”, “non-indigenous species”, “marine litter”, and “physical seabed disturbance” (the effect of climate change is considered in Section 10). Although not considered relevant for the CAO benthos today, the potential effects of artificial noise pollution and selective extraction of species are also briefly discussed.

14.4.1 Contaminants

Temporal trends and thresholds of the effects of pollutants on benthic community functions are lacking for the CAO. Pollutants entering the Arctic marine environment via atmospheric deposition and riverine inflow can accumulate in marine sediments and organisms (AMAP, 2018b and references therein). Some of these pollutants can have extremely long half-lives; most PCBs, for example, are virtually non-biodegradable in sediments, and compounds from insecticides and fire retardants can last up to a decade in the field (Augustijn-Beckers *et al.*, 1994; AMAP, 1998). Studies from Greenlandic fjords have shown sediment lead (Pb) concentrations above the threshold of 200 mg kg^{-1} that is associated with a dramatic decrease in diversity and a shift in the macrofaunal community structure toward dominance by heavy-metal-tolerant species and opportunists (Josefson *et al.*, 2008). Similar trends in community structure have been observed in other fjords impacted by anthropogenic pollution (Holte *et al.*, 1996).

Organic pollutants are hydrophobic and accumulate in lipids. Thus, lipid-rich phytoplankton and sea-ice algae are likely vectors for organic pollutant transfers to both higher trophic levels such as mammals and to the detrital pool in the CAO (AMAP, 1998). In the CAO, bioaccumulation and biomagnification of organic pollutants in marine fauna has not been well studied, but in the Barents Sea, for example, Hop *et al.* (2002) found relatively higher levels of contaminants in benthic spider crabs (*Hyas araneus*) from the Barents Sea marginal ice zone than in sympagic and pelagic invertebrates. Similarly, high concentrations of organic pollutants have been found in the scavenging amphipod *Eurythenes gryllus* which may accumulate contaminants that originate from the pelagic realm (Svendsen *et al.*, 2007). As is the case with Hg, which is discussed below, it is unlikely that trophic transfer of persistent organic pollutants from the benthos is currently a significant threat to the CAO ecosystem, since there is a lack of benthic-feeding marine mammals and other high trophic level organisms. POPs in marine biota and showed generally declining concentrations of legacy POPs over the past decades due to regulatory frameworks that are in place (Riget *et al.*, 2019).

If oil spills were to occur in the CAO, they would most likely occur from collisions between vessels or between vessels and sea ice. The potential for such spills could increase as shipping traffic increases in intensity or shipping corridors shift (Berkman *et al.*, 2022a,b). For example, a proposed Transpolar Sea Route could develop concurrent with reduced sea-ice extent and thickness (Stevenson *et al.*, 2019). Oil components are not currently a direct threat to benthic fauna in the ecoregion unless transport across large distances and great depths were to occur. Substantial acute, chronic, and interactive effects of oil compounds on benthic biota have been documented from other shallow, cold-water areas such as the Gulf of Alaska (Petersen *et al.*, 2003).

Mercury enters the CAO via atmospheric deposition, rivers, erosion, and ocean currents [reviewed in Dastoor *et al.* (2022)]. Concentrations, in the form of monomethyl mercury, in Arctic organisms are high compared to those at lower latitudes (Dietz *et al.*, 2009) and these organisms (mainly fish and marine mammals) provide a conduit for contamination to humans through fishing and hunting activities. Again, current knowledge stems primarily from Arctic shelves since there are very limited or no data on mercury species in biota from the CAO. The concentrations of monomethyl mercury and particulate elemental Hg in sediments and the water column are greatest on the Chukchi shelf and in the Bering Strait, which act as the main sources to the rest of the Arctic Ocean (Agather *et al.*, 2019). This results in a gradient of Hg concentrations decreasing from west to east (Riget *et al.*, 2011a). On the Atlantic Arctic side, Hg concentrations in surface sediments are, in fact, higher in the Nansen and Amundsen basins (to 116 ng g^{-1}) than on the Barents Sea shelf, attributed to transport of fine-grained sediment into the basin (Kohler *et al.*, 2022). Although the biological transfer of Hg is most likely to occur in surface waters, most Arctic Ocean Hg is found in shelf and basin sediments or in the deep ocean, with only 7% estimated to be in the ocean surface layers (Soerensen *et al.*, 2016). Biomagnification of Hg in benthic fauna of the shallow Chukchi Sea has been documented (Fox *et al.*, 2014), but it differed among benthic invertebrate feeding types. Scavenging benthos that feed upon pelagic organisms have been observed to accumulate relatively high concentrations of Hg (Svendsen *et al.*, 2007; Bidleman *et al.*, 2013). Overall, however, the biomagnification power of Hg in benthos in the CAO is likely lower than has been documented elsewhere. Without deep-diving and benthic-foraging mammals in the CAO, trophic transfer of Jg from benthos is likely minimal.

The anthropogenic contribution of Hg within Arctic organisms has increased over the past 150 years (Dietz *et al.*, 2013). However, very few studies of Hg content in benthic biota exist to provide a baseline with which to compare in the future [see Bidleman *et al.* (2013) for concentrations in benthic scavenging amphipods]. No clear spatial trend in mercury content of biota has been observed, but data from Canada and Greenland have shown increasing trends compared to the Atlantic Arctic (Riget *et al.*, 2011b). In both referenced publications, the authors stress that only time-series providing several decades of coverage could show statistically significant trends.

14.4.2 Non-indigenous species

While the risk of NIS introductions into shallow, coastal Arctic ecosystems remains high, there are several factors that limit the introduction and establishment of benthic NIS in the CAO. Reduced sea ice within the ecoregion will reduce ice scour on ships that usually removes hull-fouling organisms along sailing routes, as seen in the Antarctic, where hull-fouling organisms survived during transit along ice-free routes (Lewis *et al.*, 2004; Lee and Chown, 2009; Hughes and Ashton, 2017). Indeed, in the Canadian Arctic, hull fouling transported a high diversity and abundance of organisms, suggesting that it already poses a high risk to Arctic coastal and shelf ecosystems (Chan *et al.*, 2015); yet deep-water CAO systems are distinctly different. Additionally, ballast water exchange is limited to the deepest portions of the ecoregion, where establishment of benthic taxa released thousands of metres above the seabed is unlikely. For example, transoceanic vessels entering Canadian ports are required to exchange ballast water at depths greater than 2 000 m and at more than 200 nmi from the Canadian coast, when possible (Holbech and Pedersen, 2018). The IMO International Convention for the Control and Management of Ships' Ballast Water and Sediments mandates the treatment and exchange of ballast water in such a way that minimizes the introduction of potentially invasive species (mostly to coastal regions), and this convention has now been adopted by 35% of the world's shipping fleet (IMO, 2017; Holbech and Pedersen, 2018). However, future shipping routes across the CAO are likely to take less time than at present because of reduced sea ice (Stevenson *et al.*, 2019) increasing the likelihood of survival of organisms within ballast water. Additionally, many trans-Arctic routes connect similar habitats (i.e. Arctic and sub-Arctic) increasing the likelihood for trans-Arctic establishment if surviving organisms are released into the coastal environment—yet less so for the CAO.

14.4.3 Marine litter, incl. microplastics

Despite the comparatively low human population levels in areas around the Arctic Ocean, the ocean is not less polluted by marine litter and plastics than marine areas further south (Collard and Ask, 2021). Microplastics are widespread at the gateway to the CAO in the Fram Strait at the HAUSGARTEN Observatory (42–6 595 microplastics kg^{-1} sediment), with the highest quantities at the northernmost stations (Bergmann *et al.*, 2017). Microplastics have also been identified from sediments far inside the ecoregion, with quantities reaching up to 200 pieces kg^{-1} sediment (Kanhai *et al.*, 2019). The only available time-series in from HAUSGARTEN in the Fram Strait (2 500 m depth) suggests that marine litter densities have increased over time from < 4 000 between 2002 and 2011 (Bergman and Klages, 2012) to > 7 500 items km^{-2} by 2014 (Tekman *et al.*, 2017). Plastics constituted about half of the total litter recorded, followed by black fabric (11%) and cardboard and paper (7%; Bergmann and Klages, 2012).

Different origins and transport mechanisms have been proposed for microplastics found in the CAO. Similar to the study by Bergmann *et al.* (2017), the presence of microplastics in surface sediments of the deep ecoregion suggests processes that facilitate the vertical transport of fragments (Kanhai *et al.*, 2019). Microplastic abundance in sediments from the Chukchi Sea was positively correlated with the reduction in Arctic sea ice, suggesting that the melting sea ice contributes to the increase in microplastic levels in the sediment (Fang *et al.*, 2021). Bergmann *et al.* (2017) postulate that a positive correlation between microplastic abundance and algal biomass suggests vertical export via incorporation onto sinking sympagic algal aggregates. The authors point out that microplastic quantities in the Fram Strait are among the highest recorded from any benthic sediments, confirming earlier findings that the deep sea serves as a major sink for microplastics. In addition, they postulate that the accumulation of microplastics in the Fram Strait is related to transport of the plastics via the North Atlantic thermohaline circulation. Yet links between increased Arctic shipping traffic (as opposed to outside sources) and plastic/litter have also been shown in the Arctic (Sheffield *et al.*, 2021).

Few studies have so far documented the impact of microplastics on deep-sea biota. Yet the finding that about three-quarters of the plastic items found at HAUSGARTEN were entangled in or colonized by invertebrates such as sponges and sea anemones (Parga Martinez *et al.*, 2020) documents an interaction between these living organisms and litter components.

14.4.4 Artificial noise pollution

Artificial noise pollution is not considered relevant for benthos in the CAO. Possible future seabed mining, however, may induce underwater noise associated with seismic exploration activities that may, in turn, influence the condition of benthic species (Oak, 2020).

14.4.5 Selective extraction of species

The selective extraction of species is not considered relevant for benthos in the CAO, since scientific collections are currently done in extremely small areas of the seabed (typically < 1 m^2 per sample). Sampling covering hundreds of square metres at a time is conducted with non-invasive imaging tools (e.g. Rybakova *et al.*, 2019; Zhulay *et al.*, 2019).

14.4.6 Physical seabed and sea ice disturbance

Scientific studies of benthic organisms in the CAO are typically conducted using sediment cores, grabs, and remotely operated vehicles or autonomous platforms. These methods generally remove sediments and organisms from a small area (e.g. < 1 m^2 or individual organisms) or non-destructively observe the seabed over hundreds of metres. Great water depth and sea -ice cover prevent widespread sampling across the ecoregion (see Figure 1.1), thus the total seabed footprint of biological scientific research activities is likely small relative to the ecoregion area.

The Green Development transition from fossil energy use to electrified sources will require minerals, and seabed mining in the CAO may be a future possible pressure on benthic organisms. For most benthic species and seabed habitats, potential impacts are related to direct seabed disturbance and discharges of sediments that can increase the suspended matter concentrations in the sea because of the extraction process (Oak, 2020). In fact, an ecological risk assessment for deep-sea mining identified habitat removal and burial from sediment plumes as the most important potential impacts for benthic fauna from mining activities across different habitat and mining types (Washburn *et al.*, 2019). The impact of placing pipelines, moorings, pilings, or footings associated with mining activities may destroy local habitat by breaking up or covering organisms present within or on top of the sediment, in a similar way to the installations of the oil and gas industry (Cordes *et al.*, 2016). Generally, seabed disturbance from mining activities is expected to reduce species abundance and species richness within the tracks made by mining vehicles (reviewed in Jones *et al.*, 2017), while sediment plumes may carry fine-grained sediments several hundred metres away from mined sites (Sharma *et al.*, 2001). This may be especially relevant for sessile invertebrates such as deep-water corals and sponges as well as other filter feeders and suspension feeders. In the case of suspension effects from deposition of cuttings from drilling, contaminants introduced during the operation may also impact benthos (Oak, 2020). The resilience of benthic organisms to mining impacts are not well known and will depend on the spatial and temporal scale of the disturbance, as well as traits of the organisms present in the area (Gollner *et al.*, 2017). Studies from test-mining sites in the abyssal Pacific Ocean suggest that recovery of benthic communities and their functions after mining disturbances requires several decades (Simon-Lledo *et al.*, 2019; Stratmann *et al.*, 2018), or may not occur at all (Gollner *et al.*, 2017).

Although no test mining studies have been conducted in the CAO, impacts to benthic organisms are expected to be similar to those observed in other deep basins with similar sedimentary environments, low current speeds, and low densities of organisms.

14.5 Uncertainties and knowledge gaps

Knowledge gaps are substantial in essentially all areas discussed, and uncertainties are, therefore, not even definable. Targeted studies of the CAO are needed, including experiments assessing multiple-stressor responses.

15 Fish

Haakon Hop, Hauke Flores, Pauline Snoeijs-Leijonmalm, Edda Johannesen, and Kevin Hedges

15.1 The groups

15.1.1 Sympagic fishes

Sympagic fishes are associated with sea ice for at least part of their lifetimes. They use sea ice as a shelter from predators, such as seals, and as a source of ice-associated prey, such as sympagic amphipods (Lønne and Gulliksen, 1989; Gradinger and Bluhm, 2004). There are two sympagic fishes in the Arctic Ocean: the ice cod (*Arctogadus glacialis*) and the polar cod (*Boreogadus saida*). In both species, mainly the juveniles are associated with sea ice (Bouchard and Fortier, 2011). A summary of the role of sympagic fishes in the CAO was provided by Flores and Volckaert (2020). Based on the paucity of quantitative information on such fishes, their total population size in the CAO remains undetermined.

15.1.2 Mesopelagic fishes

A hydroacoustic deep-scattering layer (DSL) consisting of fishes and zooplankton was observed for the first time in the CAO during a scientific expedition with the Swedish icebreaker Oden in 2016. This DSL was situated in the Atlantic Water Layer at a depth of ca. 200–500 m where water temperature is above 0°C (up to ca. 2°C), while the water layers above and below the DSL are below 0°C (Snoeijs-Leijonmalm *et al.*, 2021). Crossing the Eurasian Basin, an uninterrupted 3 170 km-long DSL in the Atlantic water layer at 100–500 m, with zooplankton and small fishes, was again documented during the MOSAiC drift expedition in 2019–2020 (Snoeijs-Leijonmalm *et al.*, 2022). Unexpectedly, the DSL also contained low abundances of Atlantic cod (*Gadus morhua*), along with lanternfish (*Benthosema glaciale*), armhook squid (*Gonatus fabricii*), and one individual that was most likely walleye pollock (*Gadus chalcogrammus*). The Atlantic cod originated from Norwegian spawning grounds (based on genetic analysis) and had lived in Arctic water temperature for up to six years (based on otolith analysis).

15.1.3 Benthic and benthopelagic fishes

The limited data available regarding the fish community associated with seabed habitat in the CAO suggests the community is more species-rich than fish communities in sympagic and pelagic habitats. Benthic fishes include non-commercial species such as eelpouts (Zoarcidae), sculpins (Cottidae), and snailfishes (Liparidae). A single record exists of a juvenile Greenland halibut (*Reinhardtius hippoglossoides*) in the CAO, although the individual was caught close to the continental slope (FISCAO, 2017). Benthic and benthopelagic fishes have mainly been observed by camera systems on deep-sea sampling equipment.

15.2 Spatial coverage in the CAO

Among 229 fish species have been reported for the Arctic region. Distribution maps and records (Mecklenburg *et al.*, 2018) for 19 overlap with the CAO LME (*Somniosus microcephalus*, *Amblyraja hyperborea*, *Benthosema glaciale*, *Arctogadus glacialis*, *Boreogadus saida*, *Icelus bicornis*, *Myoxocephalus quadricornis*, *Myoxocephalus scorpius*, *Triglops nybelini*, *Triglops pingelii*, *Cottunculus microps*, *Aspidophoroides olrikii*, *Liparis fabricii*, *Paraliparis bathybius*, *Rhodichthys regina*, *Lycodes adolfi*, *Lycodes frigidus*, *Lycodes polaris*, and *Reinhardtius hippoglossoides*).

Ice cod populations occur mainly north of Greenland and the Canadian Arctic Archipelago. Their distribution in the CAO is unknown. Polar cod occur throughout the ecoregion, but data are scattered in space and time, and there is almost no quantitative information (Melnikov and Chernova, 2013). The first large-scale under-ice sampling activity, using a special surface and under-ice trawl (SUIT), indicated that Transpolar Drift transports young polar cod from hatching areas on the Siberian Shelf across the ecoregion (David *et al.*, 2016). It is estimated that there is a mean abundance of 5 000 ind. km^{-2} in the Eurasian Basin, mostly 1-year-old fish associated with sea ice.

Based on acoustic observations, the mesopelagic DSL is widespread in the CAO, but the number of individuals is extremely low. However, the DSL was not present in the vicinity of the North Pole, and no fish were caught by pelagic trawling or longlining (Dodd *et al.*, 2022). It is unknown how widespread benthic and benthopelagic fishes are. They are probably widespread, but the number of individuals is low because of the low productivity of the CAO ecosystem and long winter conditions.

15.3 Temporal occurrence in the CAO

There is insufficient knowledge about the temporal variability of the presence of sympagic, pelagic, and benthic fishes in the CAO. Polar cod has been observed dwelling under sea ice in the CAO in all seasons (e.g. Andriyashev *et al.*, 1980; Melnikov and Chernova, 2013; David *et al.*, 2016). The DSL also occurs year-round as observed during the MOSAiC expedition. Diel vertical migration (DVM) of this central Arctic DSL was lacking for most of the year when daily light variation was absent. DVM was only observed during the short twilight zones in March and October when there were dark and light periods within a single day. During the polar night, with almost half a year of continuous darkness, the DSL is higher up in the water column than during the polar day, with almost half a year of continuous light (Snoeijs-Leijonmalm *et al.*, 2022).

15.4 Vulnerability toward pressures from human activities

15.4.1 Contaminating compounds (pollution)

Acute chemical pollution, even at a sublethal level for adult fishes, might affect the survival of eggs and larvae (Bender *et al.*, 2021). If exposed for long periods, chemical pollution might render fish unfit as food for humans (Vieweg *et al.*, 2021). An oil spill following a shipwreck or blow-out from an oil rig would scare adult fishes away and could negatively affect their reproductive development and the survival of their eggs and larvae (Bender *et al.*, 2016, 2021).

15.4.2 Non-indigenous species

NIS could act as novel competitors and predators of native species, which would have negative impacts on the affected species. As populations of introduced species grow, native species will eventually begin to identify them as prey items and will begin exerting predation pressure and gaining resources, although NIS may not represent equally valuable prey resources as native forage fish (e.g. capelin vs. polar cod).

15.4.3 Marine litter, incl. microplastics

Microplastics may be ingested by fish (Kühn *et al.*, 2018) and possibly affect their ability to grow and survive. Microplastics and larger plastics, which are likely widespread in the CAO (Bergmann *et al.*, 2022; Huserbråten *et al.*, 2022; Tekman *et al.*, 2022), can directly affect the buoyancy of animals and result in gut fullness, reduced food intake, and longer-term physiological impacts (Bergmann *et al.*, 2022).

15.4.4 Artificial noise pollution

Underwater noise from seismic activity or from increased ship traffic may scare fish species away from their natural habitats and disturb their feeding or mating activities (Ivanova *et al.*, 2020).

15.4.5 Nutrient and organic enrichment

Inputs of nutrients and energy to surface waters through human activities will have little direct impact on any fishes other than sympagic species, which may be able to directly consume deposited material. Pelagic, benthopelagic, and benthic fishes would be affected only indirectly through changes in overall ecosystem productivity, starting with the algae, microbes, and zooplankton that are able to utilize the novel resources.

15.4.6 Extraction of species

If fishing or exploratory fishing in the CAO becomes feasible and interesting, extraction of fish would affect the stocks involved (as target species or as bycatch), their predators, and their prey. An international Agreement to Prevent Unregulated Commercial Fishing in the High Seas of the Central Arctic Ocean (CAOFA) was ratified by Canada, China, Denmark (in respect of Greenland and the Faroe Islands), EU, Iceland, Japan, Norway, the Russian Federation, South Korea, and USA and came in force in June 2020. This agreement establishes a 16-year moratorium on commercial fishing in most of the CAO. While CAOFA prohibits commercial fishing until 2037, scientific surveys and exploratory fishing are both allowed under the agreement, as long as activities adhere to conservation and management measures established under the agreement. So far, there are no indications of substantial fish resources in the ecoregion (e.g. Ingvaldsen *et al.*, 2023), but hydroacoustic surveys and pelagic trawling have been very limited because of sea ice and logistical challenges.

15.4.7 Extraction of non-living resources from the seabed and subsoil

Extractive activities that disturb the seabed would alter and destroy fish habitat in the local area and create a plume of suspended sediments that would move with the current and settle over a much wider area, the scale of which would depend on the scale of the local disturbance.

15.4.8 Physical seabed or ice-cover disturbance

Destruction and disturbance of sea ice by icebreakers would directly affect sympagic species in a local area but would not have widespread effects on populations.

The use of trawls or equipment on the seabed might affect bottom-dwelling fish species by disturbing benthic habitats, removing structural complexity in the form of topographic variation, coral, or sponge beds, and increasing sediment deposition from suspended sediments, which can blanket adjacent and down-current habitats (Jørgensen *et al.*, 2019). While bottom trawling would only be relevant along the shelves surrounding the CAO (Jørgensen *et al.*, 2020), the activity can remove large benthic organisms such as sponges, sea fans, and other large, sessile organisms from previously undisturbed areas.

15.4.9 Artificial light pollution

A changed light regime may alter the behaviour of fish living in the euphotic zone, the feeding conditions for visual feeders, and the risk of predation (Varpe *et al.*, 2015). Light disturbances caused by increased shipping (breaks in ice cover and direct emissions from vessels) may cause episodic disturbances, while light emission from permanent activities such as petroleum extraction platforms might change the behaviour of fish species more permanently, either by attracting them or repelling them (Berge *et al.*, 2020a).

15.4.10 Unintended injury and mortalities

Unintended injuries to fish from human activities other than fishing and seabed disturbances are expected to be minimal. Bycatch from commercial fisheries would represent regular mortality beyond natural levels but would presumably be constrained within a conservation limit. Seabed disturbances could cause direct injury and mortality to animals present at the time of activity, and indirect injury and morality through clogging of gills with suspended sediment and smothering of habitat and individuals when sediments settled back to the seabed.

16 Seabirds

Anders Mosbech and Kathy Kuletz

16.1 The groups

More than 30 species of marine birds have been recorded in the CAO basin and on the slopes, but only eight of these occur regularly in the ecoregion. Two of these are largely dependent on ice for foraging. See Table 16.1 and Gavrilo *et al.* 2022 for details on seabird occurrence in the CAO. The following seabird groups have been defined for this report.

16.1.1 Transient seabirds

Transient seabird species have been recorded in the CAO, but do not occur on a regular basis, and the CAO does not appear to be important for their populations. There are currently about 22 species in this category, comprised of Alcids (nine spp), gulls (five spp), skuas/jaegers (four spp), and shearwater (one spp).

16.1.2 Seasonal seabird residents

There are six seabird species in this group, which include the surface foragers northern fulmar (*Fulmarus glacialis*), black-legged kittiwake (*Rissa tridactyla*), and glaucous gull (*Larus hyperboreus*), which are often observed as ship followers. The diving foragers little auk (*Alle alle*), thick-billed murre (*Uria lomvia*), and black guillemot (*Cepphus grille*) are regularly observed in the CAO but in very low densities, and the ecoregion appears to have low importance for their populations.

16.1.3 Ice obligate seabirds

Two seabird species are ice obligates: ivory gull (*Pagophila eburnean*) and Ross's gull (*Rhodostethia rosea*) and are the truly pagophilic (ice loving) seabirds. Satellite tracking data have shown recurrent foraging within the CAO, including during nesting for ivory gulls.

Ivory gull, an ice-obligate seabird species, scavenging on polar bear leftovers on the sea ice. Credit: Otto.plantema@planet.nl

Table 16.1. Species of birds recorded in the CAO (including the slope), with information on the degree of occurrence and the role the CAO plays for the species. Reproduced with permission from Gavrilo *et al.* (2022).

Species name	Latin name	Occurrence	Geographic area	Role of CAO
Northern fulmar	*Fulmarus glacialis*	Regular visitor	All	Low
Short-tailed shearwater	*Ardenna tenuirostris*	Irregular foraging migration	Pacific	Low
Ivory gull	*Pagophila eburnea*	Common	All	Non-breeding, post-breeding habitat, migration
Ross's gull	*Rhodostethia rosea*	Common	All	Non-breeding, post-breeding habitat, migration
Sabine's gull	*Xema sabini*	Rare	All	Low (on migration)
Black-legged kittiwake	*Rissa tridactyla*	Common	All	Low
Glaucous gull	*Larus hyperboreus*	Rare	All	Low
Arctic tern	*Sterna paradisea*	Vagrant	All	Negligible
Great skua	*Stercorarius skua*	Occasional vagrant	Atlantic	Negligible
Long-tailed jaeger	*Stercorarius longicaudus*	Vagrant	All	Negligible
Parasitic jaeger	*Stercorarius parasiticus*	Vagrant	All	Negligible
Pomarine jaeger	*Stercorarius pomarinus*	Vagrant	All	Negligible
Dovekie	*Alle alle*	Common	Atlantic	Low
Thick-billed murre	*Uria lomvia*	Common	All	Low
Black guillemot	*Cepphus grylle*	Common	All	Low
Least auklet	*Aethia pusilla*	Rare Vagrant	Pacific	Negligible
Ancient murrelet	*Synthliboramphus antiquus*	Vagrant	Pacific	Negligible
Crested auklet	*Aethia cristatella*	Vagrant	Pacific	Low
Kittlitz's murrelet	*Brachyramphus brevirostris*	Vagrant	Pacific	Negligible
Atlantic puffin	*Fratercula arctica*	Vagrant	Atlantic	Negligible
Horned puffin	*Fratercula corniculata*	Rare Vagrant	Pacific	Negligible
Red-necked phalarope	*Phalaropus lobatus*	Rare vagrant	All	Negligible
Red phalarope	*Phalaropus fulicarius*	Vagrant	Pacific	Negligible

Table 16.1 (cont.)

Species name	Latin name	Occurrence	Geographic area	Role of CAO
Purple sandpiper	*Calidris maritima*	Rare transit vagrant	All	Negligible
Common ringed plover	*Charadrius hiaticula*	Rare transit vagrant	Eurasia	Negligible
Common eider	*Somateria mollissima*	Rare vagrant	All	Negligible
King eider	*Somateria spectabilis*	Rare vagrant	Pacific	Negligible
Long-tailed duck	*Clangula hyemalis*	Rare vagrant	All	Negligible
Surf scoter	*Melanitta perspicillata*	Rare vagrant	Pacific	Negligible
Red-throated loon	*Gavia stellata*	Rare vagrant	Pacific?	Negligible
Pacific loon	*Gavia pacifica*	Rare vagrant	Pacific	Negligible
White wagtail	*Motacilla alba*	Occasional transit vagrant	Eurasia	Negligible
Wheatear	*Oenanthe oenanthe*	Occasional transit vagrant	Pacific	Negligible
Snow bunting	*Plectrophenax nivalis*	Transit vagrant	All	Negligible
Lapland Bunting	*Calcarius lapponicus*	Occasional transit vagrant	Pacific	Negligible

16.2 Spatial coverage in the CAO

Seabird numbers are extremely low in the CAO basin and on the slopes, and likely include primarily non-breeding birds migrating over circumpolar regions. Breeding colonies on coastal islands or the mainland are in most areas too distant for foraging trips to the ecoregion (Figures 16.1 and 16.2). However, in the Wandel Sea corner of the ecoregion off Northeast Greenland, where the continental shelf is narrow, ivory gulls from breeding colonies in Northeast Greenland forage in the sea-ice habitat. Tracking of ivory gulls also documents foraging areas in ice habitats north of Svalbard and Franz Joseph Land up to 85°N (Gilg *et al.*, 2016a; Strøm *et al.*, 2019).

16.2.1 Longevity and resilience of seabirds

All seabirds are long-lived, with a life expectancy of above 10 years, meaning that recovery from a mass mortality event like a large oil spill would be slow. On the other hand, seabirds are adapted to be resilient to year-to-year variations in the environment, and recovery from a lost breeding season is common.

16.3 Temporal occurrence in the CAO

Use of the CAO by seabirds will mainly be during post-breeding movements in the autumn [see above; and Gavrilo *et al.* (2022)] although ivory gulls also forage in the ecoregion during summer.

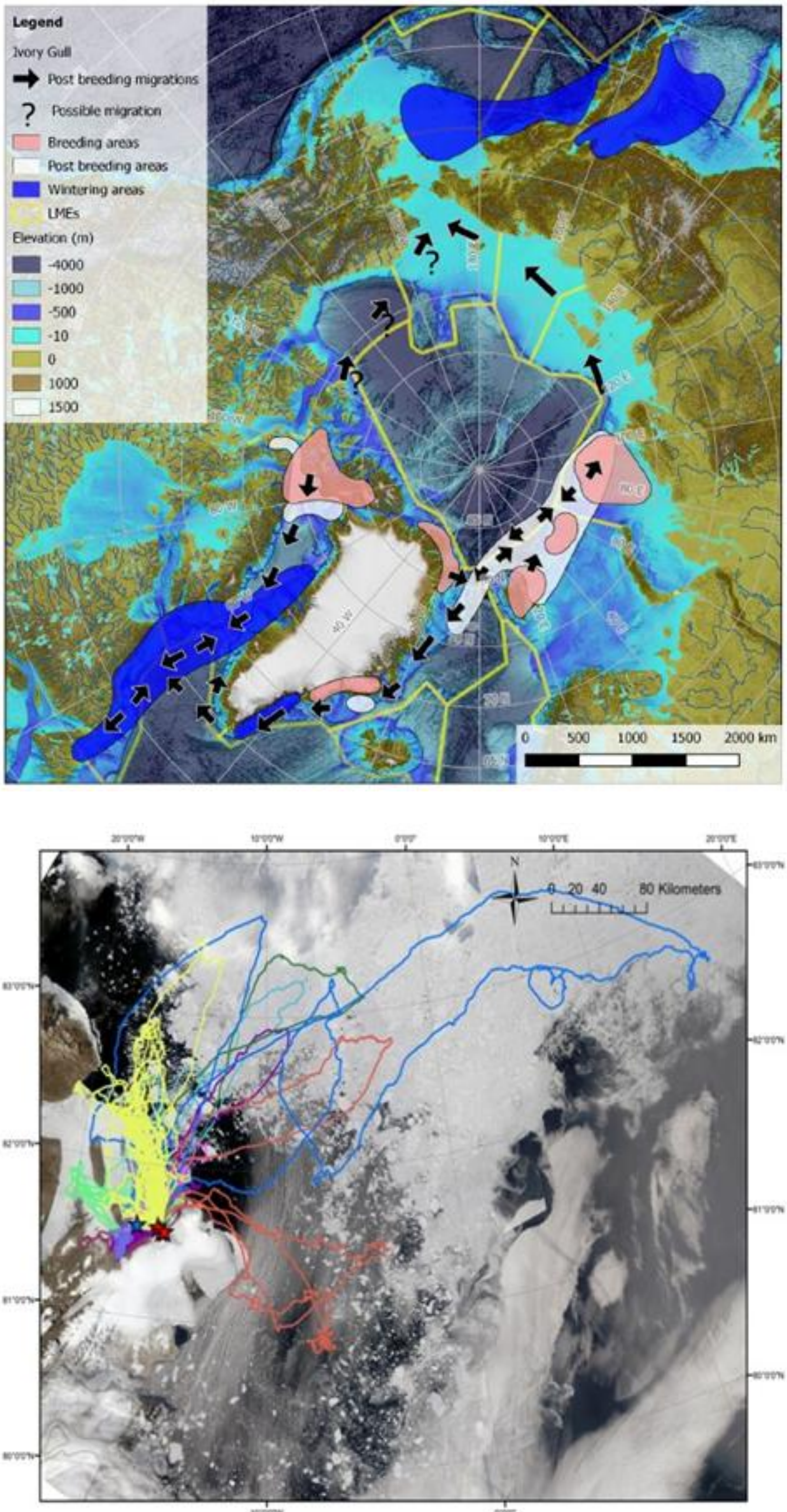


Figure 16.1. Upper panel: Ivory gull distribution during the annual cycle, showing breeding areas, post-breeding foraging areas, migration patterns, and wintering areas in the marginal ice zone in the Atlantic and Pacific sectors. Reproduced from Gavrilo *et al.* (2022). Lower panel: Foraging trips into the CAO (Wandel Sea) by ivory gulls breeding in Northeast Greenland. Dumas *et al.* (2022); reproduced from Frederiksen *et al.* (2019).

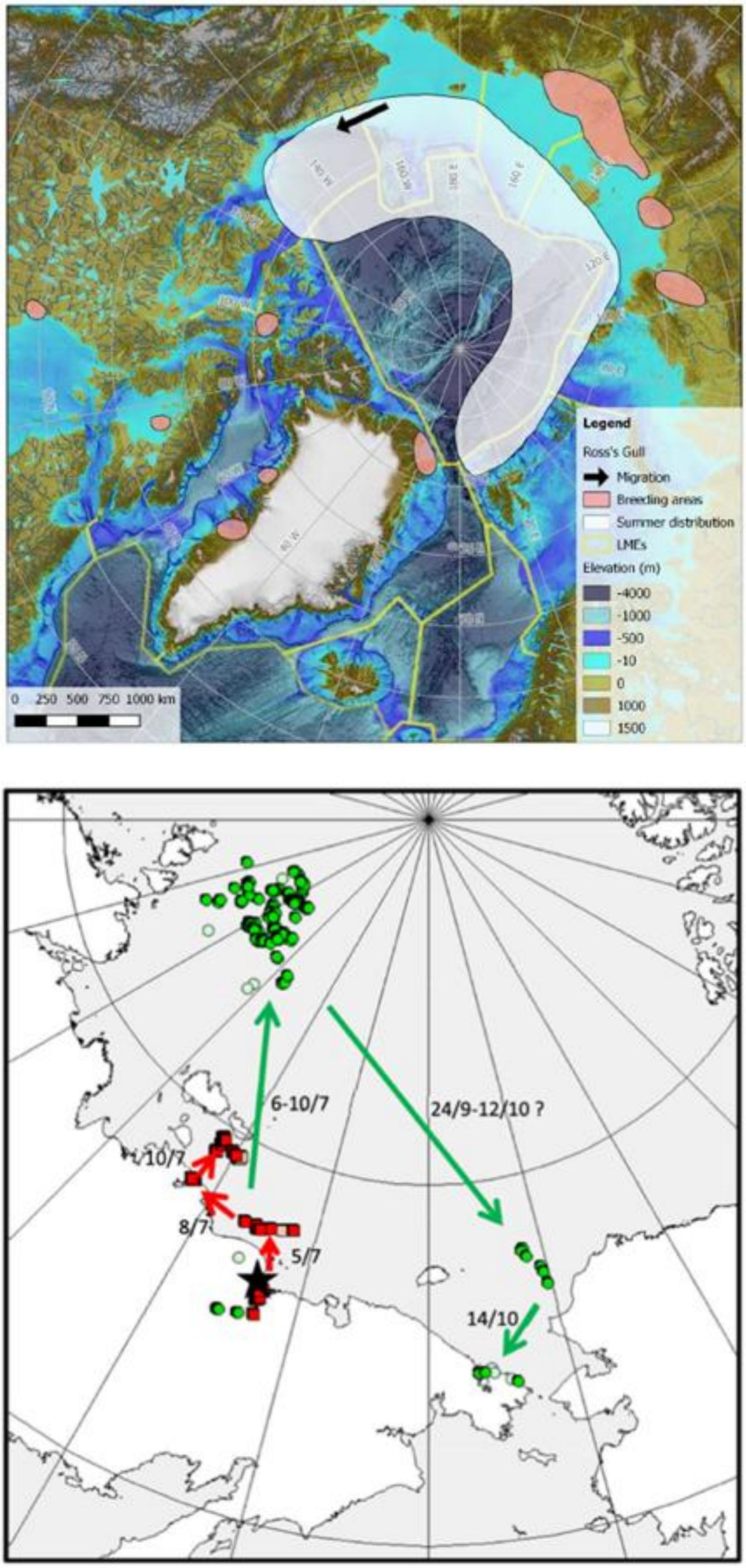


Figure 16.2. Upper panel: Ross's gull general distribution. Reprinted from Gavrilo *et al.* (2022). Lower panel: post-breeding movements of two Ross's Gulls monitored between 24 June and 3 November 2013. Reproduced with permission from Gilg *et al.* (2016b); female: red symbols, male; green symbols. The breeding site is indicated by a black star, while the arrows show the main directions and dates of post-breeding movements.

16.4 Vulnerability toward pressures from human activities

Little if any direct impact on seabirds is likely in the CAO itself, since bottom-feeding seabirds are coastal or on the continental shelf, and diving auks tend to forage on the shelf or shelf edge and not at the depths of the ecoregion. Some surface-feeding species may forage near the shelf edge or over the slope, where upwelling concentrates prey at the surface, but seabird densities are very low in the CAO.

16.4.1 Contaminants

The increase in ship traffic in the CAO will undoubtedly lead to an increase in marine pollutants, in addition to long-distance transported contaminants, such as persistent organic pollutants (POPs) and Hg (see section 16.4.1.1), which accumulate in seabirds and their habitats (Mallory and Braune, 2012). Vessels that are expected to use the Northwest Passage pose, at the very minimum, a threat of losing cargo overboard (Cobb *et al.*, 2008). This cargo could include anything from large vehicles to small packaging plastics and harmful chemicals.

16.4.1.1 Mercury (Hg)

AMAP has monitored and reviewed the knowledge on Hg in the Arctic, and this section is mainly based on the new AMAP Mercury assessment (Albert *et al.*, 2021; AMAP, 2021a; Chastel *et al.*, 2022) and the AMAP assessment of Biological Effects of Contaminants (AMAP, 2018b; Dietz *et al.*, 2019). Hg is a critical contaminant with documented effects on Arctic seabirds. Avian reproduction is especially sensitive to methylmercury (MeHg) toxicity, with even low levels of exposure leading to adverse effects (Dietz *et al.*, 2019). Hg comes to the Arctic through atmospheric, sea current, and riverine long-range transport, but is also, to a lesser extent, mobilized within the Arctic from melting glacier ice and permafrost (AMAP Assessment, 2021a). MeHg biomagnifies to high levels in Arctic marine food webs because of long food chains and long-lived species. However, feather moult represents a major excretion pathway in birds; 60–90% of accumulated Hg is excreted yearly, thus lowering the body burden. The AMAP Assessment (Chastel *et al.*, 2022), concludes that seabird Hg concentrations are above toxicity benchmarks in several Arctic seabird populations, based on the threshold levels for estimated risk to total Hg (Ackerman *et al.*, 2016).

Based on these toxicity benchmarks, the AMAP Assessment (2021a) found that 50% of Arctic seabird individuals sampled had tissue Hg concentrations that were above the level of no adverse health effects (a blood-equivalent mercury concentration of 0.2 $\mu g\ g^{-1}$ ww) and that 1% of the analysed birds were either at high or severe risk (see AMAP Assessment 2021a). However, most (95%) Arctic seabirds were generally at lower risk (i.e. were in one of the three lowest risk categories) of toxicity from Hg exposure.

Toxicological effects of Hg that have been detected in Arctic birds include effects on hormone levels, changes in parental behaviour, and reduced reproductive performance. Only a few studies of Arctic seabirds have documented population effects, despite effects linked to Hg exposure on reproductive performance (Amélineau *et al.*, 2019; Fort *et al.*, 2014, 2016). These studies report only modest effects on demographic parameters and no effect on adult survival.

Because Hg concentrations in seabird feathers reflect Hg concentrations in blood when the feathers were produced, different feathers can reflect the mercury exposure in different seasons. Albert *et al.* (2021) compared body feathers (breeding season) with head feathers (winter season) and found that Arctic seabirds in general are exposed to lower Hg concentrations during the breeding season in the Arctic than during the winter season when they migrate farther south (figures 16.1 and 16.3). Thus, Hg acquired at non-Arctic wintering areas in the Northwest Atlantic Ocean can be transported to Arctic breeding areas by migratory birds and has the potential to affect reproductive success (Fort *et al.*, 2014; Amélineau *et al.*, 2019). These results underline the complexity of pollution-effect mechanisms in migratory seabirds and that mercury pollution is a global issue (https://minamataconvention.org/en).

The AMAP Assessment (2021a) concluded that mercury concentrations in Arctic seabirds tended to increase historically within the Arctic (e.g. Bond *et al.*, 2015), and while trends have flattened recently in some Arctic regions, mercury concentrations are still increasing in a few monitored populations. A close monitoring and further studies into combined effects of pollutants and climate change is needed.

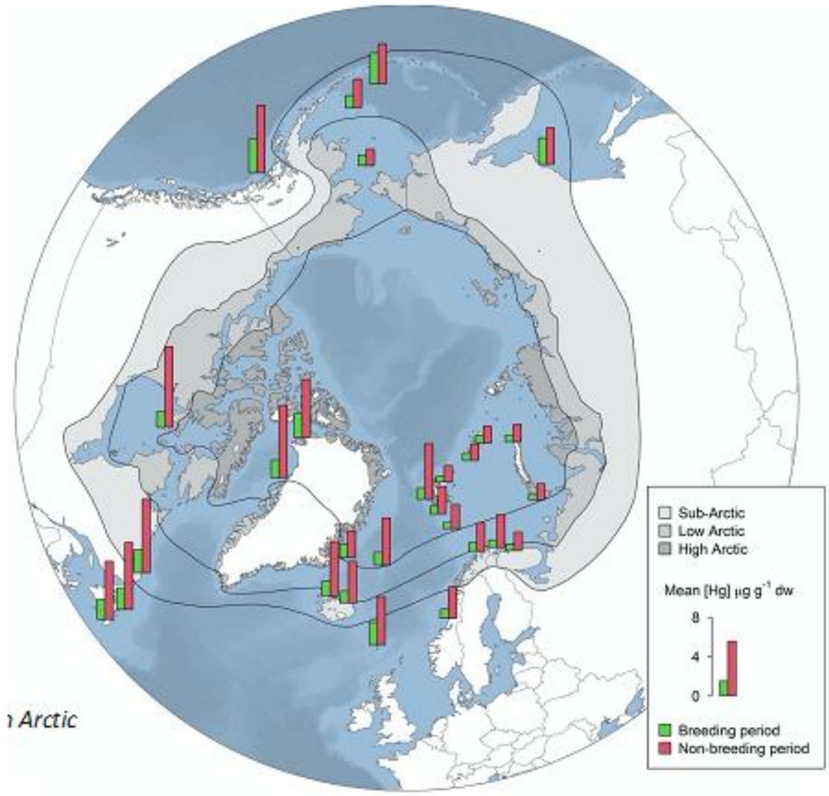


Figure 16.3. Multispecies seabird Hg concentrations during the breeding (body-feathers – green) and non-breeding period (head feathers – red) for each study colony (several seabird species). Reproduced with permission from Albert *et al.* (2021).

16.4.1.2 Persistent Organic Pollutants (POPs)

The effect of POPs on seabirds has recently been assessed and reviewed by AMAP (AMAP, 2016a, 2017a, 2018b; Dietz *et al.*, 2019). Risk quotients (RQ = BR/CBR) were calculated for eight species in the Arctic region where sufficient published data were available. Because PCB concentrations are the dominant effect contributor among POPs, a conservative PCB CBR of 10 μg g^{-1} lw was used for the RQ calculations. For most seabirds, PCB data were only available for eggs and blood, resulting in less accurate RQs. Concentrations of PCBs in seabird eggs from Alaska, Canada, East Greenland, and Norway (Bjørnøya) all translated into RQs of < 1. These scores indicate little risk of PCB-mediated effects on seabird immune or hormone systems. In contrast, based on PCBs in blood, glaucous gulls from Bjørnøya had a much higher risk of PCB-mediated effects, with most birds having RQs that fell within the range of 1–10 (90% of females, 85% of males). Relatively few birds had RQs within the highest risk group (10–100; 5% of females, 11% of males) or lowest risk group (< 1.5% of females, 4% of males).

Riget *et al.* (2019) conducted a meta-analysis of more than 1 000 time-series of POPs in Arctic biota including 114 time-series in seabirds. The time-trend analyses showed that legacy POPs like PCBs and organochlorine pesticides (OCs) generally decreased in Arctic biota during the last 20–30 years, likely because of national and international regulations. However, new POPs continue to emerge, and newer POPs show a more mixed pattern of trends (Riget *et al.*, 2019). Continuing the existing time-series would lead to more powerful trend detection. As with Hg, more complete knowledge will require monitoring and studies into the combined effects of pollutant mixtures and climate change.

16.4.1.3 Oil spills

The Arctic basin acts in some ways as a closed system, with currents that transport water in or out and that maintain a turnover time of the order of 11 years (Östlund and Hut, 1984). CAO waters are very remote, with sparsely distributed coast guard stations, which makes it virtually impossible for adequate response in the case of an oil spill in the central Arctic.

A potentially serious effect on seabirds would be from either an accidental oil spill from a ship inside the CAO or from oil drifting into the CAO. If the oil is not a light evaporating one, it would disperse and degrade very slowly in the cold seawater and could spread across vast areas. Oil spill cleanup would be hampered by sea ice and would, in most instances, be very inefficient (see EPPR Circumpolar Oil Spill Response Viability Analysis – COSRVA, 2024). It is well documented that seabirds in cold environments are extremely sensitive to oil spills, and if a high proportion of a bird population is exposed to high concentrations of oil, population level effects could occur (Boertmann *et al.*, 2020). However, seabird densities in the CAO are low and numbers killed directly by oiling from a spill would most likely be low in the ecoregion itself, although numbers could be substantial in the shelf areas where seabird densities can be high. For an endangered species like the ivory gull, even a small death toll can be significant for the population.

16.4.2 Marine litter, including microplastics

Recent studies have revealed a global and increasing distribution of both macro- and microplastics, including to the most remote areas of the Arctic Ocean (Walther and Bergmann, 2022). Marine litter, including both these types of plastics, is currently coming almost exclusively from outside the CAO and from a variety of sources. The primary maritime activities around the ecoregion are fishing and shipping, including cruise tourism (which also occurs in the ecoregion itself); offshore resource exploration and aquaculture activities, which are also increasing. The major land-based contributors are waste and wastewater management. Rivers, currents, sea-ice drift, and weather and storms in the atmosphere all contribute to spread marine litter and microplastics into the CAO, and the latter two to redistribution within the CAO.

More research is needed to determine the full extent of the contribution from each activity, the pathways, and the precise distribution of litter originating from each source (PAME, Regional Action Plan on Marine Litter in the Arctic, May 2021).

Globally, most investigated marine species have been shown to be affected by marine litter through entanglement in marine debris or ingestion of smaller particles (Kühn *et al.*, 2015; Kühn and van Franeker, 2020). Most of the documented interactions of marine biota with plastics have impacts at the organism- or sub-organism level; however, the most ecologically relevant effects are predicted at the population level and beyond, including impacts on species, habitats, and ecosystems.

Recently revealed increases in both macro- and microplastic pollution in the Arctic marine environment pose new threats to seabirds. Due to the emergent nature of this issue, plastic accumulation and impacts on the food chain, and particularly on birds, have been poorly studied in the Arctic region in general. The issue of plastic pollution and Arctic birds was addressed in a recent AMBI/CAFF project "Plastics and Seabirds: Habitat mitigation", which aimed at increasing understanding of and ability to respond accordingly to the distribution and effects of plastic pollution on Arctic marine birds. Marine birds interact with the plastic pollution of their habitats through ingestion, entanglement, and nest incorporation, the latter of which may lead to entanglement (Votier *et al.*, 2011). Additional impact may originate from enhanced POPs contamination associated with ingested plastic particles (Yamashita *et al.*, 2021).

Seabirds mistake plastic debris for prey species or ingest plastic through transfer from their prey. Baak *et al.* (2020, 2021) recently reviewed plastic ingestion by seabirds in the circumpolar Arctic and found 32 articles that reported plastic ingestion by seabirds. Of the 64 seabird species that breed in the Arctic, 40 species (63%) have been examined for plastic ingestion in the Arctic. Of these 40 species, 22 (55%) have incidences of plastic ingestion greater than zero. It is well documented that plastic ingestion in seabirds can result in internal wounds, blockages in the gastrointestinal tract, or reduced feeding (GESAMP, 2016). However, the level of impact and thresholds for harm is hard to assess, and threshold values for harm have not yet been established (Kühn and van Franeker, 2020; von Franeker *et al.*, 2021).

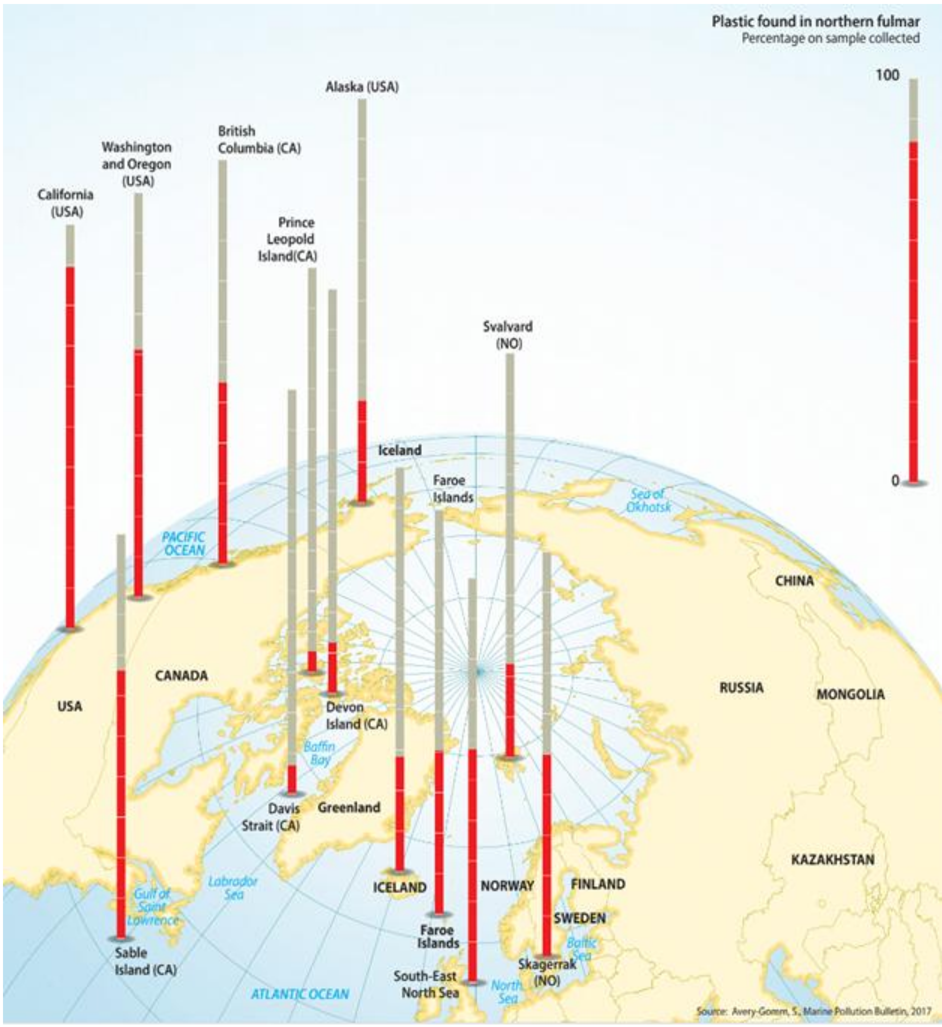


Figure 16.4. Plastic ingested by Northen fulmar in the Arctic. Reproduced with permission from PAME and GridArendal.

The northern fulmar is the most studied seabird species for plastic ingestion. It is a suitable biomonitor of plastic pollution because of its surface foraging ecology and large migratory range and is one of the more common species observed in the CAO (Figure 16.4). Northern fulmars have the highest rate of plastic ingestion among northern seabirds that have been examined. Levels of plastic ingestion in fulmars globally have increased over time, and it belongs to the seabird group (Procellariiformes) with the highest frequency of plastic ingestion. Fulmars are widely used as an indicator organism for monitoring plastic debris in the marine environment; thus, it is used as an EcoQO in the OSPAR region (Baak *et al.*, 2021, van Franeker *et al.*, 2021). In the CAFF and AMBI report (Baak *et al.*, 2021), it is also recommended to use the northern fulmar as an indicator of marine plastic in the Arctic, together with the pursuit-diving thick-billed murre and surface-feeding and plunge-diving black-legged kittiwake.

In addition to ingestion, the potential toxicological impact caused by hazardous chemicals associated with ingested plastics is concerning (Teuten *et al.*, 2009) because marine plastic debris contains many hazardous chemicals (chemical additives and absorbed toxicants; Hirai *et al.*, 2011). A recent global study by Yamashita *et al.* (2021) analysed 145 preen gland oil samples from 32 seabird species belonging to eight families with different foraging habits and life history strategies for plastic additives and legacy POPs. This study found patterns that can be explained if the additives in gland oil are mainly from ingested plastics rather than diet, demonstrating that a significant proportion of the examined seabirds accumulated chemicals from ingested plastics. The only high-Arctic species examined, the little auk from Greenland, did not show any additives in its gland oil; however, all seabirds sampled from the sub-Arctic Bering Sea were positive. More studies are needed on this issue.

Seabird entanglement in derelict fishing gear is a growing problem globally, and it is occurring throughout Arctic shelf seas, including waters bordering the CAO. Death by entanglement has been observed in seabirds in the northern Barents and Kara seas – specifically, thick-billed murre, black guillemot, black-legged kittiwake, and little auk (Gavrilo, 2019).

Data on the incorporation of plastics in nests is mostly anecdotal in the Arctic. However, this phenomenon is widely observed throughout the Arctic, including most remote high-Arctic islands. For the Russian Arctic, plastic in nests has been documented for 12 marine bird species (Gavrilo, 2019).

16.4.3 Artificial noise pollution

Compared to marine mammals, little is known about the direct effect of underwater noise on seabirds. Some diving species are known to react to underwater noise, i.e. common murre (*Uria aalge*) and great cormorant (*Phalacracorax carbo*; Anderson Hansen *et al.*, 2017, 2020; Johansen *et al.*, 2016), but studies are at the initial stage (HELCOM, 2019). Available information suggests that diving seabirds, i.e. auks and sea ducks, may be more sensitive to underwater noise than other types of marine birds.

Potentially hazardous underwater noise may be associated with seismic exploration in the CAO, and this could affect physiology and cause physical injury, behavioural avoidance, and indirect impacts due to effects on prey. If operations in the CAO include underwater blasts (i.e. military activity or geological exploration), this could result in seabird mortality, most likely to diving seabirds, although larids (gulls) have also been killed by underwater blasts (Cooper, 1982).

Seabird densities in the ecoregion, especially of diving auks or sea ducks, are very low, and numbers affected by underwater noise would most likely be low. However, impacts could be greater in the shelf areas, especially close to breeding colonies on high-Arctic islands and associated offshore foraging grounds. Further studies are required to evaluate the impact of underwater noise on birds.

16.4.4 Selective extraction of species

If commercial fisheries expand into the CAO, they potentially could impact seabirds directly through entanglement in gear and removal of prey, or indirectly via bycatch of prey species in fishing gear, providing additional food as discard, light disturbance, chemical pollutants, and plastic debris (especially lost fishing gear). The latter impacts are reviewed in corresponding sections of this report. Commercial fishing for small pelagic schooling fish, such as sand lance (*Ammodytes hexapterus*), capelin, or herring, is well documented to deplete the food base of seabirds if poorly managed and unsustainable (Cury *et al.*, 2011). Currently in the CAO, only the polar cod is considered a potential fishing resource and is also an important prey of Arctic seabirds (Matley *et al.*, 2012; Provencher *et al.*, 2012). Therefore, a risk of competition between fisheries and seabirds does exist, but impacts will depend on the fishery scenario as well as what species of seabirds shift into the region. The potential impact on breeding populations should be low, as seabirds do not forage in the ecoregion while raising young. However, non-breeding or post-breeding birds that cross the ecoregion for migration and wintering risk conflicts, including the disruption of foraging (e.g. Krüger *et al.*, 2017) and bycatch or vessel strikes during fishing operations.

As the CAO seabed is at too great a depth to be reached by seabirds, there will be no direct impact of seabed extraction. However, marine mining of the seabed can cause plumes of silt in the surface waters. Such plumes can hamper seabird foraging as seabirds are dependent on visually spotting their prey items. Plumes would have to cover a significant area of surface water to have an impact on seabirds, which are very mobile. There could be additional, indirect impacts to seabirds if extraction directly impacts their prey, or if the ecosystem is disturbed such that prey are affected.

Similarly, the depth of CAO waters means that there will be no direct impact to seabirds from seabed disturbance. However, as with resource extraction, indirect effects are possible due to changes to the prey on which seabirds depend.

16.4.5 Artificial light pollution

Globally, light pollution is a growing concern, and ecological impacts will most likely be greatest in regions where biological communities have not evolved in conjunction with nighttime artificial light (Marangoni *et al.*, 2022). Many species use natural light cues (sun, moon, stars, and aurora borealis) to migrate vertically in the water column or navigate across regions, and the recent occurrence of artificial light sources can interfere with these cycles, as well as animal foraging and breeding activities (review in Davies and Smyth, 2018). The increase in vessel traffic and other developments in the CAO and adjacent waters will lead to an increase in artificial lights, which will in turn increase local impacts to marine taxa.

Artificial lights attract and cause injury and death to marine birds, which become disoriented by lights and then fly into coastal buildings, stationary and moving vessels, and offshore platforms (Day *et al.*, 2015). The numbers of affected birds per incident range from individuals to hundreds. Secondary mortality occurs when birds have trouble taking off from a vessel and hide in deck spaces where they are exposed to oil contaminants, which soils feathers and thereby causes hypothermia (Ryan *et al.*, 2021). Common factors associated with these events include time of year (newly fledged birds tend to be more susceptible), hours of darkness (especially with little or no moonlight), poor visibility (stormy or foggy weather), high winds, and high light radiance emanating from the vessel or platform (Merkel and Johansen, 2011; Day *et al.*, 2015; Gjerdrum *et al.*, 2021; Ryan *et al.*, 2021; Rodriguez *et al.*, 2022). Which species are affected by light pollution depends on the geographic location, but common species groups affected include eiders, fulmars, shearwaters, storm-petrels, and auklets, all of which occur in or near the CAO (ICES, 2020).

Changes in seabird distribution because of loss of sea ice and shifts in prey distribution may exacerbate impacts from light pollution in the CAO and adjacent shelf waters. For example, some seabirds in the Bering Strait region, such as short-tailed shearwaters and thick-billed murres, have shifted their distribution farther north on the Chukchi Shelf, near the edge of the CAO (Kuletz *et al.*, 2020), but they must still return south through the Bering Strait. Other marine birds, such as eiders, maintain the timing of their post-breeding southward migration from the Arctic coast through the Bering Strait region. Due to lack of sea ice, these southward migration patterns now overlap with increased vessel traffic (Kapsar *et al.*, 2023) during months of nighttime darkness, potentially resulting in higher risk of vessel–bird collisions (see Appendix 6 in Labunski *et al.*, 2022). The new overlap of human activities during fall migration of marine birds could pose challenges to marine bird conservation and to management of vessel traffic lanes throughout the region.

Potential mitigation methods to reduce vessel–bird collisions have been identified, such as reduction in radiance, downward-directed lighting, slower vessel speeds, and avoidance of high use areas during sensitive seasonal periods. These, and other best practices, have been promoted at a limited regional level but are not typically mandatory. Several projects are underway for the Arctic region that will identify areas of high risk and inform implementation of best practices and shipping lane design, and preliminary results are available (see Appendix 6 in Labunski *et al.*, 2022). These projects overlay vessel traffic using Automated Identification System (AIS) ship identifiers with data on seabird distribution (from at-sea surveys or tracking of individually tagged birds). Related projects using similar data are developing geofencing tools that will enable real-time identification of high-risk locations or time periods.

16.4.6 Cumulative effects

Recent studies on the globally threatened ivory gull, one of the species which regularly uses the CAO, is the seabird most affected by climate change and sea ice loss (Gilg *et al.*, 2016a). It is also the species most polluted by POPs and mercury among Arctic seabirds (Braune *et al.*, 2006; Miljeteig *et al.*, 2009, 2012; Bond *et al.*, 2015; Lucia *et al.*, 2015). It is of major concern that the effects of contaminants may become more severe when an organism is under additional environmental stress (Boonstra, 2004). Thus, exposure to high levels of contaminants can act in concert with additional stress to push ivory gull populations beyond their environmental tolerance limits (Miljeteig *et al.*, 2012). Levels of contaminants in the gull's eggs, blood, and feathers are among the highest ever reported in Arctic seabirds and may have sublethal effects in combination with other stressors such as climate warming (Strøm *et al.*, 2019).

17 Marine mammals

Anne Kirstine Frie and Mario Acquarone

17.1 The groups

Based on their partial dependence on the ecoregion as a habitat, polar bears, ringed seals, beluga whales, narwhals, and bowhead whales have been selected by WGICA as focal species for the evaluation of marine mammal vulnerability to anthropogenic pressures in the CAO. Walruses were also initially considered based on a few reported telemetry positions and anecdotal observations within the CAO (ICES, 2021a; Skjoldal, 2022). Since walruses are primarily benthic feeders, it was, however, concluded that their use of the ecoregion will likely always be limited to a small number of straggling animals relying on an atypical foraging pattern centred on seal predation. In the absence of further details, walruses are, therefore, not included among the focal marine mammal species. More comprehensive descriptions of all marine mammal species and populations occurring in areas within or close to the WGICA study area are given in ICES (2021) and Skjoldal (2022).

Polar bear on the icecap. Image credit: Lis Lindal Jørgensen, IMR.

17.1.1 Polar bear

Of the 19 recognized polar bear populations (Figure 17.1), between 8 and 11 have defined home ranges that include or border on parts of the WGICA area (PBSG, 2023). Most of the high seas area of the CAO lies within the defined home range of the so-called Arctic Basin population, but it is not clear whether any polar bears actually complete their entire life cycle within this area (PBSG, 2023). Most of the polar bears encountered in the Arctic Basin are believed to originate from adjacent populations. Polar bears depend on sea ice as a substrate for hunting seals, which is their most important prey. In the Atlantic gateway area, the edge of the summer sea ice has retracted into the WGICA area, and most of the Svalbard polar bear population has followed (Aars *et al.*, 2017). Pregnant females summering offshore appear to return to Svalbard to breed in snow dens on land, even if this requires swimming long distances (Lone *et al.*, 2018). In spite of this, the offshore lifestyle currently appears to be energetically superior to the coastal resident strategy adopted by some bears (Blanchet *et al.*, 2020). The time spent by polar bears in the WGICA area is, therefore, of high importance to polar bears in this region. The pack ice edge is also an important hunting habitat for Beaufort Sea polar bears (e.g. Johnson and Derocher, 2020), but very few appear to venture as far offshore as the WGICA area. Some polar bears from the Chukchi Sea and Beaufort Sea populations are, however, known to den on sea ice within the WGICA area (e.g. Olson *et al.*, 2017). It cannot be excluded that denning also occurs further into the Arctic Basin. It has recently been discovered that polar bears build maternity dens next to grounded icebergs in North and Northeast Greenland), close to the border of the WGICA area (Laidre and Stirling, 2020).

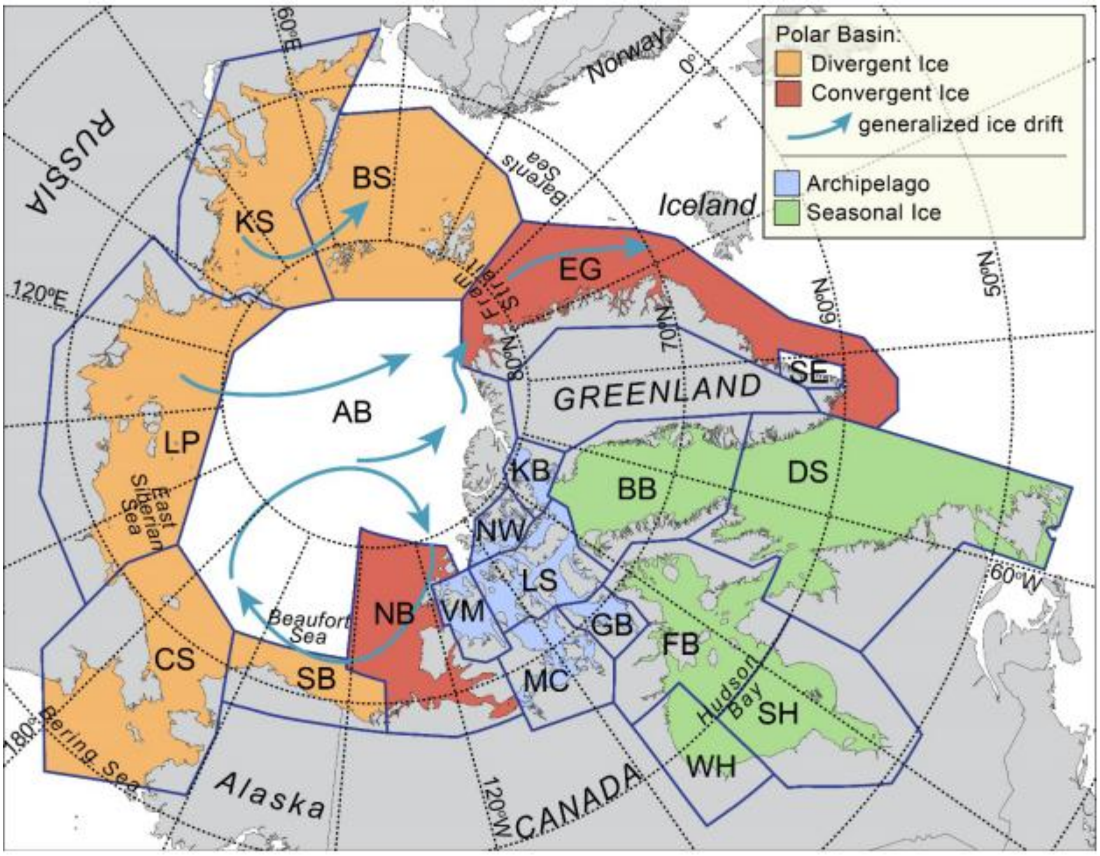


Figure 17.1. Geographic management units of 19 recognized polar bear subpopulations within four ecoregions delineated based on ice cover characteristics. The polar basin divergent ecoregion (PBDE, in orange) includes the subpopulations from Southern Beaufort Sea (SB, Chukchi Sea (CS), Laptev Sea (LS), Kara Sea (KS), and Barents Sea (BS). The polar basin convergent ecoregion (PBCE, in red) comprises the management units for East Greenland (EG) and the Northern Beaufort Sea (NB). The seasonal ice ecoregion (SIE, in green) comprises the management units for the Southern Hudson Bay (SH), Western Hudson Bay (WH), Foxe Basin (FB), Davis Strait (DS), and Baffin Bay (BB). The archipelago ecoregion (AE, in blue) comprises the management units for the Gulf of Boothia (GB), M'Clintock Channel (MC), Lancaster Sound (LS), Viscount Melville Sound (VM), Norwegian Bay (NB), and Kane Basin (KB). The Arctic basin management unit does not belong to any of the designated ecoregions. The map is published with permission from Dr Kristin Laidre (klaidre@uw.edu), co-chair of the Polar Bear Specialist Group.

17.1.2 Ringed seals

Throughout their circumpolar range (Figure 17.2), ringed seals have an affinity for ice-covered waters all year round. This species feeds mainly on pelagic and ice-associated fish and crustaceans like krill and amphipods (Crawford *et al.*, 2015; Bengtsson *et al.*, 2020). There are several anecdotal reports of the widespread occurrence of ringed seals within the Arctic Basin, but so far there are no scientific data on their abundance and habitat use within the WGICA area. In the Pacific gateway region, available telemetry studies show that ringed seals tagged in the Chukchi Sea and western Beaufort Sea in 2011–2016 generally did not go into the eastern Beaufort Sea but spread out over the Chukchi Sea and western Beaufort Sea (von Duyke *et al.*, 2020). Ringed seals tagged in 2011, however, showed an unusual affinity for the pack ice off the shelf and were thought to represent a previously unsampled offshore ecotype (von Duyke *et al.*, 2020). Most of the tagged seals spent the winter in the Bering Sea, but appreciable numbers also stayed in the southern Chukchi Sea (von Duyke *et al.*, 2020) outside the WGICA area. Surveys in the post-breeding season for ringed seals in the Chukchi Sea showed highest densities in the southern areas, and densities were expected to decline further towards the east because of lower environmental productivity (Bengtsson *et al.*, 2005).

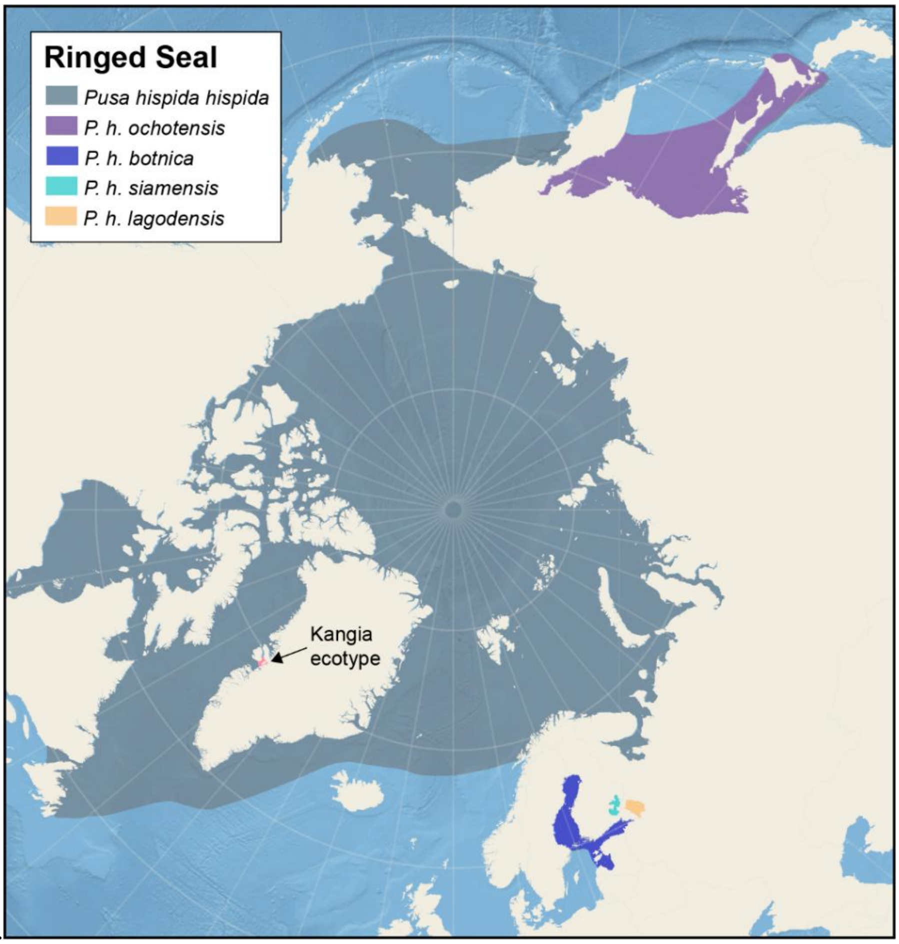


Figure 17.2. The global distribution of ringed seal subspecies. Reproduced with permission from: https://nammco.no/ringed-seal/.

In the Atlantic gateway region, subadult ringed seals tagged in western Svalbard migrate to the ice edge to the north of Svalbard in summer (Hamilton *et al.*, 2015b), while adults generally remain in Svalbard coastal waters (Hamilton *et al.*, 2016). The increasingly long summer migrations of subadult ringed seals are expected to be energetically costly and could, therefore, reduce body growth rates and lifetime reproductive output (Hamilton *et al.*, 2015b). Furthermore, severe reductions in suitable pupping ice in fjords on the western side of Svalbard may have reduced the overall abundance of ringed seal seasonal migrations into the CAO. Based on existing data, it cannot, however, be excluded that pup production has increased elsewhere in the high Arctic archipelagos or on the offshore pack ice. In the latter case, however, pup survival is expected to be very low.

17.1.3 Bowhead whales

Bowhead whales are large baleen whales feeding mainly on copepods and other crustaceans, both pelagically and along the seabed (Fortune *et al.*, 2023). They are generally found in close association with sea ice (Figure 17.3) but may also spend time in ice-free areas (Moore *et al.*, 2021). The Spitzbergen population of bowhead whales, however, seems particularly ice-associated throughout the year, and some individuals cross into the WGICA area during both summer and winter (Vacquié-Garcia *et al.*, 2017; Kovacs *et al.*, 2020). This population likely numbered around 50 000 animals before the start of whaling era in the 16th century but was nearly eradicated by the end of the 19th century (Allen and Keay, 2006; Baird and Bickham, 2021). It is currently estimated to number a few hundred individuals and is classified as endangered (Cooke and Reeves, 2018). In contrast, the Bering–Chukchi–Beaufort Sea bowhead whale population numbers around 17 000 animals and is thought to be at or above pre-whaling numbers (Givens *et al.*, 2021). This population spends summer in the Chukchi and Beaufort seas, and some individuals occasionally cross into the WGICA area around the Chukchi Borderland (Citta *et al.*, 2021). In this area, bowhead wintering areas have traditionally been located south of the Bering Strait but have in more recent years increasingly been located within the Bering Strait itself and in the southern Beaufort Sea close to the border of the WGICA area (Citta *et al.*, 2023; Szesciorka *et al.*, 2024).

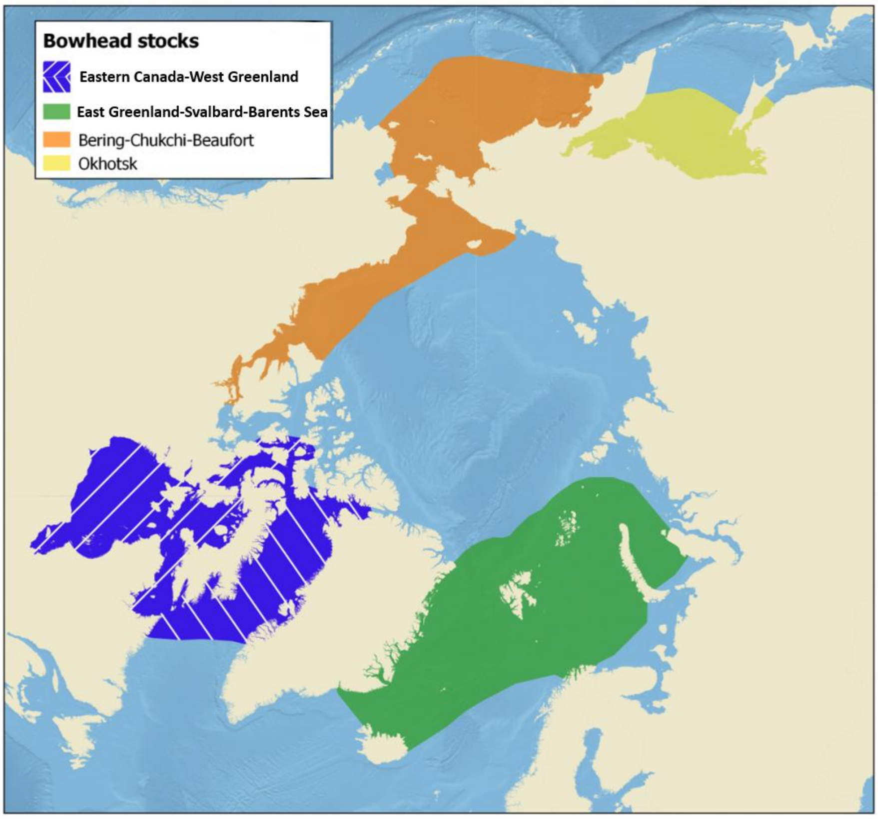


Figure 17.3. Current and historical ranges of bowhead whale stocks. Reproduced with permission from: https://nammco.no/ringed-seal/.

It has been hypothesized that the particularly strong affinity to ice observed for the Spitzbergen bowhead population is partly because of a behavioural selection pressure exerted by historical hunting, as the whales distributed farthest into the ice were most likely to escape the hunters (Boertmann *et al.*, 2015; Kovacs *et al.*, 2020). Killer whales are also known to attack bowhead whales in open water, and studies of bowhead habitat use in the Baffin Bay area show significant responses to the presence of killer whales (Matthews *et al.*, 2020). The latter have expanded their range to the north following the reduction in the summer sea ice extent (Breed, 2021). A similar northward expansion of killer whales has been observed in the Pacific gateway area (Stafford, 2018) along with an increase in observed bowhead carcasses with signs of killer whale attacks.

17.1.4 Narwhals

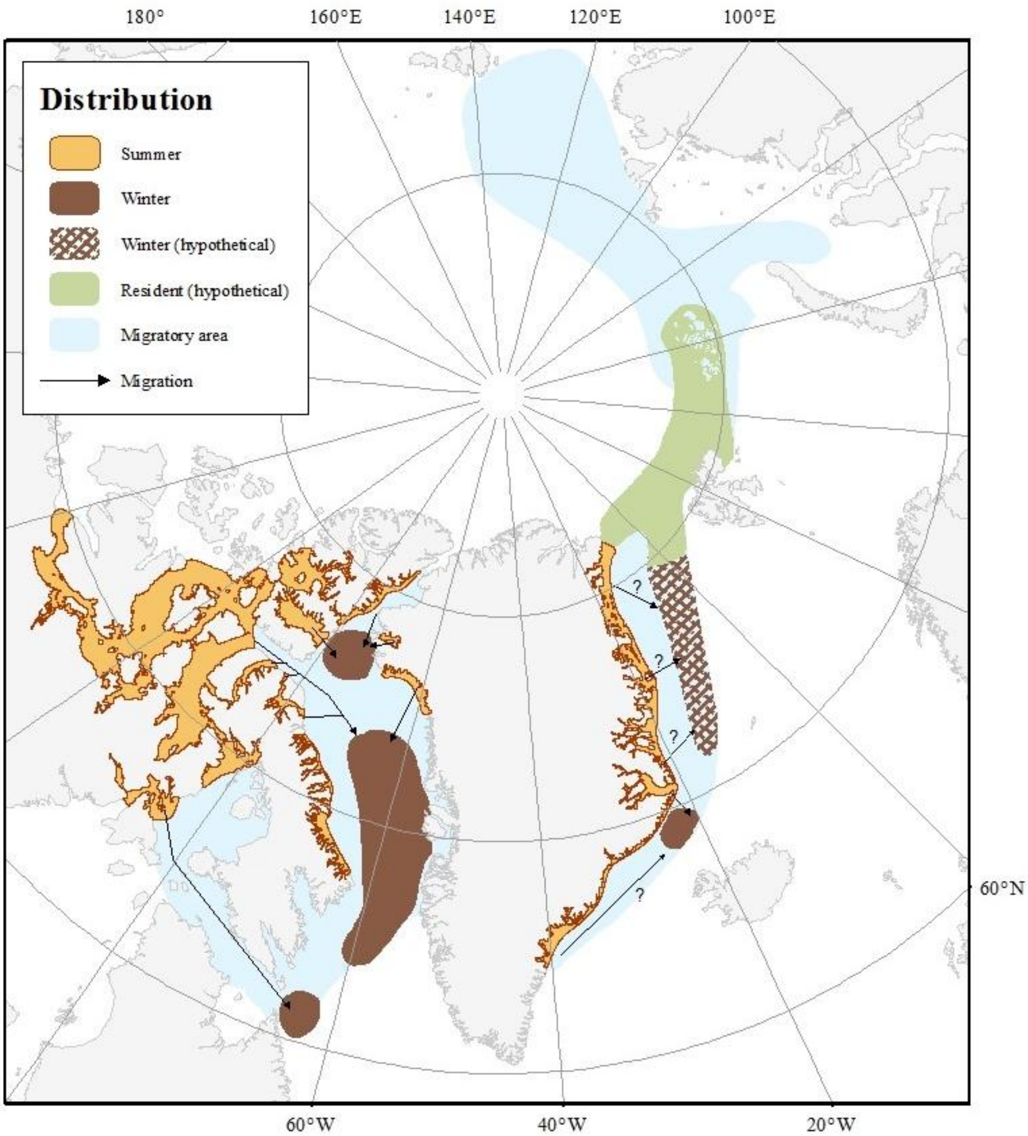


Figure 17.4. Narwhal stocks identified by their summering grounds according to the Global Review of Monodontids (2023). Ranges of stocks are differentiated into summer areas (tan), migration areas (light blue), and known wintering grounds (brown check), arrows show direction of fall migration. Number codes for stocks are as follows: 1) Somerset Island, 2) Jones Sound, 3) Smith Sound, 4) Admiralty Inlet, 5) Eclipse Sound, 6) Inglefield Bredning, 7) Melville Bay, 8) Eastern Baffin Island, 9) Northern Hudson Bay, 10) East Greenland, 11) Northeast Greenland, and 12) Svalbard–NW Russian Arctic. Reproduced from Hobbs *et al.* (2019) with permission from NAMMCO.

Narwhals are deep-diving toothed whales that feed mainly on fish, which they locate by help of an advanced biosonar system. Narwhals are generally known to feed most intensively during winter in deep waters, while summer is spent nursing newborn calves in shallow waters (e.g. Charry *et al.*, 2020). The largest global population of narwhals (numbering ~140 000) is found in the Baffin Bay area (Doniol-Vacroze *et al.*, 2020, but see also NAMMCO, 2023), which is still practically isolated from the CAO by permanent ice cover in connecting straits (Figure 17.4). Small genetically distinct narwhal populations are, however, found along the coast of Greenland and around Svalbard (Louis *et al.*, 2020; NAMMCO, 2023). The former is estimated to count around 600 individuals, while no estimates exist for the latter (NAMMCO, 2023). It is, however, considered very small (Hobbs *et al.*, 2019). Surveys have also identified a summer occurrence of at least 800 narwhals within the Nansen basin area (Vacquié-Garcia *et al.*, 2017), which could, therefore, be one of the most important summer habitats of Northeast Atlantic narwhals. It is not known how closely these narwhals are related to the three identified narwhal populations in East Greenland, which appear to have shown an overall decline and change in distribution pattern over the past decades (NAMMCO, 2023). Interestingly, however, a concentration of 2 000 narwhals has recently been surveyed in Dove Bay in the northernmost part of northeast Greenland (NAMMCO, 2023). Narwhals have been recorded acoustically in the Fram Strait area throughout the year (Ahonen *et al.*, 2019).

Both traditional knowledge and several scientific studies have highlighted the pronounced sensitivity of narwhals to underwater noise from larger vessels, small boats, and seismic airguns (NAMMCO, 2022). For example, increased ship traffic in the Canadian Eclipse Sound is considered the most likely cause for an almost complete displacement of narwhals from this traditional summering area (NAMMCO, 2022). Narwhals are also known to react strongly to the presence of killer whales by either moving into ice-covered areas or close to shore (Breed *et al.*, 2020). With declining sea-ice coverage in other areas, the WGICA area could, therefore, become an increasingly important summer refuge for narwhals.

17.1.5 Belugas

The Pacific gateway region is the summering habitat for the Chukchi Sea and Beaufort Sea beluga populations (Figure 17.5) numbering around 50 000 animals (Muto *et al.*, 2021). Some of these belugas (mainly males) cross into the WGICA area around the Chukchi borderland and in the Beaufort Sea (Hauser *et al.*, 2014, 2018; Muto *et al.*, 2021). Calving and moulting seem to occur in coastal habitats, although juveniles may also be observed offshore (Frost *et al.*, 1993; Clarke *et al.*, 2023; Mayette *et al.*, 2023).

Telemetry-based analyses of habitat use of Chukchi and Beaufort belugas suggested a certain overlap with the WGICA study area CAO during July–October (Hauser *et al.*, 2014). Later extensions of this and other dataseries have shown that belugas have prolonged their stay in areas close to the CAO in response to sea ice retreat (Hauser *et al.*, 2018; Stafford *et al.*, 2018), and that they have also increased their use of deep-water areas (Hauser *et al.*, 2018). The latest study of passive acoustic data show beluga presence in the southwestern Beaufort Sea from mid-April to mid-November (Stafford *et al.*, 2021), and based on the general increase in deep-water habitat use, it is reasonable to assume that belugas may be present in the WGICA area up to eight months of the year, satisfying the classification of common.

The Atlantic gateway region is home to the small Svalbard population of belugas, estimated at about 549 (95% CI: 436–723) whales (Vacquié-Gracia *et al.*, 2020) and further east to the Kara–Laptev population of unknown size (Hobbs *et al.*, 2019). The Svalbard population is generally considered to be very coastal with a preference for marine glacier fronts (Vacquié-Garcia *et al.*, 2018). Reports from the Russian Arctic are also mainly from nearshore areas (e.g. Belikov and

Boltunov, 2002; Fretwell *et al.*, 2023), but some observations have also been made far into the CAO during the period June–October (Belikov and Boltunov, 2002).

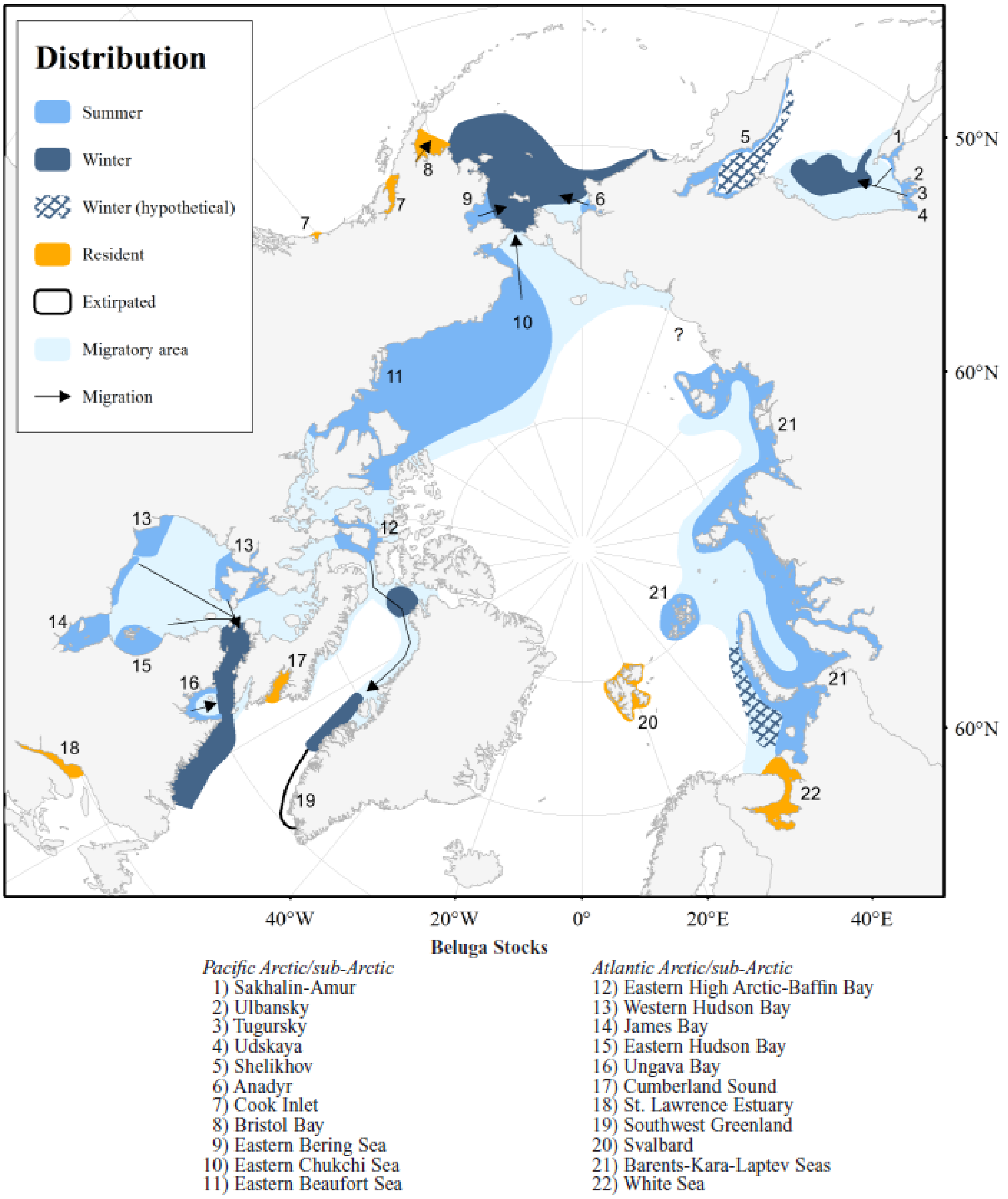


Figure 17.5. Beluga stocks recognized by the Global Review of Monodontids. Stocks are identified by their summering grounds. Ranges of stocks that migrate are differentiated into summer areas (mid-blue), migration areas (light blue), known winter grounds (dark blue), or hypothetical winter grounds (dark blue check); arrows show direction of fall migration. Ranges of stocks residing year-round in the same area are orange. Winter areas are not shown for the belugas in the Kara and Laptev seas due to lack of information. Reproduced from Hobbs *et al.* (2021), with permission from NAMMCO.

In recent years, an increasing number of belugas have been observed and hunted off the coast of east Greenland (NAMMCO, 2023). Genetic analyses suggest that these animals originate from the three different Svalbard, Kara Sea–Laptev Sea, and Beaufort Sea populations (NAMMCO, 2023). The latter finding, in particular, emphasizes the potential importance of the Arctic Ocean as a habitat and migration corridor for belugas. These whales have a very broad feeding niche, ranging from shallow water benthic prey to pelagic fish and squid (Quakenbush *et al.*, 2015). Like narwhals, they use echolocation to find their prey. They furthermore have a large vocal repertoire for social communication. In some areas, however, belugas are known to be rather silent, possibly as an antipredation strategy towards killer whales (Karlsen *et al.*, 2002). Their white skin furthermore suggests a role for camouflage as an antipredator strategy in habitats characterized by the presence of ice floes, such as glacier fronts, which is indeed a preferred beluga whale habitat in Svalbard (Vacquié-Garcia *et al.*, 2018). Currently, closeness to sea ice, however, does not generally seem to be an important direct factor for beluga habitat use in the Chukchi and Beaufort seas (Hauser *et al.*, 2014; Stafford *et al.*, 2018). This may, however, change if killer whale presence in these areas increases further (O'Corry-Crowe *et al.*, 2016).

17.2 Vulnerability toward pressures from human activities

Of the 11 pressures identified from human activities, nine were considered relevant for marine mammals in the CAO.

17.2.1 Contaminants

Of the five focal marine mammal species, narwhals, belugas, and polar bears are inherently most vulnerable to anthropogenic contaminants because of their high trophic levels. Odontocetes, furthermore, have low ability to metabolize some contaminants, including PCBs and other organic halogenated compounds [OHCs; see Pedersen *et al.* (2024) and references herein]. Metabolization, may, however, also increase the toxicity of contaminants, as suggested by the higher immunotoxicity of contaminant mixes derived from polar bear blubber than from killer whale blubber (Desforges *et al.*, 2017). These empirical contaminant mixes showed stronger *in vitro* immunosuppressive effects than expected based on data for single-compound studies suggesting that many of these studies may overestimate threshold concentrations for effects. Nevertheless, many of the single-compound studies conducted over the past decades have shown significant effects of a wide range of anthropogenic compounds on various biomarker and histopathology endpoints for the narwhals, belugas, and polar bears [summarized in Dietz *et al.* (2019)].

Despite bans and stricter regulations on use, legacy chemicals like PCBs and Hg continue to be of concern for marine mammals in parts of the Arctic (Dietz *et al.*, 2019; AMAP, 2021a). In some cases, levels have even been reported to increase, temporarily or permanently. This could be due to local releases of accumulated deposits of these compounds in multiyear sea ice or frozen deposits on land (Rigét *et al.*, 2019). Changes in diets driven by changes in ice distribution and phenology may also modulate contaminant levels in such mammals, as seen for east Greenland polar bears (McKinney *et al.*, 2013). In the Svalbard subpopulation, bears summering in the CAO are found to have higher levels of some PFAS compounds (known as "forever chemicals") than resident bears, and levels also appear to increase towards the northeast where little monitoring occurs (Tartu *et al.*, 2018). Increasing levels of PFAS are expected to constitute a health risk to polar bears denning in Svalbard and possibly in adjacent subpopulations (Routti *et al.*, 2019b).

Climate change–induced changes in habitats and diets are also thought to affect contaminant levels in Beaufort Sea belugas (Smythe *et al.*, 2018). Although levels are generally low in belugas from this area, effects on vitamin levels are, nevertheless, inferred (Desforges *et al.*, 2013). Contaminant levels in Svalbard belugas are considered high and appear likely to affect levels of thyroid hormones (Villanger *et al.*, 2011). An earlier study by Wolkers *et al.* (2006) found that narwhals in the Svalbard area have higher levels of PCB and other OHCs than belugas, but lower levels than Northwest Atlantic narwhals (Dietz *et al.*, 2019; Pedersen *et al.*, 2024; Wolkers *et al.*, 2006). This is consistent with greater reliance on lower trophic level prey in east Atlantic narwhals found by Watt *et al.* (2013). In contrast to narwhals from West Greenland, no histopathological conditions have been found in East Greenland narwhals (Dietz *et al.*, 2019), and contaminant levels have not been considered relevant for the observed low reproductive rates and declining abundance of narwhals in East Greenland (Garde *et al.*, 2022). A few local studies have found biomarker effects of contaminants in Arctic ringed seals, but generally this rather low trophic level species does not appear to be significantly affected by contaminants (Dietz *et al.*, 2019). Data on persistent organic pollutants in bowhead whales are only available for the Bering–Chukchi–Beaufort Sea stock and show very low levels decreasing over time (Bolton *et al.*, 2020).

So far, no observed population-level changes in marine mammals occurring in the CAO can be attributed directly to the effects of contaminants (Dietz *et al.*, 2019). Moreover, the extent to which any observed effects can be attributed to contaminant exposure within the CAO varies between species and between populations within species, as evident from the section on spatial coverage and temporal occurrence. Even the presence a species in the ecoregion does not necessarily imply exposure to contaminants if the species' main feeding activity occurs elsewhere. The feeding location of Nansen Basin narwhals is at present uncertain. For the other species, it seems likely that the time spent in the CAO is indeed an important feeding period.

The main source of anthropogenic pollutants in Arctic marine mammals is long-range atmospheric deposits, occurring both directly and indirectly, via the release of accumulated deposits from melting multiyear ice (AMAP, 2021a). Ongoing human activity such as ship and submarine traffic may furthermore cause local exposure to acidic water from scrubbers (Lunde Hermansson *et al.*, 2024), low-radioactive water from nuclear-powered submarines and ice breakers, and minor oil leaks from diesel-powered vessels. The latter two sources are also associated with a risk of even larger exposures in the case of accidents.

All marine mammals are vulnerable to the risk of inhaling fumes from oil, which may, in some cases, cause lung diseases and other health problems (Helm *et al.*, 2014; Venn-Watson *et al.*, 2015; Rubjerg *et al.*, 2021). Odontocetes may be at a larger risk than other groups because they have a very poor sense of smell (Kishida and Thewissen, 2012), which reduces their ability to detect oil and avoid contact. They also do not have the opportunity to escape onto the surface of the ice if oil is discharged in a waterlead. This also applies to bowhead whales, which may, therefore, in practice, not be in a better position to avoid exposure to sudden oil discharges than odontocetes. Contrary to earlier beliefs, baleens do not appear to be prone to clogging by oil, since their surface is lipophobic (Rubjerg *et al.*, 2021; Werth *et al.*, 2019). This surface characteristic may, on the other hand, enhance the ingestion of harmful oil residues. Polar bears are particularly vulnerable to oil fouling because fouling may reduce the isolating capacity of their fur. Attempts to clean it may lead the animals to ingest dangerous amounts of oil. No dose-response levels exist for oil ingestion in any marine mammal species, although early experiments suggest tolerance to low levels of intake (Helm *et al.*, 2014).

17.2.2 Non-indigenous species

The clearest example of an introduced harmful NIS to Arctic waters is the occurrence of the tropical parasite *Toxoplasma gondii* in Arctic marine mammals (Reiling and Dixon, 2019) and barnacle geese (*Branta leucopsis*; Prestrud *et al.*, 2007). *T. gondii* forms tissue cysts in a wide range of warm-blooded intermediate hosts, including humans. The seroprevalence of toxoplasma in the general human population ranges between 30 and 90% between regions (de Barros *et al.*, 2022), but most infected people only experience mild clinical symptoms or none at all (Elmore *et al.*, 2010). Due to the high infection rate, however, significant numbers of people experience severe symptoms of toxoplasmosis, such as abortions, blindness, and encephalitis (which may be lethal; de Barros *et al.*, 2022).

In the WGICA study area, seropositive individuals have been found among Beaufort Sea belugas (Sharma *et al.*, 2018), southern Beaufort Sea polar bears (Kirk *et al.*, 2010), and Svalbard polar bears, and ringed seals (Jensen *et al.*, 2010), but so far, no clinical cases of toxoplasmosis have been reported (Dubey *et al.*, 2020). Further south, however, *T. gondii* has been associated with high mortalities in sea otters (*Enhydra lutris*; Conrad *et al.*, 2005; Dubey *et al.*, 2020). Latent infections with *T. gondii* have also been correlated with reduced immunological status (Kirk *et al.*, 2010) and behavioural changes (Johnson and Koshy, 2020; Contopoulos-Ioannidis *et al.*, 2022) but evidence for causality is ambiguous in both animals and humans. Transmission of infective stages of this parasite can occur trophically, and consumers of raw or undercooked meat from infected animals are, therefore, at risk (Simon *et al.*, 2011).

Sexual reproduction of *T. gondii* can only occur in a felid definitive host, which subsequently sheds large numbers of oocysts in their faeces. These may persist for months and sporulate if encountering favourable temperature conditions (Shapiro *et al.*, 2019). Sewage runoff is, therefore, likely an important transmission pathway to the marine environment in areas with large populations of domestic cats (Conrad *et al.*, 2005; Burgess *et al.*, 2018). Oocysts may, furthermore, be accumulated in cold-blooded filter-feeders like bivalves, which may put benthic feeders like sea otters at particular risk (Miller *et al.*, 2008). The transmission routes of *T. gondii* into the high Arctic are not well understood (Prestrud *et al.*, 2007; Jensen *et al.*, 2010; Reiling and Dixon; 2019; Shapiro *et al.*, 2019). Migratory species of both mammals and birds are thought to play a role, but a significant influx of infective oocysts via ocean currents and rivers has also been suggested. Little attention has so far been given to the potential role of ballast-water discharge as a vector of microscopic pathogens like *T. gondii* oocysts (Hess-Erga *et al.*, 2019; Saynli *et al.*, 2022). Based on the reported persistence of infective oocysts, ballast water discharge does, however, appear to be a possible transmission mechanism for the parasite, as also suggested by Jensen *et al.* (2010). The ecological significance would, however, depend on the volumes, origins, and treatment procedures of this water.

17.2.3 Marine litter, including microplastics

Large items of marine litter such as abandoned fishing gear and lost cargo cordage has been identified as a threat to several marine mammal populations outside the Arctic (e.g. Baulch and Perry, 2014; Gall and Thompson, 2015; Unger *et al.*, 2017; IWC, 2020). Marine mammal interactions with macroplastic are known to have caused mortality a result of entanglement and subsequent asphyxiation, physical injuries, and/or starvation. These phenomena have so far rarely been reported from the high Arctic (Lusher *et al.*, 2022; Zantis *et al.*, 2021) but could increase as fishing effort and cargo traffic closer to the CAO both increase. One case of macroplastic ingestion, however, has been revealed, following recent investigations of the gastrointestinal tracts of harp and hooded seals in the Greenland Sea (Pinzone *et al.*, 2021). A newly weaned hooded seal pup had ingested two small sheets of single-use plastic thought to originate from local littering by a vessel. Juvenile seals generally seem more prone to ingest macroplastic, probably because of their inexperience and curiosity (Unger *et al.*, 2017).

Larger datasets from the North Sea suggest that serious direct health impacts of interaction with macroplastic (both ingestion and entanglement) are rare in seals and whales although potentially detrimental to individual animals (Unger *et al.*, 2017). Polar bears are known to explore anthropogenic litter for food remains and to ingest any associated packaging material (Smith *et al.*, 2023). This likely explains observations of plastic and other debris in polar bear stomachs and faeces obtained or observed on land or close to shore (Lusher *et al.*, 2022; Smith *et al.*, 2023). The recent record of ingested microplastic in a pack-ice seal, however, suggests that polar bears may also occasionally ingest plastic through their seal prey. For all Arctic marine mammal species, harmful interactions with macroplastic and debris are so far considered unlikely to have significant population impacts.

Microplastic has been found in both pinnipeds and whales around the world (Zantis *et al.*, 2021) and is considered to pose a potential health risk both to the mammals themselves and to human consumers (AMAP, 2021b). The extent and mechanisms of health effects in marine mammals, and indeed humans, have, however, not been determined (Lee *et al.*, 2023; Lohmann, 2017). In whales, microplastic fragments have been found to translocate from the gastrointestinal tracts to the lung, blubber, melon, and acoustic fat pad (Merrill *et al.*, 2023), increasing the scope for potential effects. Microplastics often have various types of toxic additives that may leak into the environment and potentially cause harm. Phtalates are one group of additives which are known to act as endocrine disruptors and have been found in bowhead whales and polar bears (Routti *et al.*, 2021). The source was, however, not established.

So far, microplastic has only been found at very low levels or not at all in Arctic marine mammals. For example, no microplastic has been found in ringed seals and other Arctic pinnipeds sampled in the eastern and western Canadian Arctic (Bourdages *et al.*, 2020; Jardine *et al.*, 2023). Low levels of microplastic have been found in polar bears in the Canadian Arctic (Iyare *et al.*, 2024) and in the Fram Strait area (Routti *et al.*, 2021). Seven belugas in the eastern Beaufort Sea, obtained from subsistence hunters, all had some microplastic in their intestinal tracts (Moore *et al.*, 2019), likely from trophic transfer. Several fish species preyed upon by belugas in this area have been found to contain microplastic; benthic species more so than pelagic species (Moore *et al.*, 2022). Filter-feeding species like bowhead whales may ingest microplastic directly from the water column in addition to trophic transfer (Werth *et al.*, 2024). Theoretical concerns have also been voiced over the potential clogging of the bowhead baleens by both microplastic and marine debris (Werth *et al.*, 2024).

17.2.4 Artificial noise pollution

Based on a large literature review, Hauser *et al.* (2018) scored monodontids (narwhals and belugas) and bowhead whales as highly sensitive to vessel noise. For monodontids, this pertained particularly to noise from ice breakers, based on studies such as Finley *et al.* (1990), Cosens and Dueck (1993), Blane and Jackson (1994), and Erbe and Farmer (2000). Avoidance behaviours for these species have been observed at distances of 50–80 km from vessels, which may, to a large extent, disrupt optimal habitat use with respect to parameters like foraging success, social interactions, and predator avoidance. A more recent study of satellite-tagged belugas in the Beaufort and Chukchi seas supports previous reports of long-range vessel avoidance (Martin *et al.*, 2022). Increased swim speeds were observed up to 79 km from vessels, and likely lateral avoidance behaviour was observed at between 12.6 and ~43.6 km (Martin *et al.*, 2022). For satellite-tagged narwhals in East Greenland, Tervo *et al.* (2021) found that narwhal vocalization was reduced at up to 40 km from sources of mixed vessel and seismic airgun noise at very small signal-to-noise ratios. These narwhals also showed physiological responses to noise, leading to a doubling of energy use (Williams *et al.*, 2022). Specific modelling of detection ranges of narwhals to cargo ships operating from the iron ore shipping port near the Mary River mine has suggested that narwhal detection ranges for these ships are vastly lower than previously shown, which would markedly reduce the expected effects on narwhal behaviour and habitat use (Sweeney *et al.*, 2022). Nevertheless, narwhals appear to have almost abandoned previous summering areas in the nearby Eclipse Sound for the more isolated Admiralty Inlet (NAMMCO, 2022). This suggests that uncertainties still exist regarding the acoustic cues that may trigger avoidance behaviours in narwhals and whales in general.

For bowhead whales, the studies underpinning the scoring for vessel noise by Hauser *et al.* (2018) were mainly focused on reactions to seismic operations (McDonald *et al.*, 2012; Robertson *et al.*, 2016). The degree of spatial displacement of bowhead whales in response to seismic operations appears to be context-dependent, and displacement is more likely during travelling behaviour (Richardsson *et al.*, 1999) than during foraging or mating behaviour (Wartzok *et al.*, 1989; Koski *et al.*, 2009). More recent studies specifically on vessel noise in the Beaufort and Chukchi seas have shown very little bowhead avoidance behaviour to vessels well within their detection range (Martin *et al.*, 2023). Not much systematic data are available for behavioural responses within 8 km from ships, but Martin *et al.* (2023) found that little avoidance occurred down to distances of 1 km, and some whales even stayed as close as 500 m to passing vessels. This puts bowhead whales at significant risk for ship strikes, and postmortems of whales killed through subsistence hunting in Alaska, in fact, suggest a significant increase in signs of ship strikes (Stimmelmayr *et al.*, 2021). Both seismic air gun noise and vessel noise may, furthermore, mask bowhead whale calls (McDonald *et al.*, 2012; Blackwell *et al.*, 2015) and force the whales to increase sound levels or give up communicating. Modelling the aggregated exposure and responses of bowhead whales to multiple anthropogenic underwater sounds in the Beaufort Sea, Ellison *et al.* (2016) found that some bowheads exceeded defined threshold levels for physical injury.

Ringed seal sensitivity to vessel noise has not been extensively studied, but the very wide hearing frequency range of phocid seals increases the likelihood that they could experience a masking of biologically relevant sounds, including sounds made by a prey species like polar cod (Hauser *et al.*, 2018; Pine *et al.*, 2018). This type of disturbance may be particularly serious for young of the year, which are likely to occur in the WGICA study area and start feeding independently just as the vessel traffic season begins. Heart rates of hauled harbour seals (*Phoca vitulina)* have been found to increase in response to vessel detection, particularly of small vessels like kayaks and inflatables (Karpovich *et al.*, 2015). Seals that escape to the water after these initial stress reactions have lowered heart rates in the water but elevated heart rates during the next haul-out. Similar heart-rate responses have been observed for hooded seals subject to experimental military sonar exposure (Kvadsheim *et al.*, 2010). The mentioned types of disturbance, therefore, seem to have a direct energetic cost in seals in addition to the loss of benefits from the natural behaviours that were interrupted. Ringed seals have been observed at the surface close to ships involved in seismic surveys (Harris *et al.*, 2001). This has been interpreted as tolerance to seismic shooting but may, in fact, constitute a protective reaction to keep the ears out of the ensonified water. The longer-term consequences of the mentioned disturbances will likely depend on the importance of the interrupted natural behaviour and the frequency and duration of the disturbance.

Polar bears are not thought to be significantly affected by underwater noise (Hauser *et al.*, 2018). Very little is, however, known about their sensitivity to noise while swimming longer distances, as seen for polar bears returning from the CAO to their denning areas in Svalbard. Any impacts that would change the haul-out pattern and vigilance of their seal prey may, however, also affect polar bear hunting success.

Low-flying helicopters and airplanes are known to scare several species of Arctic marine mammals (e.g. Born *et al.*, 1999; Patenaude *et al.*; 2002), including polar bears (Quigley *et al.*, 2024). Airborne drones are widely considered to be less invasive than manned aircraft, but some mammal responses have been reported (e.g. Smith *et al.*, 2016).

17.2.5 Selective extraction of species

All five focal Arctic marine mammals addressed in this report have been subject to significant hunting in the nearshore areas of the Arctic although not within the borders of the WGICA area. Several mammal populations occurring in the CAO are subject to subsistence hunting at lower latitudes, such as the Beaufort and Chukchi Sea belugas and the Bering–Chukchi–Beaufort bowhead whales. It is uncertain if subsistence hunting for belugas and narwhals in East Greenland targets any populations associated with the CAO, although some individuals are targeted; these have apparently have come from the Beaufort Sea either via the CAO, Arctic Ocean shelf waters, or inner waters of the Canadian Arctic Archipelago.

17.2.6 Artificial light pollution

Artificial light may interfere with the synthesis of melatonin among a wide range of vertebrates, with potential consequences for circadian rhythms and overall fitness (Grubisic *et al.*, 2019; Stanton and Cowart, 2024). However, no specific studies on marine mammals appear to be available (Stanton and Cowart, 2024).

17.2.7 Unintended injury and mortalities

Since whales can only move in water, their safe passage through ice-covered waters depends on their ability to navigate the system of leads and the feasibility of breaking up ice (George *et al.*, 1989). Narwhals, belugas, and bowheads have all demonstrated impressive abilities to detect approaching dangers (Breed *et al.*, 2020; Matthews *et al.*, 2020; Martin *et al.*, 2023), but moving away from the best route through ice-covered waters may, in itself, cause dangers of getting stuck in or under the ice.

Narwhals in particular have shown extreme physiological fear responses during capture for tagging. Such responses may enable effective escape from dangers but could also incur negative health consequences (Blackwell *et al.*, 2017). There is, however, no evidence of this extreme fear reaction in response to other anthropogenic disturbance (e.g. Heide-Jørgensen *et al.*, 2021). Bowhead whales may show avoidance behaviour to ships at distances of up to 15 m (Richardsson and Malme, 1993), but at other times do not seem to respond (Martin *et al.*, 2023). Not much systematic data are available for behavioural responses within 8 km of ships, but Martin *et al.* (2023) found that little avoidance occurred down to distances of 1 km, and some whales even stayed as close as 500 m to passing vessels. This puts bowhead whales at significant risk for ship strikes, and postmortems of whales killed through subsistence hunting in Alaska, in fact, suggest a significant increase in signs of ship strikes (Stimmelmayr *et al.*, 2021). Due to their rather slow movements, these whales may be particularly at risk for collisions with fast and stealthy military vessels. A changed migration pattern of the Bering–Chukchi–Beaufort bowhead stock increases their vulnerability to vessel traffic occurring near or within the WGICA study area (Szesciorka *et al.*, 2024).

Although seals and polar bears can escape over the ice, this may not completely eliminate the danger of injuries caused by human activity. Small body size could limit the ability of ringed seals to move fast enough away from approaching vessels. During moulting, ringed seals may, furthermore, be hesitant to enter the water because of the increased rate of heat loss during this stage. The moulting period of Arctic ringed seals is during spring and early summer and may, therefore, partly overlap with the shipping season in the CAO. Helicopters landing on the ice may also pose a danger to ringed seals, as small individuals may be blown across the ice, possibly hitting hard surfaces and sharp edges at high speed. Polar bears may simply be too fearless to take action in time (Smultea *et al.*, 2010). The few polar bears that den on the sea ice in the Beaufort and Chukchi seas are, furthermore, vulnerable to any ice breaker activity that might occur in their denning area.

Little is known about marine mammal reactions to underwater drones (gliders), which are increasingly used for marine monitoring (Aniceto *et al.*, 2020; Helal *et al.*, 2024).

17.2.8 Human presence on ice

Polar bears are curious and fearless animals that may approach and engage humans when present on or near the ice (i.e. in small boats). Although the bears may sometimes be scared off with flare guns, there is a substantial risk that the bear will have to be killed to save human lives (Balto, 2020). Human presence on the ice is likely to disturb ringed seal haul-out behaviour but likely has little effect on nearby whales.

17.2.9 Physical seabed and sea-ice disturbance

Ice breakers may directly disrupt the ice habitat of ringed seals and polar bears. This would only affect a small area in relation to the total habitat available, but the population impact will depend on the importance of the affected area and the timing, duration, and frequency of the ice-breaking activity. It has also been suggested that ice breaking may affect the ability of bowhead whales to navigate in the system of ice leads.

18 Vulnerability of ecosystem components toward CAO pressures and spatial-temporal occurrences

This chapter contains a compilation of the information and evidence described by the section authors across sections 10–17 in the form of a vulnerability table (Table 18.1), a table of the spatial distribution of ecosystem groups and species (Table 18.2), and a table the temporal occurrences of groups and species (Table 18.3).

Table 18.1. Vulnerability of ecosystem groups/species toward eleven pressures. The different colours are explained below the table (see next page) and provide the vulnerability of the ecosystem components (vertical, read more in sections 10–17) toward the identified pressures (horizontal, read more in sections 2–8). The different numbers are explained in the footnotes to this table (see next page). This table is the background information for further risk analyses outside the scope of this report.

Groups/species \ Pressures	Contaminants	Non-indigenous species	Litter, incl. micro plastics	Artificial noise pollution	Nutrient and organic enrichment	Extraction of species	Extraction of non-living resources[11]	Physical seabed disturbance[12]	Artificial light pollution	Unintended injury and mortality	Human presence
Ice prokaryotes and viruses											
Water column prokaryotes and viruses											
Seabed prokaryotes and viruses											
Ice algae	1	x	2	x	3	x	x	x	4	x	x
Phytoplankton	1	6	2	x	3	x	x	x	4	x	x
Ice invertebrates	5										
Zooplankton											
Pelagic squid											
Soft-bottom invertebrate species	7		7	x	x			7	x	x	x
Hard-bottom invertebrate species	7		7	x	x			7	x	x	x
Sympagic fish											
Mesopelagic fish											
Demersal and bentho-pelagic fish											
Polar bear	13	x			x	x	x	8	x	x	9
Ringed seal		x			x	x	x	8	x		
Bowhead		x	10		x	x	x	8	x		x
Narwhal/beluga		x			x	x	x	8	x		x
Transients birds											
Seasonal seabird residents											
Ice obligates: ivory gull, Ross's gull											

Table 18.1 footnotes

[1] Important to distinguish between direct effects on primary producers and trophic related effects. No documented effects on primary producer communities in nature (effects have been induced in experimental studies.

[2] Only microplastic is considered.

[3] In general, supply of nutrients may increase primary production (positive) and in some coastal areas result in eutrophication (negative).

[4] May possibly react to artificial light (depend on wavelength), but unknow for how long and what amount is needed for it to have an effect (positive or negative), especially since this is only an issue when in it is dark, i.e. when there are fewer primary producers. Thus, it is unlikely that artificial light will influence primary production or species composition at a level of significance in the CAO.

[5] Ice algae: thinner ice may result in higher production for a short time, but loss of habitat because of climate change is more serious in the long run. Phytoplankton: Only potential positive if enough nutrients are available and the mixed layer is not too deep and stable. In the case of reduced nutrient availability (increased freshwater input may cause increased stability), there will be a negative effect also on phytoplankton.

[6] Not introduced species in general, depends on which one (related to competition, etc).

[7] Most information is from outside the CAO and confidence is therefore low.

[8] See also "noise" for ship traffic in ice.

[9] Polar bears in danger of being shot with human presence.

[10] Bowheads are filter-feeders and consume microplastic.

[11] Extraction of non-living resources will be removal from the seabed of rock and sediment for scientific research.

[12] Physical seabed disturbance will be abrasion pressures related to disturbance of the substrate at or below the surface of the seabed; aggregate and other mineral extraction is not covered by this pressure.

[13] Only direct effects of locally emitted or discharged pollutants are considered. Polar bears are scoring higher than other marine mammals here because of the potential damage of routine oil discharges to the insulating capacity of the polar bear fur. Attempts to clean the fur by licking it may furthermore lead to acute poisoning. The effect is nevertheless considered moderate as we have not considered catastrophic oil spills, only routine discharges of small amounts of oil.

Table 18.1 - Vulnerability colour scale

	Very vulnerable
	Moderately vulnerable
	Low vulnerablity
	Not vulnerable
	No information
x	Not relevant for the ecosystem component
	Potential positive effect

Table 18.2. The spatial coverage in the CAO of the ecosystem groups/species (read also sections 10–17). This table is the background information for further risk analyses outside the scope of this report.

	Site: >0–5%	Local: 5–50%	Widespread patchy: >50%	Widespread even: >50%
Ice prokaryotes and viruses			x	
Water and seabed prokaryotes and viruses				x
Sea ice algae			x	
Water column phytoplankton			x	
Sea ice invertebrates			x	x
Zooplankton				x
Soft- and hard-bottom benthos				x
Sympagic mesopelagic and benthic, benthopelagic fish*		x		
Transient seabirds			x	
Seasonal seabird residents		x		
Ice obligate seabirds: ivory gull, Ross's gull		x		
Polar bear and ringed seal			x	x
Bowhead and narwhal		x		
Beluga	x			

* Observations from trawl surveys in open water; all catches indicate very low abundances. Fishes may be present more broadly at very low densities.

Bathycaris sp. Shrimp. Image credit: MAREANO, IMR

Table 18.3. The temporal occurrences in the CAO of the ecosystem groups/species (read also sections 10–17). This table is the background information for further risk analyses outside the scope of this report.

	Rare: occurs up to one month per year	**Occasional:** occurs up to four months per year	**Common:** occurs up to eight months per year	**Persistent:** occurs every month of the year
Ice prokaryotes and viruses			x	
Water and seabed prokaryotes and viruses				x
Sea ice algae		x[1]		x[1]
Water column phytoplankton			x[2]	x[2]
Sea ice invertebrates				x
Zooplankton				x
Soft- and hard-bottom benthos				x
Sympagic mesopelagic and benthic, benthopelagic fish[3]				x
Transient seabirds		x		
Seasonal seabird residents		x		
Ice obligate seabirds: ivory gull, Ross's gull			x	
Polar bear and ringed seal				x
Bowhead and narwhal			x	
Beluga			x	

[1] If there is sea ice, a few cells will usually be present, both typical ice species and sometimes also resting stages of phytoplankton. Higher abundances occur for shorter periods, depending on location and ice type.

[2] A few cells will be present in the water column all year-round, but higher biomasses (e.g. blooms) may occur for about 5 months, depending on latitude.

[3] Observations from trawl surveys in open water. No data to indicate season migrations between the Central Arctic Ocean and adjacent habitats.

References

Aars, J., Marques, T. A., Lone, K., Andersen, M., Wiig, Ø., Bardalen Fløystad, I. M., Hagen, S. B., *et al.* 2017. The number and distribution of polar bears in the western Barents Sea. Polar Research, 36(1): 1374125. https://doi.org/10.1080/17518369.2017.1374125

Abelmann, A. 1992. Diatom assemblages in Arctic sea ice—indicator for ice drift pathways. Deep Sea Research Part A. Oceanographic Research Papers, 39(2): S525–S538. https://doi.org/10.1016/S0198-0149(06)80019-1

ACAP. 2021. Kola Waste Project: Cleaning of the Sámi Territory in the Murmansk Region (2018-2020). Arctic Contaminants Action Program. http://hdl.handle.net/11374/2606

ACIA (Arctic Climate Impact Assessment). 2004. https://www.amap.no/documents/doc/arctic-climate-impact-assessment-acia/711 (accessed 2024).

Ackerman, J. T., Eagles-Smith, C. A., Herzog, M. P., Hartman, C. A., Peterson, S. H., Evers, D. C., Jackson, A. K., *et al.* 2016. Avian mercury exposure and toxicological risk across western North America: A synthesis. Science of The Total Environment, 568: 749–769. https://doi.org/10.1016/j.scitotenv.2016.03.071

AFP. 2021. Lost in the Med: Pacific grey whale ventures far from home., France 24. https://www.france24.com/en/live-news/20210503-lost-in-the-med-pacific-grey-whale-ventures-far-from-home (accessed 2024).

Agather, A. M., Bowman, K. L., Lamborg, C. H., and Hammerschmidt, C. R. 2019. Distribution of mercury species in the Western Arctic Ocean (U.S. GEOTRACES GN01). Marine Chemistry, 216: 103686. https://doi.org/10.1016/j.marchem.2019.103686

Agersted, M. D., Møller, E. F., and Gustavson, K. 2018. Bioaccumulation of oil compounds in the high-Arctic copepod *Calanus hyperboreus*. Aquatic Toxicology, 195: 8–14. https://doi.org/10.1016/j.aquatox.2017.12.001

Ahonen, H., Stafford, K. M., Lydersen, C., De Steur, L., and Kovacs, K. M. 2019. A multi-year study of narwhal occurrence in the western Fram Strait—detected via passive acoustic monitoring. Polar Research, 38(0). https://doi.org/10.33265/polar.v38.3468

Alamgir, M., Campbell, M. J., Sloan, S., Goosem, M., Clements, G. R., Mahmoud, M. I., and Laurance, W. F. 2017. Economic, Socio-Political and Environmental Risks of Road Development in the Tropics. Current Biology, 27(20): R1130–R1140. https://doi.org/10.1016/j.cub.2017.08.067

Albert, C., Helgason, H. H., Brault-Favrou, M., Robertson, G. J., Descamps, S., Amélineau, F., Danielsen, J., *et al.* 2021. Seasonal variation of mercury contamination in Arctic seabirds: A pan-Arctic assessment. Science of The Total Environment, 750: 142201. https://doi.org/10.1016/j.scitotenv.2020.142201

Allen, R. C., and Keay, I. 2006. Bowhead Whales in the Eastern Arctic, 1611-1911: Population Reconstruction with Historical Whaling. Environment and History, 12(1): 89–113. https://doi.org/10.3197/096734006776026791

Almeda, R., Rodriguez-Torres, R., Rist, S., Winding, M. H. S., Stief, P., Hansen, B. H., and Nielsen, T. G. 2021. Microplastics do not increase bioaccumulation of petroleum hydrocarbons in Arctic zooplankton but trigger feeding suppression under co-exposure conditions. Science of The Total Environment, 751: 141264. https://doi.org/10.1016/j.scitotenv.2020.141264

Alrabeei, S., Subbey, S., Gundersen, S., and Gjøsæter, H. 2021. Spatial and temporal patterns of capelin (*Mallotus villosus*) spawning sites in the Barents Sea. Fisheries Research, 244: 106117.

Alter, S. E., Meyer, M., Post, K., Czechowski, P., Gravlund, P., Gaines, C., Rosenbaum, H. C., *et al.* 2015. Climate impacts on transocean dispersal and habitat in gray whales from the Pleistocene to 2100. Molecular Ecology, 24(7): 1510–1522. https://doi.org/10.1111/mec.13121

AMAP. 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme, Oslo, Norway.

AMAP. 2011. AMAP Assessment 2011: Mercury in the Arctic. Arctic Monitoring and Assessment Programme, Oslo, Norway.

AMAP. 2015. AMAP Assessment 2015: Radioactivity in the Arctic. Arctic Monitoring and Assessment Programme, Oslo, Norway.

AMAP. 2016a. AMAP Assessment 2015: Temporal Trends in Persistent Organic Pollutants in the Arctic. Arctic Monitoring and Assessment Programme, Oslo, Norway.

AMAP. 2017a. AMAP Assessment 2016: Chemicals of Emerging Arctic Concern. Arctic Monitoring and Assessment Programme, Oslo, Norway.

AMAP. 2017b. Snow, Water, Ice and Permafrost in the Arctic (SWIPA). Arctic Monitoring and Assessment Programme, Oslo, Norway.

AMAP. 2018a. AMAP Assessment 2018: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme, Tromsø, Norway.

AMAP. 2018b. AMAP Assessment 2018: Biological Effects of Contaminants on Arctic Wildlife and Fish. Arctic Monitoring and Assessment Programme, Oslo, Norway.

AMAP. 2021a. AMAP Assessment 2021: Mercury in the Arctic. Arctic Monitoring and Assessment Programme, Tromsø, Norway.

AMAP. 2021b. AMAP Litter and Microplastics Monitoring Plan. Arctic Monitoring and Assessment Programme, Tromsø, Norway.

AMAP. 2021c. AMAP Litter and Microplastics Monitoring Guidelines. Version 1.0.

Amara, I., Miled, W., Slama, R. B., and Ladhari, N. 2018. Antifouling processes and toxicity effects of antifouling paints on marine environment. A review. Environmental Toxicology and Pharmacology, 57: 115–130. https://doi.org/10.1016/j.etap.2017.12.001

Ambrose, W. G., Quillfeldt, C. V., Clough, L. M., Tilney, P. V. R., and Tucker, T. 2005. The sub-ice algal community in the Chukchi Sea: large- and small-scale patterns of abundance based on images from a remotely operated vehicle. Polar Biology, 28(10): 784–795. https://doi.org/10.1007/s00300-005-0002-8

Amélineau, F., Grémillet, D., Harding, A. M. A., Walkusz, W., Choquet, R., and Fort, J. 2019. Arctic climate change and pollution impact little auk foraging and fitness across a decade. Scientific Reports, 9(1): 1014. https://doi.org/10.1038/s41598-018-38042-z

Andersen, M., Kovacs, K. M., and Lydersen, C. 2021b. Stable ringed seal (*Pusa hispida*) demography despite significant habitat change in Svalbard, Norway. Polar Research, 40. https://doi.org/10.33265/polar.v40.5391

Anderson, D. M., Fachon, E., Pickart, R. S., Lin, P., Fischer, A. D., Richlen, M. L., Uva, V., *et al.* 2021a. Evidence for massive and recurrent toxic blooms of *Alexandrium catenella* in the Alaskan Arctic. Proceedings of the National Academy of Sciences, 118(41): e2107387118. https://doi.org/10.1073/pnas.2107387118

Anderson Hansen, K., Hernandez, A., Mooney, T. A., Rasmussen, M. H., Sørensen, K., and Wahlberg, M. 2020. The common murre (*Uria aalge*), an auk seabird, reacts to underwater sound. The Journal of the Acoustical Society of America, 147(6): 4069–4074. https://doi.org/10.1121/10.0001400

Anderson Hansen, K., Maxwell, A., Siebert, U., Larsen, O. N., and Wahlberg, M. 2017. Great cormorants (*Phalacrocorax carbo*) can detect auditory cues while diving. The Science of Nature, 104(5–6): 45. https://doi.org/10.1007/s00114-017-1467-3

Andreev, A. V. 2005. Between permafrost and pack ice: the Ross gull on its Kolyma breeding grounds. Second Readings to the Commemoration of SA Buturlin, Proceedings of a Conference Held in Ulyanovsk, September 2005.

Andriyashev, A. P., Mukhomedigarov, B. F., and Pavshtiks, E. A. 1980. On mass congregations of the cryopelagic cod fishes (*Boreogadus saida* and *Arctogadus glacialis*) in circumpolar Arctic basins. *In* Biology of the Central Arctic Basin. Ed. by M. E. Vinogradov, and I. A. Melnikov. Shirshov Institute of Oceanology, Academy of Sciences, USSR.

Aniceto, A. S., Pedersen, G., Primicerio, R., Biuw, M., Lindstrøm, U., and Camus, L. 2020. Arctic Marine Data Collection Using Oceanic Gliders: Providing Ecological Context to Cetacean Vocalizations. Frontiers in Marine Science, 7: 585754. https://doi.org/10.3389/fmars.2020.585754

Arctic Council. 1996. Ottawa Declaration. http://hdl.handle.net/11374/85

Arctic Council Secretariat. 2013. Arctic Council Secretariat Annual Report 2013. Arctic Council, Tromsø, Norway. https://oaarchive.arctic-council.org/server/api/core/bitstreams/baf1206c-d013-403a-8c3e-2f06bf2b4593/content

Arnberg, M., Calosi, P., Spicer, J. I., Tandberg, A. H. S., Nilsen, M., Westerlund, S., and Bechmann, R. K. 2013. Elevated temperature elicits greater effects than decreased pH on the development, feeding and metabolism of northern shrimp (*Pandalus borealis*) larvae. Marine Biology, 160(8): 2037–2048. https://doi.org/10.1007/s00227-012-2072-9

Arrigo, K. R., Perovich, D. K., Pickart, R. S., Brown, Z. W., Van Dijken, G. L., Lowry, K. E., Mills, M. M., *et al.* 2012. Massive Phytoplankton Blooms Under Arctic Sea Ice. Science, 336(6087): 1408–1408. https://doi.org/10.1126/science.1215065

Arrigo, K. R., and Van Dijken, G. L. 2015. Continued increases in Arctic Ocean primary production. Progress in Oceanography, 136: 60–70. https://doi.org/10.1016/j.pocean.2015.05.002

Aschan, M., Fossheim, M., Greenacre, M., and Primicerio, R. 2013. Change in Fish Community Structure in the Barents Sea. PLOS One, 8(4): e62748. https://doi.org/10.1371/journal.pone.0062748

Ashjian, C. J., Campbell, R. G., Welch, H. E., Butler, M., and van Keuren, D. 2003. Annual cycle in abundance, distribution, and size in relation to hydrography of important copepod species in the western Arctic Ocean. Deep Sea Research Part I: Oceanographic Research Papers, 50(10–11): 1235–1261. https://doi.org/10.1016/S0967-0637(03)00129-8

Assmy, P., Fernández-Méndez, M., Duarte, P., Meyer, A., Randelhoff, A., Mundy, C. J., Olsen, L. M., *et al.* 2017. Leads in Arctic pack ice enable early phytoplankton blooms below snow-covered sea ice. Scientific Reports, 7(1): 40850. https://doi.org/10.1038/srep40850

Atwood, T. C., Marcot, B. G., Douglas, D. C., Amstrup, S. C., Rode, K. D., Durner, G. M., and Bromaghin, J. F. 2016. Forecasting the relative influence of environmental and anthropogenic stressors on polar bears. Ecosphere, 7(6): e01370. https://doi.org/10.1002/ecs2.1370

Au, W. W. L., Carder, D. A., Penner, R. H., and Scronce, B. L. 1985. Demonstration of adaptation in beluga whale echolocation signals. The Journal of the Acoustical Society of America, 77(2): 726–730. https://doi.org/10.1121/1.392341

Augustijn-Beckers, P. W. M., Hornsby, A. G., and Wauchope, R. D. 1994. The SCS/ARS/CES Pesticide Properties Database for Environmental Decision-Making. II. Additional Compounds. *In* Reviews of Environmental Contamination and Toxicology, pp. 1–82. Ed. by G. W. Ware. Springer, New York, NY. https://doi.org/10.1007/978-1-4612-2662-8_1

Baak, J. E., Linnebjerg, J. F., Barry, T., Gavrilo, M. V., Mallory, M. L., Price, C., and Provencher, J. F. 2020. Plastic ingestion by seabirds in the circumpolar Arctic: a review. Environmental Reviews, 28(4): 506–516. https://doi.org/10.1139/er-2020-0029

Baak, J., J. Linneberg, M. Mallory, T. Barry, M. Gavrilo, F. Merkel, C. Price, *et al.* 2021. Plastic pollution in seabirds, Developing a program to monitor plastic pollution in seabirds in the pan-Arctic region. Akureyri, Iceland: Conservation of Arctic Flora and Fauna International Secretariat. http://hdl.handle.net/11374/2640

Backman, J., Schmeisser, L., and Asmi, E. 2021. Asian emissions explain much of the Arctic Black Carbon events. Geophysical Research Letters, 48(5): 2020 091913. https://doi.org/10.1029/2020GL091913

Baduini, C. L., Hyrenbach, K. D., Coyle, K. O., Pinchuk, A., Mendenhall, V., and Hunt, G. L. 2001. Mass mortality of short-tailed shearwaters in the south-eastern Bering Sea during summer 1997. Fisheries Oceanography, 10(1): 117–130. https://doi.org/10.1046/j.1365-2419.2001.00156.x

Bailey, A., Thor, P., Browman, H. I., Fields, D. M., Runge, J., Vermont, A., Bjelland, R., *et al.* 2017. Early life stages of the Arctic copepod *Calanus glacialis* are unaffected by increased seawater pCO_2. ICES Journal of Marine Science, 74(4): 996–1004. https://doi.org/10.1093/icesjms/fsw066

Baird, A. B., and Bickham, J. W. 2021. The stocks of bowheads. *In* The Bowhead Whale, pp. 19–29. Academic Press.

Balmonte, J. P., Teske, A., and Arnosti, C. 2018. Structure and function of high Arctic pelagic, particle-associated and benthic bacterial communities. Environmental Microbiology, 20(8): 2941–2954. https://doi.org/10.1111/1462-2920.14304

Balto, A. K. 2020. When scientists head into the polar bear's realm. https://www.npolar.no/en/newsarticle/when-scientists-head-into-the-polar-bears-realm/ (accessed 2024).

Balton, D. 2021. The Arctic Fisheries Agreement Enters into Force. https://www.wilsoncenter.org/blog-post/no-9-arctic-fisheries-agreement-enters-force).

Bano, N., and Hollibaugh, J. T. 2002. Phylogenetic Composition of Bacterioplankton Assemblages from the Arctic Ocean. Applied and Environmental Microbiology, 68(2): 505–518. https://doi.org/10.1128/AEM.68.2.505-518.2002

Barber, D. G., Hop, H., Mundy, C. J., Else, B., Dmitrenko, I. A., Tremblay, J-E., Ehn, J. K., *et al.* 2015. Selected physical, biological and biogeochemical implications of a rapidly changing Arctic Marginal Ice Zone. Progress in Oceanography, 139: 122–150. https://doi.org/10.1016/j.pocean.2015.09.003

Barneo camp. 2017. That is it. No more coordinates and weather from the Barneo-2017. The season is over. Status update. April 21, 2017. Facebook. https://www.facebook.com/BarneoRu/photos/a.121371817939925/1348604608549967/

Basel Convention. 1989. https://www.basel.int/default.aspx (accessed 2024).

Baulch, S., and Perry, C. 2014. Evaluating the impacts of marine debris on cetaceans. Marine Pollution Bulletin, 80(1–2): 210–221. https://doi.org/10.1016/j.marpolbul.2013.12.050

Beaulieu, S. E., and Szafrański, K. M. 2020. InterRidge Global Database of Active Submarine Hydrothermal Vent Fields Version 3.4 [dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.917894

Belikov, S. E., and Boltunov, A. N. 2002. Distribution and migrations of cetaceans in the Russian Arctic according to observations from aerial ice reconnaissance. NAMMCO Scientific Publications, 4: 69. https://doi.org/10.7557/3.2838

Bender, M. L., Frantzen, M., Vieweg, I., Falk-Petersen, I-B., Johnsen, H. K., Rudolfsen, G., Tollefsen, K. E., *et al.* 2016. Effects of chronic dietary petroleum exposure on reproductive development in polar cod (*Boreogadus saida*). Aquatic Toxicology, 180: 196–208. https://doi.org/10.1016/j.aquatox.2016.10.005

Bender, M. L., Giebichenstein, J., Teisrud, R. N., Laurent, J., Frantzen, M., Meador, J. P., Sørensen, L., *et al.* 2021. Combined effects of crude oil exposure and warming on eggs and larvae of an Arctic forage fish. Scientific Reports, 11(1): 8410. https://doi.org/10.1038/s41598-021-87932-2

Bengtsson, J. L., Hiruki-Raring, L. M., Simpkins, M. A., and Boveng, P. L. 2005. Ringed and bearded seal densities in the eastern Chukchi Sea, 1999–2000. Polar Biology, 28(11): 833–845. https://doi.org/10.1007/s00300-005-0009-1

Bengtsson, O., Lydersen, C., Kovacs, K. M., and Lindström, U. 2020. Ringed seal (*Pusa hispida*) diet on the west coast of Spitsbergen, Svalbard, Norway: during a time of ecosystem change. Polar Biology, 43(7): 773–788. https://doi.org/10.1007/s00300-020-02684-5

Berge, J., Daase, M., Hobbs, L., Falk-Petersen, S., Darnis, G., and Søreide, J. E. 2020b. Zooplankton in the Polar Night. *In* POLAR NIGHT Marine Ecology, pp. 113–159. Ed. by J. Berge, G. Johnsen, and J. H. Cohen. Advances in Polar Ecology, Springer International Publishing. https://doi.org/10.1007/978-3-030-33208-2_5

Berge, J., Geoffroy, M., Daase, M., Cottier, F., Priou, P., Cohen, J. H., Johnsen, G., *et al.* 2020a. Artificial light during the polar night disrupts Arctic fish and zooplankton behaviour down to 200 m depth. Communications Biology, 3(1): 102. https://doi.org/10.1038/s42003-020-0807-6

Berge, J., Varpe, Ø., Moline, M. A., Wold, A., Renaud, P. E., Daase, M., and Falk-Petersen, S. 2012. Retention of ice-associated amphipods: possible consequences for an ice-free Arctic Ocean. Biology Letters, 8(6): 1012–1015. https://doi.org/10.1098/rsbl.2012.0517

Bergmann, M., Allen, S., Krumpen, T., and Allen, D. 2023. High Levels of Microplastics in the Arctic Sea Ice Alga *Melosira arctica*, a Vector to Ice-Associated and Benthic Food Webs. Environmental Science & Technology, 57(17): 6799–6807. https://doi.org/10.1021/acs.est.2c08010

Bergmann, M., Collard, F., Fabres, J., Gabrielsen, G. W., Provencher, J. F., Rochman, C. M., van Sebille, E., *et al.* 2022. Plastic pollution in the Arctic. Nature Reviews Earth & Environment, 3(5): 323–337. https://doi.org/10.1038/s43017-022-00279-8

Bergmann, M., Dannheim, J., Bauerfeind, E., and Klages, M. 2009. Trophic relationships along a bathymetric gradient at the deep-sea observatory HAUSGARTEN. Deep Sea Research Part I: Oceanographic Research Papers, 56(3): 408–424. https://doi.org/10.1016/j.dsr.2008.10.004

Bergmann, M., and Klages, M. 2012. Increase of litter at the Arctic deep-sea observatory HAUSGARTEN. Marine Pollution Bulletin, 64(12): 2734–2741. https://doi.org/10.1016/j.marpolbul.2012.09.018

Bergmann, M., Mützel, S., Primpke, S., Tekman, M. B., Trachsel, J., and Gerdts, G. 2019. White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Science Advances, 5(8): eaax1157. https://doi.org/10.1126/sciadv.aax1157

Bergmann, M., Sandhop, N., Schewe, I., and D'Hert, D. 2016. Observations of floating anthropogenic litter in the Barents Sea and Fram Strait, Arctic. Polar Biology, 39(3): 553–560. https://doi.org/10.1007/s00300-015-1795-8

Bergmann, M., Wirzberger, V., Krumpen, T., Lorenz, C., Primpke, S., Tekman, M. B., and Gerdts, G. 2017. High Quantities of Microplastic in Arctic Deep-Sea Sediments from the HAUSGARTEN Observatory. Environmental Science & Technology, 51(19): 11000–11010. https://doi.org/10.1021/acs.est.7b03331

Berkman, P. 2010. Environmental Security in the Arctic Ocean: Promoting Cooperation and Preventing Conflict. Routledge, London.

Berkman, P. A. 2009. International spaces promote peace. Nature, 462(7272): 412–413. https://doi.org/10.1038/462412a

Berkman, P. A., Fiske, G., Grebmeier, J. M., and Vylegzhanin, A. N. 2022b. (Research): Maritime Ship Traffic in the Central Arctic Ocean High Seas as a Case Study with Informed Decisionmaking. *In* Building Common Interests in the Arctic Ocean with Global Inclusion, pp. 321–346. Ed. by P. A. Berkman, A. N. Vylegzhanin, O. R. Young, D. A. Balton, and O. R. Øvretveit. Informed Decisionmaking for Sustainability. Springer International Publishing. https://doi.org/10.1007/978-3-030-89312-5_24

Berkman, P. A., Fiske, G. J., Lorenzini, D., Young, O. R., Pletnikoff, K., Grebmeier, J. M., Fernandez, L. M., *et al.* 2022a. Satellite Record of Pan-Arctic Maritime Ship Traffic. *In* NOAA Arctic Report Card 2022, pp. 9. Technical Report OAR ARC. https://www.arctic.noaa.gov/Report-Card/Report-Card-2022/ArtMID/8054/ArticleID/1004/Satellite-Record-of-Pan-Arctic-Maritime-Ship-Traffic).

Berkman, P. A., Fiske, G., Røyset, J.-A., Brigham, L. W., and Lorenzini, D. 2020. Next-Generation Arctic Marine Shipping Assessments. *In* Governing Arctic Seas: Regional Lessons from the Bering Strait and Barents Sea, pp. 241–268. Ed. by O. R. Young, P. A. Berkman, and A. N. Vylegzhan. Springer International Publishing. https://doi.org/10.1007/978-3-030-25674-6_11

Berkman, P. A., Lang, M. A., Walton, D. W. H., and Young, O. R. (Eds.). 2011. Science Diplomacy: Antarctica, Science and the Governance of International Spaces. Smithsonian Institution Scholarly Press, Washington, DC.

Berkman, P. A., Vylegzhanin, A. N., and Young, O. R. 2019. Baseline of Russian Arctic Laws, Springer Polar Sciences. Springer International Publishing. https://doi.org/10.1007/978-3-030-06262-0

Berkman, P. A., and Young, O. R. 2009. Governance and Environmental Change in the Arctic Ocean. Science, 324(5925): 339–340. https://doi.org/10.1126/science.1173200

Berkman, P. A., Young, O. R., Vylegzhanin, A. N., Balton, D. A., and Øvretveit, O. R. 2022b. (Research): Introduction: Building Common Interests with Informed Decisionmaking for Sustainability. *In* Building Common Interests in the Arctic Ocean with Global Inclusion, pp. 3–54. Ed. by P. A. Berkman, A. N. Vylegzhanin, O. R. Young, D. A. Balton, and O. R. Øvretveit. Informed Decisionmaking for Sustainability. Springer International Publishing. https://doi.org/10.1007/978-3-030-89312-5_1

Berkman, P. A., Young, O. R., Vylegzhanin, A. N., Balton, D. A., and Øvretveit, O. R. 2022c. (Research): Conclusions: Building Global Inclusion with Common Interests. *In* Building Common Interests in the Arctic Ocean with Global Inclusion, pp. 409–423. Ed. by P. A. Berkman, A. N. Vylegzhanin, O. R. Young, D. A. Balton, and O. R. Øvretveit. Informed Decisionmaking for Sustainability. Springer International Publishing. https://doi.org/10.1007/978-3-030-89312-5_35

Bidleman, T. F., Stern, G. A., Tomy, G. T., Hargrave, B. T., Jantunen, L. M., and Macdonald, R. W. 2013. Scavenging Amphipods: Sentinels for Penetration of Mercury and Persistent Organic Chemicals into Food Webs of the Deep Arctic Ocean. Environmental Science & Technology, 47(11): 5553–5561. https://doi.org/10.1021/es304398j

BigQuery Enterprise Data Warehouse. 2024. Google Cloud. https://cloud.google.com/bigquery (accessed 2024).

Bintanja, R., and Andry, O. 2017. Towards a rain-dominated Arctic. Nature Climate Change, 7(4): 263–267. https://doi.org/10.1038/nclimate3240

Blackwell, S. B., Nations, C. S., McDonald, T. L., Thode, A. M., Mathias, D., Kim, K. H., Greene, C. R., *et al.* 2015. Effects of Airgun Sounds on Bowhead Whale Calling Rates: Evidence for Two Behavioral Thresholds. PLOS One, 10(6): e0125720. https://doi.org/10.1371/journal.pone.0125720

Blanchet, M., Aars, J., Andersen, M., and Routti, H. 2020. Space-use strategy affects energy requirements in Barents Sea polar bears. Marine Ecology Progress Series, 639: 1–19. https://doi.org/10.3354/meps13290

Blane, J. M., and Jackson, R. 1994. The impact of ecotourism boats on the St Lawrence beluga whales. Environmental Conservation, 21(3): 267–269. https://doi.org/10.1017/S0376892900033282

Bluhm, B. A., Ambrose, W. G., Bergmann, M., Clough, L. M., Gebruk, A. V., Hasemann, C., Iken, K., *et al.* 2011b. Diversity of the Arctic deep-sea benthos. Marine Biodiversity, 41(1): 87–107. https://doi.org/10.1007/s12526-010-0078-4

Bluhm, B., Gebruk, A., Gradinger, R., Hopcroft, R., Huettmann, F., Kosobokova, K., Sirenko, B., *et al.* 2011a. Arctic Marine Biodiversity: An Update of Species Richness and Examples of Biodiversity Change. Oceanography, 24(3): 232–248. https://doi.org/10.5670/oceanog.2011.75

Bluhm, B. A., Hop, H., Melnikov, I. A., Poulin, M., Vihtakari, M., Collins, E. G., Gradinger, R., *et al.* 2017. Sea-ice biota. *In* State of the Arctic Marine Biodiversity Report, pp. 33–62. Conservation of Arctic Flora and Fauna International, Akureyri, Iceland. http://hdl.handle.net/11374/1945

Bluhm, B. A., Hop, H., Vihtakari, M., Gradinger, R., Iken, K., Melnikov, I. A., and Søreide, J. E. 2018. Sea ice meiofauna distribution on local to pan-Arctic scales. Ecology and Evolution, 8(4): 2350–2364. https://doi.org/10.1002/ece3.3797

Bluhm, B. A., Janout, M. A., Danielson, S. L., Ellingsen, I., Gavrilo, M., Grebmeier, J. M., Hopcroft, R. R., *et al.* 2020. The Pan-Arctic Continental Slope: Sharp Gradients of Physical Processes Affect Pelagic and Benthic Ecosystems. Frontiers in Marine Science, 7: 544386. https://doi.org/10.3389/fmars.2020.544386

Bluhm, B. A., Kosobokova, K. N., and Carmack, E. C. 2015. A tale of two basins: An integrated physical and biological perspective of the deep Arctic Ocean. Progress in Oceanography, 139: 89–121. https://doi.org/10.1016/j.pocean.2015.07.011

Boertmann, D., Blockley, D., and Mosbech, A. 2020. Greenland Sea - an updated strategic environmental impact assessment of petroleum activities. No. 375, Scientific Reports. Danish Centre for Environment and Energy, Aarhus University.

Boertmann, D., Kyhn, L. A., Witting, L., and Heide-Jørgensen, M. P. 2015. A hidden getaway for bowhead whales in the Greenland Sea. Polar Biology, 38(8): 1315–1319. https://doi.org/10.1007/s00300-015-1695-y

Boetius, A., and Bienhold, C. 2024. The Expedition PS138 of the Research Vessel Polarstern to the Arctic Ocean in 2023. Berichte zur Polar-und Meeresforschung= Reports on polar and marine research, 788. https://epic.awi.de/id/eprint/59182/20/BzPM_0788_2024.pdf

Boetius, A., and Purser, A. 2017. The Expedition PS101 of the Research Vessel POLARSTERN to the Arctic Ocean in 2016. Berichte zur Polar- und Meeresforschung No. 706. Bremerhaven: Alfred Wegener Institute for Polar and Marine Research. https://doi.org/10.2312/BzPM_0706_2017

Bohne, B. A., Yohe, E., and Thomas, J. A. 1985. Examination of potential hearing damage in Weddell seals (*Leptonychotes weddellii*) in McMurdo Sound, Antarctica. Antarctic Journal of the United States, 19(5): 174–176.

Bolton, J. L., Ylitalo, G. M., Chittaro, P., George, J. C., Suydam, R., Person, B. T., Gates, J. B., *et al.* 2020. Multi-year assessment (2006–2015) of persistent organic pollutant concentrations in blubber and muscle from Western Arctic bowhead whales (*Balaena mysticetus*), North Slope, Alaska. Marine Pollution Bulletin, 151: 110857. https://doi.org/10.1016/j.marpolbul.2019.110857

Boltovskoy, D., Almada, P., and Correa, N. 2011. Biological invasions: assessment of threat from ballast-water discharge in Patagonian (Argentina) ports. Environmental Science & Policy, 14(5): 578–583. https://doi.org/10.1016/j.envsci.2011.03.007

Bond, A. L., Hobson, K. A., and Branfireun, B. A. 2015. Rapidly increasing methyl mercury in endangered ivory gull (*Pagophila eburnea*) feathers over a 130 year record. Proceedings of the Royal Society B: Biological Sciences, 282(1805): 20150032. https://doi.org/10.1098/rspb.2015.0032

Boonstra, R. 2004. Coping with changing northern environments: the role of the stress axis in birds and mammals. Integrative and Comparative Biology, 44: 95–108. https://doi.org/10.1093/icb/44.2.95

Borgå, K., Wolkers, H., Skaare, J. U., Hop, H., Muir, D. C. G., and Gabrielsen, G. W. 2004. Bioaccumulation of PCBs in Arctic seabirds: influence of dietary exposure and congener biotransformation. Environmental Pollution, 134 (2005): 397–409. https://brage.npolar.no/npolar-xmlui/bitstream/handle/11250/174230/BorgaEnvirPoll2005.pdf?sequence=1

Born, E. W., Riget, F. F., Dietz, R., and Andriashek, D. 1999. Escape responses of hauled out ringed seals (*Phoca hispida*) to aircraft disturbance. Polar Biology, 21(3): 171–178. https://doi.org/10.1007/s003000050349

Botterell, Z. L. R., Bergmann, M., Hildebrandt, N., Krumpen, T., Steinke, M., Thompson, R. C., and Lindeque, P. K. 2022. Microplastic ingestion in zooplankton from the Fram Strait in the Arctic. Science of The Total Environment, 831: 154886. https://doi.org/10.1016/j.scitotenv.2022.154886

Bouchard, C., and Fortier, L. 2011. Circum-arctic comparison of the hatching season of polar cod *Boreogadus saida*: A test of the freshwater winter refuge hypothesis. Progress in Oceanography, 90(1–4): 105–116. https://doi.org/10.1016/j.pocean.2011.02.008

Bourdages, M. P. T., Provencher, J. F., Sudlovenick, E., Ferguson, S. H., Young, B. G., Pelletier, N., Murphy, M. J. J., *et al.* 2020. No plastics detected in seal (Phocidae) stomachs harvested in the eastern Canadian Arctic. Marine Pollution Bulletin, 150: 110772. https://doi.org/10.1016/j.marpolbul.2019.110772

Bourke, R. H., and Garrett, R. P. 1987. Sea ice thickness distribution in the Arctic Ocean. Cold Regions Science and Technology, 13(3): 259–280. https://doi.org/10.1016/0165-232X(87)90007-3

Boveng, P. L., Bengtson, J. L., Cameron, M. F., Dahle, S. P., Logerwell, E. A., London, J. M., Overland, J. E., *et al.* 2013. Status review of the ribbon seal (*Histriophoca fasciata*). No. 255, NOAA Technical Memorandum NMFS-AFSC. Alaska Fisheries Science Center, Seattle, WA. https://repository.library.noaa.gov/view/noaa/4451

Bowman, J. S., Rasmussen, S., Blom, N., Deming, J. W., Rysgaard, S., and Sicheritz-Ponten, T. 2012. Microbial community structure of Arctic multiyear sea ice and surface seawater by 454 sequencing of the 16S RNA gene. The ISME Journal, 6(1): 11–20. https://doi.org/10.1038/ismej.2011.76

Brandt, S., Wassmann, P., and Piepenburg, D. 2023. Revisiting the footprints of climate change in Arctic marine food webs: An assessment of knowledge gained since 2010. Frontiers in Marine Science, 10: 1096222. https://doi.org/10.3389/fmars.2023.1096222

Braune, B. M., Mallory, M. L., and Gilchrist, H. G. 2006. Elevated mercury levels in a declining population of ivory gulls in the Canadian Arctic. Marine Pollution Bulletin, 52(8): 978–982. https://doi.org/10.1016/j.marpolbul.2006.04.013

Breed, G. A. 2021. Predators and impacts of predation. *In* The Bowhead Whale, pp. 457–470. Academic Press.

Breed, G. A., Matthews, C. J. D., Marcoux, M., Higdon, J. W., LeBlanc, B., Petersen, S. D., Orr, J., *et al.* 2017. Sustained disruption of narwhal habitat use and behavior in the presence of Arctic killer whales. Proceedings of the National Academy of Sciences, 114(10): 2628–2633. https://doi.org/10.1073/pnas.1611707114

Breed, G. A., Matthews, C. J. D., Marcoux, M., Higdon, J. W., LeBlanc, B., Stephen, D., Petersen, S.,D., *et al.* 2020. Sustained disruption of narwhal habitat use and behavior in the presence of Arctic killer whales. Proceedings of the National Academy of Sciences, 117(12): 6590–6598. https://doi.org/10.1073/pnas.1611707114

Broccoli, A., Anselmi, S., Cavallo, A., Ferrari, V., Prevedelli, D., Pastorino, P., and Renzi, M. 2021. Ecotoxicological effects of new generation pollutants (nanoparticles, amoxicillin and white musk) on freshwater and marine phytoplankton species. Chemosphere, 279: 130623. https://doi.org/10.1016/j.chemosphere.2021.130623

Brown, T. A., Assmy, P., Hop, H., Wold, A., and Belt, S. T. 2017. Transfer of ice algae carbon to ice-associated amphipods in the high-Arctic pack ice environment. Journal of Plankton Research, 39(4): 664–674. https://doi.org/10.1093/plankt/fbx030

Budge, S. M., Wooller, M. J., Springer, A. M., Iverson, S. J., McRoy, C. P., and Divoky, G. J. 2008. Tracing carbon flow in an Arctic marine food web using fatty acid-stable isotope analysis. Oecologia, 157(1): 117–129. https://doi.org/10.1007/s00442-008-1053-7

Burgess, T. L., Tim Tinker, M., Miller, M. A., Bodkin, J. L., Murray, M. J., Saarinen, J. A., Nichol, L. M., *et al.* 2018. Defining the risk landscape in the context of pathogen pollution: *Toxoplasma gondii* in sea otters along the Pacific Rim. Royal Society Open Science, 5(7): 171178. https://doi.org/10.1098/rsos.171178

Bünz, S, Ramirez-Llodra, E., HACON19 cruise participants. 2019. RV Kronprins Håkon (cruise no. 2019708): Longyearbyen—Longyearbyen (19.09.–16. 10.2019). Cruise Report: 100. https://haconfrinatek.files.wordpress.com/2020/01/cruisereport-hacon19.pdf

Bünz, S., Ramirez-Llodra, E., HACON21 cruise participants. 2021. RV Kronprins Håkon (cruise no. 2021711): Longyearbyen—Longyearbyen (19.09.-16.10.2019): Hot vents in an ice-covered ocean—HACON21 expedition. Cruise Report: 81. https://haconfrinatek.files.wordpress.com/2020/01/cruise-report-hacon21_final.pdf.

CAFF. 2013. Arctic Biodiversity Assessment 2013: Report for Policy Makers. http://hdl.handle.net/11374/224

CAFF. 2017. Status and trends of Arctic marine biodiversity and monitoring. Akureyri, Iceland: Conservation of Arctic Flora and Fauna International Secretariat. http://hdl.handle.net/11374/1945

Cambridge Dictionary. 2023. https://dictionary.cambridge.org/us/dictionary/english/armed-forces

CAOFA. 2018. Central Arctic Ocean Fisheries Agreement. https://vlab.noaa.gov/web/caofa (accessed 2024).

Carlsson, P., Breivik, K., Brorström-Lundén, E., Cousins, I., Christensen, J., Grimalt, J. O., Halsall, C., *et al.* 2018. Polychlorinated biphenyls (PCBs) as sentinels for the elucidation of Arctic environmental change processes: a comprehensive review combined with ArcRisk project results. Environmental Science and Pollution Research, 25(23): 22499–22528. https://doi.org/10.1007/s11356-018-2625-7

Carlton, J. T. 2001. Introduced Species in U.S. Coastal Waters: Environmental Impacts and Management Priorities. Pew Oceans Commission. https://www.iatp.org/sites/default/files/Introduced_Species_in_US_Coastal_Waters_Enviro.htm

Carrizo, D., and Gustafsson, Ö. 2011a. Distribution and Inventories of Polychlorinated Biphenyls in the Polar Mixed Layer of Seven Pan-Arctic Shelf Seas and the Interior Basins. Environmental Science & Technology, 45(4): 1420–1427. https://doi.org/10.1021/es103542f

Carrizo, D. and Gustafsson, Ö. 2011b. Pan-Arctic river fluxes of polychlorinated biphenyls. Environmental Science & Technology, 45(19): 8377–8384. https://doi.org/10.1021/es201766z

Carrizo, D., Sobek, A., Salvadó, J. A., and Gustafsson, Ö. 2017. Spatial distributions of DDTs in the water masses of the Arctic Ocean. Environmental Science & Technology, 51(14): 7913–7919. https://doi.org/10.1021/acs.est.7b01369

Carroll, J., Savinov, V., Savinova, T., Dahle, S., McCrea, R. and Muir, D. C. 2008. PCBs, PBDEs and pesticides released to the Arctic Ocean by the Russian Rivers Ob and Yenisei. Environmental Science & Technology, 42(1): 69–74. https://doi.org/10.1021/es071673l

Carslaw, D., Beevers, S., Ropkins, K., and Bell, M. 2006. Detecting and quantifying aircraft and other on-airport contributions to ambient nitrogen oxides in the vicinity of a large international airport. Atmospheric Environment, 40(28): 5424–5434. https://doi.org/10.1016/j.atmosenv.2006.04.062

Castellani, G., Veyssière, G., Karcher, M., Stroeve, J., Banas, S. N., Bouman, A. H., Brierley, S. A., *et al.* 2022. Shine a light: Under-ice light and its ecological implications in a changing Arctic Ocean. Ambio, 51(2): 307–317. https://doi.org/10.1007/s13280-021-01662-3

Chambault, P., Albertsen, C. M., Patterson, T. A., Hansen, R. G., Tervo, O., Laidre, K. L., and Heide-Jørgensen, M. P. 2018. Sea surface temperature predicts the movements of an Arctic cetacean: the bowhead whale. Scientific Reports, 8(1): 9658. https://doi.org/10.1038/s41598-018-27966-1

Chan, F. T., MacIsaac, H. J., and Bailey, S. A. 2015. Relative importance of vessel hull fouling and ballast water as transport vectors of nonindigenous species to the Canadian Arctic. Canadian Journal of Fisheries and Aquatic Sciences, 72(8): 1230–1242. https://doi.org/10.1139/cjfas-2014-0473

Chan, F. T., Stanislawczyk, K., Sneekes, A. C., Dvoretsky, A., Gollasch, S., Minchin, D., David, M., *et al.* 2019. Climate change opens new frontiers for marine species in the Arctic: Current trends and future invasion risks. Global Change Biology, 25(1): 25–38. https://doi.org/10.1111/gcb.14469

Charette, M. A., Kipp, L. E., Jensen, L. T., Dabrowski, J. S., Whitmore, L. M., Fitzsimmons, J. N., Williford, T., *et al.* 2020. The Transpolar Drift as a Source of Riverine and Shelf-Derived Trace Elements to the Central Arctic Ocean. Journal of Geophysical Research: Oceans, 125(5): e2019JC015920. https://doi.org/10.1029/2019JC015920

Charry, B., Marcoux, M., Cardille, J. A., Giroux-Bougard, X., and Humphries, M. M. 2020. Hierarchical Classification of Narwhal Subpopulations Using Social Distance. The Journal of Wildlife Management, 84(2): 311–319. https://doi.org/10.1002/jwmg.21799

Chastel, O., Fort, J., Ackerman, J. T., Albert, C., Angelier, F., Basu, N., Blévin, P., *et al.* 2022. Mercury contamination and potential health risks to Arctic seabirds and shorebirds. Science of The Total Environment, 844: 156944. https://doi.org/10.1016/j.scitotenv.2022.156944

Chen, C., Hilário, A., Rodrigues, C. F., and Ramirez-Llodra, E. 2022. Integrative taxonomy of a new cocculinid limpet dominating the Aurora Vent Field in the central Arctic ocean. Royal Society Open Science, 9(10): 220885. https://doi.org/10.1098/rsos.220885

CITES. 2024. How CITES works. https://cites.org/eng/disc/how.php (accessed 2024).

Citta, J. J., Breed, G. A., Okkonen, S. R., Druckenmiller, M. L., Quakenbush, L., George, J. C., Adams, B., *et al.* 2023. Shifts in bowhead whale distribution, behavior, and condition following rapid sea ice change in the Bering sea. Continental Shelf Research, 256: 104959. https://doi.org/10.1016/j.csr.2023.104959

Citta, J. J., Okkonen, S. R., Quakenbush, L. T., Maslowski, W., Osinski, R., George, J. C., Small, R. J., *et al.* 2018. Oceanographic characteristics associated with autumn movements of bowhead whales in the Chukchi Sea. Deep Sea Research Part II: Topical Studies in Oceanography, 152: 121–131. https://doi.org/10.1016/j.dsr2.2017.03.009

Citta, J. J., Quakenbush, L., and George, J. C. 2021. Distribution and behavior of Bering–Chukchi–Beaufort bowhead whales as inferred by telemetry. *In* The Bowhead Whale, pp. 31–56. Ed. by J. C. George, and J. G. M. Thewissen. Elsevier. https://doi.org/10.1016/B978-0-12-818969-6.00004-2

Clairbaux, M., Fort, J., Mathewson, P., Porter, W., Strøm, H., and Grémillet, D. 2019. Climate change could overturn bird migration: Transarctic flights and high-latitude residency in a sea ice free Arctic. Scientific Reports, 9(1): 17767. https://doi.org/10.1038/s41598-019-54228-5

Clarke, J. T., Kennedy, A. S., and Ferguson, M. C. 2016. Bowhead and gray whale distributions, sighting rates, and habitat associations in the eastern Chukchi Sea, summer and fall 2009–2015, with a retrospective comparison to 1982–91. Arctic, 69 (4): 359–377. https://www.jstor.org/stable/24878034

Clarke, J. T., Ferguson, M. C., Brower, A. A., Fujioka, E., and Deland, S. 2023. Biologically important areas II for cetaceans in U.S. and adjacent waters - Arctic region. Frontiers in Marine Science, 10: 1040123. https://doi.org/10.3389/fmars.2023.1040123

Clement Kinney, J., Frants, M., Maslowski, W., Osinski, R., Jeffery, N., Jin, M., and Lee, Y. J. 2023. Investigation of Under-Ice Phytoplankton Growth in the Fully-Coupled, High-Resolution Regional Arctic System Model. Journal of Geophysical Research: Oceans, 128(9): e2022JC019000. https://doi.org/10.1029/2022JC019000

CMS (Convention on the Conservation of Migratory Species of Wild Animals). 1979. https://www.cms.int/ (accessed 2024).

Cobb, D., Fast, H., Papst, M. H., Rosenberg, D., Rutherford, R., Sareault, J. E. and Department of Fisheries and Oceans, Winnipeg, MB (Canada). Central and Arctic Reg. 2008. Beaufort Sea large ocean management area: ecosystem overview and assessment report. Canadian Technical Report of Fisheries and Aquatic Sciences, 2780.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., and Galloway, T. S. 2013. Microplastic Ingestion by Zooplankton. Environmental Science & Technology, 47(12): 6646–6655. https://doi.org/10.1021/es400663f

Collard, F., and Ask, A. 2021. Plastic ingestion by Arctic fauna: A review. Science of The Total Environment, 786: 147462. https://doi.org/10.1016/j.scitotenv.2021.147462

Collie, J., Hiddink, J. G., van Kooten, T., Rijnsdorp, A. D., Kaiser, M. J., Jennings, S. and Hilborn, R. 2017. Indirect effects of bottom fishing on the productivity of marine fish. Fish and Fisheries, 18: 619–637. https://doi.org/10.1111/faf.12193

Conover, R. J., and Siferd, T. D. 1993. Dark-Season Survival Strategies of Coastal Zone Zooplankton in the Canadian Arctic. ARCTIC, 46(4): 303–311. https://doi.org/10.14430/arctic1357

Conrad, P. A., Miller, M. A., Kreuder, C., James, E. R., Mazet, J., Dabritz, H., Jessup, D. A., *et al.* 2005. Transmission of Toxoplasma: Clues from the study of sea otters as sentinels of *Toxoplasma gondii* flow into the marine environment. International Journal for Parasitology, 35(11–12): 1155–1168. https://doi.org/10.1016/j.ijpara.2005.07.002

Consultative Process - Background. 1997. https://www.un.org/Depts/los/consultative_process/consultative_process_background.htm (accessed 2024).

Contopoulos-Ioannidis, D. G., Gianniki, M., Ai-Nhi Truong, A., and Montoya, J. G. 2022. Toxoplasmosis and Schizophrenia: A Systematic Review and Meta-Analysis of Prevalence and Associations and Future Directions. Psychiatric Research and Clinical Practice, 4(2): 48–60. https://doi.org/10.1176/appi.prcp.20210041

Convention on Biological Diversity. 1992. Convention on Biological Diversity. https://www.cbd.int/ (accessed 2024).

Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. 1972. https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx (accessed 2024).

Cooke, J. G., and Reeves, R. 2018. *Balaena mysticetus.* The IUCN Red List of Threatened Species 2018. https://doi.org/10.2305/IUCN.UK.2018-1.RLTS.T2467A50347659.en

Cooper, J. 1982. Methods of reducing mortality of seabirds caused by underwater blasting. Marine Ornithology, 10: 109–114. https://doi.org/10.5038/2074-1235.10.2.99

Cordes, E. E., Jones, D. O. B., Schlacher, T. A., Amon, D. J., Bernardino, A. F., Brooke, S., Carney, R., *et al.* 2016. Environmental Impacts of the Deep-Water Oil and Gas Industry: A Review to Guide Management Strategies. Frontiers in Environmental Science, 4. https://doi.org/10.3389/fenvs.2016.00058

Cosens, S. E., and Dueck, L. P. 1993. Icebreaker noise in Lancaster Sound, N.W.T, Canada: implications for marine mammal behavior. Marine Mammal Science, 9(3): 285–300. https://doi.org/10.1111/j.1748-7692.1993.tb00456.x

COSRVA. 2024. Circumpolar Oil Spill Response Viability Analysis. Arctic Council. https://arctic-council.org/projects/circumpolar-oil-spill-response-viability-analysis-cosrva/ (accessed 2024).

Cota, G. F., Legendre, L., Gosselin, M., and Ingram, R. G. 1991. Ecology of bottom ice algae: I. Environmental controls and variability. Journal of Marine Systems, 2(3–4): 257–277. https://doi.org/10.1016/0924-7963(91)90036-T

Crawford, J. A., Quakenbush, L. T., and Citta, J. J. 2015. A comparison of ringed and bearded seal diet, condition and productivity between historical (1975–1984) and recent (2003–2012) periods in the Alaskan Bering and Chukchi seas. Progress in Oceanography, 136: 133–150. https://doi.org/10.1016/j.pocean.2015.05.011

Crawford, R. E. 2016. Occurrence of a gelatinous predator (*Cyanea capillata*) may affect the distribution of *Boreogadus saida*, a key Arctic prey fish species. Polar Biology, 39(6): 1049–1055. https://doi.org/10.1007/s00300-015-1779-8

CSIS. 2025. Arctic Military Activity Tracker. Center for Strategic and International Studies (CSIS). https://arcticmilitarytracker.csis.org/

Cullinane, K., and Cullinane, S. 2013. Atmospheric Emissions from Shipping: The Need for Regulation and Approaches to Compliance. Transport Reviews, 33(4): 377–401. https://doi.org/10.1080/01441647.2013.806604

Cury, P. M., Boyd, I. L., Bonhommeau, S., Anker-Nilssen, T., Crawford, R. J. M., Furness, R. W., Mills, J. A., *et al.* 2011. Global Seabird Response to Forage Fish Depletion—One-Third for the Birds. Science, 334(6063): 1703–1706. https://doi.org/10.1126/science.1212928

Daase, M., Falk-Petersen, S., Varpe, Ø., Darnis, G., Søreide, J. E., Wold, A., Leu, E., *et al.* 2013. Timing of reproductive events in the marine copepod *Calanus glacialis* : a pan-Arctic perspective. Canadian Journal of Fisheries and Aquatic Sciences, 70(6): 871–884. https://doi.org/10.1139/cjfas-2012-0401

Dahlke, F. T., Leo, E., Mark, F. C., Pörtner, H., Bickmeyer, U., Frickenhaus, S., and Storch, D. 2017. Effects of ocean acidification increase embryonic sensitivity to thermal extremes in Atlantic cod, *Gadus morhua*. Global Change Biology, 23(4): 1499–1510. https://doi.org/10.1111/gcb.13527

Dalpadado, P., Arrigo, K. R., Van Dijken, G. L., Skjoldal, H. R., Bagøien, E., Dolgov, A. V., Prokopchuk, I. P., *et al.* 2020. Climate effects on temporal and spatial dynamics of phytoplankton and zooplankton in the Barents Sea. Progress in Oceanography, 185: 102320. https://doi.org/10.1016/j.pocean.2020.102320

Daniëls, F. J. A., Gillespie, L. J., Poulin, M., Afonina, O. M., Alsos, I. G., Bültmann, H., Ickert-Bond, S., *et al.* 2013. Plants. *In* Arctic Biodiversity Assessment: Status and trends in Arctic biodiversity. Conservation of Arctic Flora and Fauna, pp. 310–353. Ed. by H. Meltofte. Arctic Council, Tromsö, Norway. http://hdl.handle.net/11374/223

Dastoor, A., Wilson, S. J., Travnikov, O., Ryjkov, A., Angot, H., Christensen, J. H., Steenhuisen, F., *et al.* 2022. Arctic atmospheric mercury: Sources and changes. Science of The Total Environment, 839, 15 September 2022, 156213. https://doi.org/10.1016/j.scitotenv.2022.156213

David, C., Lange, B., Krumpen, T., Schaafsma, F., van Franeker, J. A., and Flores, H. 2016. Under-ice distribution of polar cod *Boreogadus saida* in the central Arctic Ocean and their association with sea-ice habitat properties. Polar Biology, 39(6): 981–994. https://doi.org/10.1007/s00300-015-1774-0

David, C., Lange, B., Rabe, B., and Flores, H. 2015. Community structure of under-ice fauna in the Eurasian central Arctic Ocean in relation to environmental properties of sea-ice habitats. Marine Ecology Progress Series, 522: 15–32. https://doi.org/10.3354/meps11156

Davies, T. W., and Smyth, T. 2018. Why artificial light at night should be a focus for global change research in the 21st century. Global Change Biology, 24(3): 872–882. https://doi.org/10.1111/gcb.13927

Day, R. H., Rose, J. R., Prichard, A. K., and Streever, B. 2015. Effects of gas flaring on the behavior of night-migrating birds at an artificial oil-production island, Arctic Alaska. *Arctic,* 68: 367–379. https://doi.org/10.14430/arctic4507

D'Costa, P. M., D'Silva, M. S., and Naik, R. K. 2017. Impact of Pollution on Phytoplankton and Implications for Marine Econiches. *In* Marine Pollution and Microbial Remediation, pp. 205–222. Ed. by M. M. Naik, and S. K. Dubey. Singapore: Springer Singapore. https://doi.org/10.1007/978-981-10-1044-6_13

de Barros, R. A. M., Torrecilhas, A. C., Marciano, M. A. M., Mazuz, M. L., Pereira-Chioccola, V. L., and Fux, B. 2022. Toxoplasmosis in Human and Animals Around the World. Diagnosis and Perspectives in the One Health Approach. Acta Tropica, 231: 106432. https://doi.org/10.1016/j.actatropica.2022.106432

de Boer, M., Janinhoff, N., Nijs, G., and Verdaat, H. 2019. Encouraging encounters: unusual aggregations of bowhead whales *Balaena mysticetus* in the western Fram Strait. Endangered Species Research, 39: 51–62. https://doi.org/10.3354/esr00948

Degen, R., Vedenin, A., Gusky, M., Boetius, A., and Brey, A. 2015. Patterns and trends of macrobenthic abundance, biomass and production in the deep Arctic Ocean. Polar Research, 34, https://www.tandfonline.com/doi/full/10.3402/polar.v34.24008

de Vreese, S., van der Schaar, M., Weissenberger, J., Erbs, F., Kosecka, M., Solé, M., and André, M. 2018. Marine mammal acoustic detections in the Greenland and Barents Sea, 2013 – 2014 seasons. Scientific Reports, 8(1): 16882. https://doi.org/10.1038/s41598-018-34624-z

Demarais, S., Tazik, D. J., Guertin, P. J., and Jorgensen, E. E. 1999. Disturbance associated with military exercises. *In* Ecosystems of Disturbed Ground, pp. 385–396. Ed. by L. R. Walker. Elsevier Science B. V., Amsterdam.

Derksen, C., and Brown, R. 2012. Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections. Geophysical Research Letters, 39(19): 2012GL053387. https://doi.org/10.1029/2012GL053387

Derwent, R. G., Stevenson, D. S., Doherty, R. M., Collins, W. J., Sanderson, M. G., Johnson, C. E., Cofala, J., *et al.* 2005. The Contribution from Shipping Emissions to Air Quality and Acid Deposition in Europe. AMBIO: A Journal of the Human Environment, 34(1): 54–59. https://doi.org/10.1579/0044-7447-34.1.54

Desforges, J-P., Levin, M., Jasperse, L., de Guise, S., Eulaers, I., Letcher, R. J., Acquarone, M., *et al.* 2017. Effects of Polar Bear and Killer Whale Derived Contaminant Cocktails on Marine Mammal Immunity. Environmental Science & Technology, 51(19): 11431–11439. https://doi.org/10.1021/acs.est.7b03532

Desforges, J-P. W., Galbraith, M., and Ross, P. S. 2015. Ingestion of Microplastics by Zooplankton in the Northeast Pacific Ocean. Archives of Environmental Contamination and Toxicology, 69(3): 320–330. https://doi.org/10.1007/s00244-015-0172-5

Desforges, J-P. W., Ross, P. S., Dangerfield, N., Palace, V. P., Whiticar, M., and Loseto, L. L. 2013. Vitamin A and E profiles as biomarkers of PCB exposure in beluga whales (*Delphinapterus leucas*) from the western Canadian Arctic. Aquatic Toxicology, 142–143: 317–328. https://doi.org/10.1016/j.aquatox.2013.08.004

Dewey, S., and Mackie, S. 2023. Managing Plastic Pollution in the Arctic Ocean: An Integrated Quantitative Flux Estimate and Policy Study. *Polar Record*, 59 (2023): e36.

Dhifallah, F., Rochon, A., Simard, N., McKindsey, C. W., Gosselin, M., and Howland, K. L. 2022. Dinoflagellate communities in high-risk Canadian Arctic ports. Estuarine, Coastal and Shelf Science, 266: 107731. https://doi.org/10.1016/j.ecss.2021.107731

Dietz, R., Desforges, J-P., Eulaers, I., Jenssen, B. M., Letcher, B. J., McKinney, M. A., and Sonne, C. 2018. Contaminant exposure and effects in a changing Arctic. *In* AMAP Assessment 2018: Biological Effects of Contaminants on Arctic Wildlife and Fish, pp. 3–4. Arctic Monitoring and Assessment Programme, Tromsø, Norway. https://www.amap.no/documents/download/3080/inline

Dietz, R., Letcher, R. J., Desforges, J-P., Eulaers, I., Sonne, C., Wilson, S., Andersen-Ranberg, E., *et al.* 2019. Current state of knowledge on biological effects from contaminants on Arctic wildlife and fish. Science of The Total Environment, 696: 133792. https://doi.org/10.1016/j.scitotenv.2019.133792

Dietz, R., Outridge, P. M., and Hobson, K. A. 2009. Anthropogenic contributions to mercury levels in present-day Arctic animals—A review. Science of The Total Environment, 407(24): 6120–6131. https://doi.org/10.1016/j.scitotenv.2009.08.036

Dietz, R., Sonne, C., Basu, N., Braune, B., O'Hara, T., Letcher, R. J., Scheuhammer, T., *et al.* 2013. What are the toxicological effects of mercury in Arctic biota? Science of The Total Environment, 443: 775–790. https://doi.org/10.1016/j.scitotenv.2012.11.046

Dodd, P. A., Nikolopoulos, A., Buckley, S., Campbell, K., Divine, D., Eggen, V., Gonçalves-Araujo, R., *et al.* 2022. Arctic Ocean 2022 cruise report. No. IMR Cruise ID 2022710, Toktrapporter/Cruise reports. Norsk Polarinstitutt. https://hdl.handle.net/11250/3013026

Dong, C., Bai, X., Sheng, H., Jiao, L., Zhou, H., and Shao, Z. 2015. Distribution of PAHs and the PAH-degrading bacteria in the deep-sea sediments of the high-latitude Arctic Ocean. Biogeosciences, 12(7): 2163–2177. https://doi.org/10.5194/bg-12-2163-2015

Doniol-Valcroze, T., Gosselin, J-F., Pike, D. G., Lawson, J. W., Asselin, N. C., Hedges, K., and Ferguson, S. H. 2020. Narwhal Abundance in the Eastern Canadian High Arctic in 2013. NAMMCO Scientific Publications, 11. https://doi.org/10.7557/3.5100

Douglas, T. A., Loseto, L. L., Macdonald, R. W., Outridge, P., Dommergue, A., Poulain, A., Amyot, M., *et al.* 2012. The fate of mercury in Arctic terrestrial and aquatic ecosystems, a review. Environmental Chemistry, 9(4): 321–355. https://doi.org/10.1071/EN11140

Drake, L. A., Doblin, M. A., and Dobbs, F. C. 2007. Potential microbial bioinvasions via ships' ballast water, sediment, and biofilm. Marine Pollution Bulletin, 55(7–9): 333–341. https://doi.org/10.1016/j.marpolbul.2006.11.007

Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., Erbe, C., *et al.* 2021. The soundscape of the Anthropocene ocean. Science, 371(6529): eaba4658. https://doi.org/10.1126/science.aba4658

Duarte, P., Assmy, P., Campbell, K., and Sundfjord, A. 2022. The importance of turbulent ocean–sea ice nutrient exchanges for simulation of ice algal biomass and production with CICE6.1 and Icepack 1.2. Geoscientific Model Development, 15(2): 841–857. https://doi.org/10.5194/gmd-15-841-2022

Dubey, J. P., Murata, F. H. A., Cerqueira-Cézar, C. K., Kwok, O. C. H., and Grigg, M. E. 2020. Recent epidemiologic and clinical importance of *Toxoplasma gondii* infections in marine mammals: 2009–2020. Veterinary Parasitology, 288: 109296. https://doi.org/10.1016/j.vetpar.2020.109296

Dudley, J. P., Ginsberg, J. R., Plumptre, A. J., Hart, J. A., and Campos, L. C. 2002. Effects of War and Civil Strife on Wildlife and Wildlife Habitats. Conservation Biology, 16(2): 319–329. https://doi.org/10.1046/j.1523-1739.2002.00306.x

Dumas, K., Gilg, O., Courbin, N., Corregidor-Castro, A., Evanno, G., Strøm, H., Mosbech, A., *et al.* 2022. Influence of sea-ice-related features and anthropogenic subsidies on the foraging behaviour of a high-Arctic seabird, the ivory gull (*Pagophila eburnea*). Marine Biology, 169(11): 151. https://doi.org/10.1007/s00227-022-04137-5

Duncan, R. J., Nielsen, D., Søreide, J. E., Varpe, Ø., Tobin, M. J., Pitusi, V., Heraud, P., *et al.* 2024. Biomolecular profiles of Arctic sea-ice diatoms highlight the role of under-ice light in cellular energy allocation. ISME Communications, 4(1): ycad010. https://doi.org/10.1093/ismeco/ycad010

Dziak, R. P., Bohnenstiehl, D. R., Stafford, K. M., Matsumoto, H., Park, M., Lee, W. S., Fowler, M. J., *et al.* 2015. Sources and Levels of Ambient Ocean Sound near the Antarctic Peninsula. PLOS One, 10(4): e0123425. https://doi.org/10.1371/journal.pone.0123425

Echeveste, P., Agustí, S., and Dachs, J. 2011. Cell size dependence of additive versus synergetic effects of UV radiation and PAHs on oceanic phytoplankton. Environmental Pollution, 159(5): 1307–1316. https://doi.org/10.1016/j.envpol.2011.01.023

Eckhardt, S., Breivik, K., Manø, S., and Stohl, A. 2007. Record high peaks in PCB concentrations in the Arctic atmosphere due to long-range transport of biomass burning emissions. Atmospheric Chemistry and Physics, 7(17): 4527–4536. https://doi.org/10.5194/acp-7-4527-2007

Edmonds, H. N., Michael, P. J., Baker, E. T., Connelly, D. P., Snow, J. E., Langmuir, C. H., Dick, H. J. B., *et al.* 2003. Discovery of abundant hydrothermal venting on the ultraslow-spreading Gakkel Ridge in the Arctic Ocean. Nature, 421(6920): 252–256. https://doi.org/10.1038/nature01351

Egardt, J., Nilsson, P., and Dahllöf, I. 2017. Sediments indicate the continued use of banned antifouling compounds. Marine Pollution Bulletin, 125(1–2): 282–288. https://doi.org/10.1016/j.marpolbul.2017.08.035

Ehrlich, J., Bluhm, B. A., Peeken, I., Massicotte, P., Schaafsma, F. L., Castellani, G., Brandt, A., *et al.* 2021. Sea-ice associated carbon flux in Arctic spring. Elementa: Science of the Anthropocene, 9(1): 00169. https://doi.org/10.1525/elementa.2020.00169

Ehrlich, J., Schaafsma, F. L., Bluhm, B. A., Peeken, I., Castellani, G., Brandt, A., and Flores, H. 2020. Sympagic Fauna in and Under Arctic Pack Ice in the Annual Sea-Ice System of the New Arctic. Frontiers in Marine Science, 7: 452. https://doi.org/10.3389/fmars.2020.00452

Ellison, W., Racca, R., Clark, C., Streever, B., Frankel, A., Fleishman, E., Angliss, R., *et al.* 2016. Modeling the aggregated exposure and responses of bowhead whales *Balaena mysticetus* to multiple sources of anthropogenic underwater sound. Endangered Species Research, 30: 95–108. https://doi.org/10.3354/esr00727

Elmore, S. A., Jones, J. L., Conrad, P. A., Patton, S., Lindsay, D. S., and Dubey, J. P. 2010. *Toxoplasma gondii*: epidemiology, feline clinical aspects, and prevention. Trends in Parasitology, 26(4): 190–196. https://doi.org/10.1016/j.pt.2010.01.009

Elwen, S. H., and Gridley, T. 2013. Gray whale (*Eschrichtius robustus*) sighting in Namibia (SE Atlantic) - first record for Southern Hemisphere. No. SC-65a-BRG30, Scientific Committee Meeting Document. International Whaling Commission. https://archive.iwc.int/?r=19280&k=ea60bac0f2

Engelhard, G. H., Peck, M. A., Rindorf, A., Smout, S. C., van Deurs, M., Raab, K., Andersen, K. H., *et al.* 2014. Forage fish, their fisheries, and their predators: who drives whom? *ICES Journal of Marine Science.*71 (1): 90-104. https://doi.org/10.1093/icesjms/fst087

Erbe, C., and Farmer, D. M. 2000. Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea. The Journal of the Acoustical Society of America, 108(3): 1332–1340. https://doi.org/10.1121/1.1288938

Eriksen, E. 2016. Do scyphozoan jellyfish limit the habitat of pelagic species in the Barents Sea during the late feeding period? ICES Journal of Marine Science, 73(2): 217–226. https://doi.org/10.1093/icesjms/fsv183

Eriksen, E., Skjoldal, H. R., Gjøsæter, H., and Primicerio, R. 2017. Spatial and temporal changes in the Barents Sea pelagic compartment during the recent warming. Progress in Oceanography, 151: 206–226. https://doi.org/10.1016/j.pocean.2016.12.009

Ershova, E. A., Kosobokova, K. N., Banas, N. S., Ellingsen, I., Niehoff, B., Hildebrandt, N., and Hirche, H. 2021. Sea ice decline drives biogeographical shifts of key *Calanus* species in the central Arctic Ocean. Global Change Biology, 27(10): 2128–2143. https://doi.org/10.1111/gcb.15562

Ershova, E., Hopcroft, R., Kosobokova, K., Matsuno, K., Nelson, R. J., Yamaguchi, A., and Eisner, L. 2015. Long-Term Changes in Summer Zooplankton Communities of the Western Chukchi Sea, 1945–2012. Oceanography, 28(3): 100–115. https://doi.org/10.5670/oceanog.2015.60

ESRI. 2024. Create Space Time Cube By Aggregating Points (Space Time Pattern Mining)—ArcGIS Pro | Documentation. https://pro.arcgis.com/en/pro-app/latest/tool-reference/space-time-pattern-mining/create-space-time-cube.htm (accessed 2024).

European Union. 2021. Arctic: Agreement to prevent unregulated fishing enters into force., European Commission: Oceans and Fisheries. https://oceans-and-fisheries.ec.europa.eu/news/arctic-agreement-prevent-unregulated-fishing-enters-force-2021-06-25_en

Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., and Stohl, A. 2020. Atmospheric transport is a major pathway of microplastics to remote regions. Nature Communications, 11(1): 3381. https://doi.org/10.1038/s41467-020-17201-9

Eyring, V., Isaksen, I. S. A., Berntsen, T., Collins, W. J., Corbett, J. J., Endresen, O., Grainger, R. G., *et al.* 2010. Transport impacts on atmosphere and climate: Shipping. Atmospheric Environment, 44(37): 4735–4771. https://doi.org/10.1016/j.atmosenv.2009.04.059

Eyring, V., Köhler, H. W., Lauer, A., and Lemper, B. 2005. Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. Journal of Geophysical Research: Atmospheres, 110(D17): 2004JD005620. https://doi.org/10.1029/2004JD005620

Ezhov, A., Gavrilo, M., Krasnov, Y., Bråthen, V., Moe, B., Baranskaya, A., and Strøm, H. 2021. Transpolar and bi-directional migration strategies of black-legged kittiwakes *Rissa tridactyla* from a colony in Novaya Zemlya, Barents Sea, Russia. Marine Ecology Progress Series, 676: 189–203. https://doi.org/10.3354/meps13889

Falk-Petersen, S., Mayzaud, P., Kattner, G., and Sargent, J. R. 2009. Lipids and life strategy of Arctic *Calanus*. Marine Biology Research, 5(1): 18–39. https://doi.org/10.1080/17451000802512267

Fang, C., Zheng, R., Hong, F., Jiang, Y., Chen, J., Lin, H., Lin, L., *et al.* 2021. Microplastics in three typical benthic species from the Arctic: Occurrence, characteristics, sources, and environmental implications. Environmental Research, 192: 110326. https://doi.org/10.1016/j.envres.2020.110326

Fang, C., Zheng, R., Zhang, Y., Hong, F., Mu, J., Chen, M., Song, P., *et al.* 2018. Microplastic contamination in benthic organisms from the Arctic and sub-Arctic regions. Chemosphere, 209: 298–306. https://doi.org/10.1016/j.chemosphere.2018.06.101

FAO. 1993. Agreement to promote compliance with international conservation and management measures by fishing vessels on the high seas (FAO Compliance Agreement). https://www.fao.org/iuu-fishing/international-framework/fao-compliance-agreement/en/ (accessed 2024).

FAO. 1995. Code of Conduct for Responsible Fisheries. https://www.fao.org/3/v9878e/v9878e00.htm (accessed 2024).

FAO. 2016. Agreement on port state measures to prevent, deter and eliminate illegal, unreported and unregulated fishing.

Félix, F., and van Waerebeek, K. 2005. Whale mortality from ship strikes in Ecuador and West Africa. Latin American Journal of Aquatic Mammals, 4(1): 55–60. https://doi.org/10.5597/lajam00070

Fernandez, L., Kaiser, B. A., and Vestergaard, N. 2014. Marine invasive species in the Arctic. No. 2014: 547, TemaNord. Nordic Council of Ministers. https://doi.org/10.6027/TN2014-547

Fernández-Gómez, B., Díez, B., Polz, M. F., Arroyo, J. I., Alfaro, F. D., Marchandon, G., Sanhueza, C., *et al.* 2019. Bacterial community structure in a sympagic habitat expanding with global warming: brackish ice brine at 85–90°N. The ISME Journal, 13(2): 316–333. https://doi.org/10.1038/s41396-018-0268-9

Finley, K. J., Miller, G. W., Davis, R. A., and Greene, C. R. 1990. Reactions of belugas, *Delphinapterus leucas*, and narwhals, *Monodon monoceros*, to ice-breaking ships in the Canadian high Arctic. *In* Advances in research on the beluga whale, *Delphinapterus leucas*, pp. 97–117. Ed. by T. G. Smith, D. J. St. Aubin, and J. R. Geraci. Canadian Bulletin of Fisheries and Aquatic Sciences, Fisheries and Oceans Canada, Ottawa. https://publications.gc.ca/collections/collection_2025/mpo-dfo/Fs94-224-eng.pdf

FISCAO. 2017. Final Report of the Fourth Meeting of Scientific Experts on Fish Stocks in the Central Arctic Ocean. Tromsø, Norway https://apps-afsc.fisheries.noaa.gov/documents/Arctic_fish_stocks_fourth_meeting/508_Documents/508_FourthFiSCAOreportfinalJan26_2017.pdf (accessed 2024).

Flores, H., David, C., Ehrlich, J., Hardge, K., Kohlbach, D., Lange, B. A., Niehoff, B., *et al.* 2019. Sea-ice properties and nutrient concentration as drivers of the taxonomic and trophic structure of high-Arctic protist and metazoan communities. Polar Biology, 42(7): 1377–1395. https://doi.org/10.1007/s00300-019-02526-z

Flores, H., van Franeker, J-A., Cisewski, B., Leach, H., Van de Putte, A. P., Meesters, E. (H. W. G.), Bathmann, U., *et al.* 2011. Macrofauna under sea ice and in the open surface layer of the Lazarev Sea, Southern Ocean. Deep Sea Research Part II: Topical Studies in Oceanography, 58(19–20): 1948–1961. https://doi.org/10.1016/j.dsr2.2011.01.010

Flores, H., Veyssière, G., Castellani, G., Wilkinson, J., Hoppmann, M., Karcher, M., Valcic, L., *et al.* 2023. Sea-ice decline could keep zooplankton deeper for longer. Nature Climate Change, 13(10): 1122–1130. https://doi.org/10.1038/s41558-023-01779-1

Flores, H., and Volckaert, F. 2020. Sympagic fish: species, population dynamics, distribution. *In* Review of the research knowledge and gaps on fish populations, fisheries and linked ecosystems in the Central Arctic Ocean (CAO), pp. 25–38. Ed. by P. Snoeijs-Leijonmalm, H. Flores, F. Volckaert, B. Niehoff, F. L. Schaafsma, J. Hjelm, J. Hentati-Sundberg, *et al.* EU Publications Office, Luxembourg. https://data.europa.eu/doi/10.2826/387890

Fort, J., Grémillet, D., Traisnel, G., Amélineau, F., and Bustamante, P. 2016. Does temporal variation of mercury levels in Arctic seabirds reflect changes in global environmental contamination, or a modification of Arctic marine food web functioning? Environmental Pollution, 211: 382–388. https://doi.org/10.1016/j.envpol.2015.12.061

Fort, J., Robertson, G. J., Grémillet, D., Traisnel, G., and Bustamante, P. 2014. Spatial Ecotoxicology: Migratory Arctic Seabirds Are Exposed to Mercury Contamination While Overwintering in the Northwest Atlantic. Environmental Science & Technology, 48(19): 11560–11567. https://doi.org/10.1021/es504045g

Fortune, S. M. E., Trites, A. W., LeMay, V., Baumgartner, M. F., and Ferguson, S. H. 2023. Year-round foraging across large spatial scales suggest that bowhead whales have the potential to adapt to climate change. Frontiers in Marine Science, 9: 853525. https://doi.org/10.3389/fmars.2022.853525

Fossheim, M., Primicerio, R., Johannesen, E., Ingvaldsen, R. B., Aschan, M. M., and Dolgov, A. V. 2015. Recent warming leads to a rapid borealization of fish communities in the Arctic. Nature Climate Change, 5(7): 673–677. https://doi.org/10.1038/nclimate2647

Fox, A. L., Hughes, E. A., Trocine, R. P., Trefry, J. H., Schonberg, S. V., McTigue, N. D., Lasorsa, B. K., *et al.* 2014. Mercury in the northeastern Chukchi Sea: Distribution patterns in seawater and sediments and biomagnification in the benthic food web. Deep Sea Research Part II: Topical Studies in Oceanography, 102: 56–67. https://doi.org/10.1016/j.dsr2.2013.07.012

Frainer, A., Primicerio, R., Kortsch, S., Aune, M., Dolgov, A. V., Fossheim, M., and Aschan, M. M. 2017. Climate-driven changes in functional biogeography of Arctic marine fish communities. Proceedings of the National Academy of Sciences, 114(46): 12202–12207.

Fransson, A., Bluhm, B., Arumi, M., Assmann, K., Gravelle, A., M. B., Bratrein, M., Buvik, K., *et al.* 2022. Joint cruise 2-2 2021: Cruise report. The Nansen Legacy Report Series, 30/2022. https://doi.org/10.7557/nlrs.6413

Frederiksen, M. 2017. Synthesis: Status and trends of Arctic marine biodiversity and monitoring. *In* State of the Arctic Marine Biodiversity Report, pp. 175–195. Conservation of Arctic Flora and Fauna International, Akureyri, Iceland. http://hdl.handle.net/11374/1945

Frederiksen, M., Mosbech, A., Andersson, A., Castro, A. C., Egevang, C., Fort, J., Grémillet, D., *et al.* 2019. Population size and habitat use of breeding seabirds in Northeast Greenland. Field studies 2017–18, Scientific Reports. DCE – Danish Centre for Environment and Energy, Aarhus University. https://dce.au.dk/udgivelser/vr/nr-301-350/abstracts/no-337-population-size-and-habitat-use-of-breeding-seabirds-in-northeast-greenland

Fretwell, P. T., Cubaynes, H. C., and Shpak, O. V. 2023. Satellite image survey of beluga whales in the southern Kara Sea. Marine Mammal Science, 39(4): 1204–1214. https://doi.org/10.1111/mms.13044

Frommel, A. Y., Maneja, R., Lowe, D., Malzahn, A. M., Geffen, A. J., Folkvord, A., Piatkowski, U., *et al.* 2012. Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. Nature Climate Change, 2(1): 42–46. https://doi.org/10.1038/nclimate1324

Frost, K. J., Lowry, L. F., and Carroll, G. 1993. Beluga whale and spotted seal use of a coastal lagoon system in the northeastern Chukchi Sea. Arctic, 46(1): 8–16. https://www.jstor.org/stable/40511357

Fuglestvedt, J., Berntsen, T., Eyring, V., Isaksen, I., Lee, D. S., and Sausen, R. 2009. Shipping Emissions: From Cooling to Warming of Climate—and Reducing Impacts on Health. Environmental Science & Technology, 43(24): 9057–9062. https://doi.org/10.1021/es901944r

Galand, P. E., Potvin, M., Casamayor, E. O., and Lovejoy, C. 2010. Hydrography shapes bacterial biogeography of the deep Arctic Ocean. The ISME Journal, 4(4): 564–576. https://doi.org/10.1038/ismej.2009.134

Gall, S. C., and Thompson, R. C. 2015. The impact of debris on marine life. Marine Pollution Bulletin, 92(1–2): 170–179. https://doi.org/10.1016/j.marpolbul.2014.12.041

Garde, E., Tervo, O. M., Sinding, M-H. S., Nielsen, N. H., Cornett, C., and Heide-Jørgensen, M. P. 2022. Biological parameters in a declining population of narwhals (*Monodon monoceros*) in Scoresby Sound, Southeast Greenland. Arctic Science, 8(2): 329–348. https://doi.org/10.1139/as-2021-0009

Gasol, J. M., and Kirchman, D. L. (Eds.). 2018. Microbial Ecology of the Oceans, Third edition. John Wiley & Sons/Blackwell, Hoboken, NJ.

Gavrilo, M. 2019. Plastic Pollution and Seabirds in the Russian Arctic, Workshop Report. Arctic Migratory Birds Initiative. Conservation of Arctic Flora and Fauna, Akureyri, Iceland. https://oaarchive.arctic-council.org/server/api/core/bitstreams/c390129c-06c9-4684-80d8-084dc348d958/content

Gavrilo, M., Kuletz, K. and Skjoldal, H. R. 2022. Marine birds: species occurrence and habitat use. *In* Ecosystem assessment of the Central Arctic Ocean: Description of the ecosystem, pp. 161–198. Ed. by H. R. Skjoldal. ICES Cooperative Research Report 365. https://doi.org/10.17895/ICES.PUB.20191787

Gazeau, F., Quiblier, C., Jansen, J. M., Gattuso, J., Middelburg, J. J., and Heip, C. H. R. 2007. Impact of elevated CO_2 on shellfish calcification. Geophysical Research Letters, 34(7): 2006GL028554. https://doi.org/10.1029/2006GL028554

Gencarelli, C., Hedgecock, I., Sprovieri, F., Schürmann, G., and Pirrone, N. 2014. Importance of Ship Emissions to Local Summertime Ozone Production in the Mediterranean Marine Boundary Layer: A Modeling Study. Atmosphere, 5(4): 937–958. https://doi.org/10.3390/atmos5040937

Geoffroy, M., Berge, J., Majaneva, S., Johnsen, G., Langbehn, T. J., Cottier, F., Mogstad, A. A., *et al.* 2018. Increased occurrence of the jellyfish *Periphylla periphylla* in the European high Arctic. Polar Biology, 41(12): 2615–2619. https://doi.org/10.1007/s00300-018-2368-4

Geoffroy, M., Bouchard, C., Flores, H., Robert, D., Gjøsæter, H., Hoover, C., Hop, H., *et al.* 2023. The circumpolar impacts of climate change and anthropogenic stressors on Arctic cod (*Boreogadus saida*) and its ecosystem. *Elementa: Science of the Anthropocene*, 11(1): 00097. https://doi.org/10.1525/elementa.2022.00097

George, J. C., Clark, C., Carroll, G. M., and Ellison, W. T. 1989. Observations on the Ice-Breaking and Ice Navigation Behavior of Migrating Bowhead Whales (*Balaena Mysticetus*) near Point Barrow, Alaska, Spring 1985. ARCTIC, 42(1): 24–30. https://doi.org/10.14430/arctic1636

George, J. C., Druckenmiller, M. L., Laidre, K. L., Suydam, R., and Person, B. 2015. Bowhead whale body condition and links to summer sea ice and upwelling in the Beaufort Sea. Progress in Oceanography, 136: 250–262. https://doi.org/10.1016/j.pocean.2015.05.001

George, J. C., Sheffield, G., Reed, D. J., Tudor, B., Stimmelmayr, R., Person, B. T., Sformo, T., *et al.* 2017. Frequency of Injuries from Line Entanglements, Killer Whales, and Ship Strikes on Bering–Chukchi–Beaufort Seas Bowhead Whales. ARCTIC, 70(1). https://doi.org/10.14430/arctic4631

George, J. C., and Thewissen, J. G. M. (Eds.). 2020. The Bowhead Whale: *Balaena mysticetus*: Biology and Human Interactions. Academic Press.

GESAMP. 2016. Sources, fate and effects of microplastics in the marine environment: part two of a global assessment. Ed. by P. J. Kershaw, and C. M. Rochman. (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Repports and Studies GESAMP No. 93. IMO, London. http://www.gesamp.org/site/assets/files/1275/sources-fate-and-effects-of-microplastics-in-the-marine-environment-part-2-of-a-global-assessment-en.pdf

Ghiglione, J-F., Galand, P. E., Pommier, T., Pedrós-Alió, C., Maas, E. W., Bakker, K., Bertilson, S., *et al.* 2012. Pole-to-pole biogeography of surface and deep marine bacterial communities. Proceedings of the National Academy of Sciences, 109(43): 17633–17638. https://doi.org/10.1073/pnas.1208160109

Gilg, O., Andreev, A., Aebischer, A., Kondratyev, A., Sokolov, A., and Dixon, A. 2016b. Satellite tracking of Ross's Gull *Rhodostethia rosea* in the Arctic Ocean. Journal of Ornithology, 157(1): 249–253. https://doi.org/10.1007/s10336-015-1273-7

Gilg, O., Istomina, L., Heygster, G., Strøm, H., Gavrilo, M. V., Mallory, M. L., Gilchrist, G., *et al.* 2016a. Living on the edge of a shrinking habitat: the ivory gull, *Pagophila eburnea*, an endangered sea-ice specialist. Biology Letters, 12(11): 20160277. https://doi.org/10.1098/rsbl.2016.0277

Gilg, O., Strøm, H., Aebischer, A., Gavrilo, M. V., Volkov, A. E., Miljeteig, C., and Sabard, B. 2010. Post-breeding movements of northeast Atlantic ivory gull *Pagophila eburnea* populations. Journal of Avian Biology, 41(5): 532–542. https://doi.org/10.1111/j.1600-048X.2010.05125.x

Gioia, R., Dachs, J., Nizzetto, L., Berrojalbiz, N., Galbán, C., Del Vento, S., Méjanelle, L., *et al.* 2011. Sources, Transport and Fate of Organic Pollutants in the Oceanic Environment. *In* Persistent Pollution – Past, Present and Future, pp. 111–139. Ed. by M. Quante, R. Ebinghaus, and G. Flöser. Springer, Berlin Heidelberg. https://doi.org/10.1007/978-3-642-17419-3_8

Gioia, R., Lohmann, R., Dachs, J., Temme, C., Lakaschus, S., Schulz-Bull, D., Hand, I., *et al.* 2008. Polychlorinated biphenyls in air and water of the North Atlantic and Arctic Ocean. Journal of Geophysical Research: Atmospheres, 113(D19): 2007JD009750. https://doi.org/10.1029/2007JD009750

Givens, G. H., George, J. C., Suydam, R., Tudor, B., Duyke, A. V., Person, B., and Scheimreif, K. 2021. Correcting the 2019 survey abundance of Bering–Chukchi–Beaufort Seas bowhead whales for disturbance from powered skiffs. Report submitted to the Scientific Committee of the International Whaling Commission No. SC/68C/ASI01. IWC.

Gjerdrum, C., Ronconi, R. A., Turner, K. L., and Hamer, T. E. 2021. Bird strandings and bright lights at coastal and offshore industrial sites in Atlantic Canada. Avian Conservation and Ecology, 16(1): art22. https://doi.org/10.5751/ACE-01860-160122

Gleason, J. D., Blum, J. D., Moore, T. C., Polyak, L., Jakobsson, M., Meyers, P. A., and Biswas, A. 2017. Sources and cycling of mercury in the paleo Arctic Ocean from Hg stable isotope variations in Eocene and Quaternary sediments. Geochimica et Cosmochimica Acta, 197: 245–262. https://doi.org/10.1016/j.gca.2016.10.033

Goethel, C. L., Grebmeier, J. M., Cooper, L. W., and Miller, T. J. 2017. Implications of ocean acidification in the Pacific Arctic: Experimental responses of three Arctic bivalves to decreased pH and food availability. Deep Sea Research Part II: Topical Studies in Oceanography, 144: 112–124. https://doi.org/10.1016/j.dsr2.2017.08.013

Goldsmit, J., McKindsey, C. W., Schlegel, R. W., Stewart, D. B., Archambault, P., and Howland, K. L. 2020. What and where? Predicting invasion hotspots in the Arctic marine realm. Global Change Biology, 26(9): 4752–4771. https://doi.org/10.1111/gcb.15159

Gollner, S., Kaiser, S., Menzel, L., Jones, D. O. B., Brown, A., Mestre, N. C., van Oevelen, D., *et al.* 2017. Resilience of benthic deep-sea fauna to mining activities. Marine Environmental Research, 129: 76–101. https://doi.org/10.1016/j.marenvres.2017.04.010

Good Morning America. 2024. Increased military operations in the Arctic. Good Morning America. 30

November 2024. https://www.youtube.com/watch?v=_TJYAYhlIwE

GO-SHIP Global Ocean Ship-Based Hydrographic Investigations Program. 2024. https://www.go-ship.org/ (accessed 2024).

Gradinger, R., Bluhm, B., and Iken, K. 2010. Arctic sea-ice ridges—Safe heavens for sea-ice fauna during periods of extreme ice melt? Deep Sea Research Part II: Topical Studies in Oceanography, 57(1–2): 86–95. https://doi.org/10.1016/j.dsr2.2009.08.008

Gradinger, R. R., and Bluhm, B. A. 2004. *In-situ* observations on the distribution and behavior of amphipods and Arctic cod (*Boreogadus saida*) under the sea ice of the High Arctic Canada Basin. Polar Biology, 27(10). https://doi.org/10.1007/s00300-004-0630-4

Gradinger, R. R., Meiners, K., Plumley, G., Zhang, Q., and Bluhm, B. A. 2005. Abundance and composition of the sea-ice meiofauna in off-shore pack ice of the Beaufort Gyre in summer 2002 and 2003. Polar Biology, 28(3): 171–181. https://doi.org/10.1007/s00300-004-0674-5

Grebmeier, J. M., and Barry, J. P. 2007. Chapter 11 Benthic Processes in Polynyas. *In* Volume 74: Polynyas: Windows to the World, Elsevier Oceanography Series, pp. 363–390. Ed. by W. O. Smith, and D. G. Barber. Elsevier. https://doi.org/10.1016/S0422-9894(06)74011-9

Grebmeier, J. M., and Jørgensen, L. L. 2022. Arctic benthos. *In* Ecosystem assessment of the Central Arctic Ocean: Description of the ecosystem, pp. 126–128. Ed. by H. R. Skjoldal. ICES Cooperative Research Reports Vol. 355. https://doi.org/10.17895/ices.pub.20191787

Groulx, M., Lemieux, C., Dawson, J., Stewart, E., and Yudina, O. 2016. Motivations to engage in last chance tourism in the Churchill Wildlife Management Area and Wapusk National Park: the role of place identity and nature relatedness. Journal of Sustainable Tourism, 24(11): 1523–1540. https://doi.org/10.1080/09669582.2015.1134556

Grubisic, M., Haim, A., Bhusal, P., Dominoni, D. M., Gabriel, K. M. A., Jechow, A., Kupprat, F., *et al.* 2019. Light Pollution, Circadian Photoreception, and Melatonin in Vertebrates. Sustainability, 11(22): 6400. https://doi.org/10.3390/su11226400

Grøsvik, B. E., Granberg, M. E., Kögel, T., Lusher, A. L., Gomiero, A., Halldorsson, H. P., Madsen, A. K., *et al.* 2022. Microplastics in Arctic invertebrates: status on occurrence and recommendations for future monitoring. Arctic Science, 9(1): 165–175. https://doi.org/10.1139/as-2022-0004

Grøsvik, B. E., Prokhorova, T., Eriksen, E., Krivosheya, P., Horneland, P. A., and Prozorkevich, D. 2018. Assessment of Marine Litter in the Barents Sea, a Part of the Joint Norwegian–Russian Ecosystem Survey. Frontiers in Marine Science, 5: 72. https://doi.org/10.3389/fmars.2018.00072

Gwynn, J., Heldal, H. E., Flo, J. K., Sværen, I., Gäfvert, T., Haanes, H., Føyn, L., *et al.* 2018. Norwegian monitoring (1990-2015) of the marine environment around the sunken nuclear submarine Komsomolets. Journal of Environmental Radioactivity, 182: 52–62. https://doi.org/10.1016/j.jenvrad.2017.11.015

Häder, D. P., and Gao, K. 2015. Interactions of anthropogenic stress factors on marine phytoplankton. Frontiers in Environmental Science, 3. https://doi.org/10.3389/fenvs.2015.00014

Hagen, D., Vistad, O., Eide, N. E., Flyen, A., and Fangel, K. 2012. Managing visitor sites in Svalbard: from a precautionary approach towards knowledge-based management. Polar Research, 31(1): 18432. https://doi.org/10.3402/polar.v31i0.18432

Hallanger, I. G., Ruus, A., Herzke, D., Warner, N. A., Evenset, A., Heimstad, E. S., Gabrielsen, G. W., *et al.* 2011a. Influence of season, location, and feeding strategy on bioaccumulation of halogenated organic contaminants in Arctic marine zooplankton. Environmental Toxicology and Chemistry, 30(1): 77–87. https://doi.org/10.1002/etc.362

Hallanger, I. G., Warner, N. A., Ruus, A., Evenset, A., Christensen, G., Herzke, D., Gabrielsen, G. W., *et al.* 2011b. Seasonality in contaminant accumulation in Arctic marine pelagic food webs using trophic magnification factor as a measure of bioaccumulation. Environmental Toxicology and Chemistry, 30(5): 1026–1035. https://doi.org/10.1002/etc.488

Hallanger, W. D., Barclay, D., Barkley, A. N., Cook, E., Dawson, J., Hilliard, R. C., Hussey, N. E., *et al.* 2021. Underwater sound levels in the Canadian Arctic, 2014–2019. Marine Pollution Bulletin, 168: 112437. https://doi.org/10.1016/j.marpolbul.2021.112437

Halliday, W. D., Pine, M. K., and Insley, S. J. 2020. Underwater noise and Arctic marine mammals: review and policy recommendations. Environmental Reviews, 28(4): 438–448. https://doi.org/10.1139/er-2019-0033

Halliday, W. D., Têtu, P-L., Dawson, J., Insley, S. J., and Hilliard, R. C. 2018. Tourist vessel traffic in important whale areas in the western Canadian Arctic: Risks and possible management solutions. Marine Policy, 97: 72–81. https://doi.org/10.1016/j.marpol.2018.08.035

Hamilton, C., Kovacs, K., and Lydersen, C. 2015a. Year-round haul-out behaviour of male walruses *Odobenus rosmarus* in the Northern Barents Sea. Marine Ecology Progress Series, 519: 251–263. https://doi.org/10.3354/meps11089

Hamilton, C., Lydersen, C., Aars, J., Biuw, M., Boltunov, A., Born, E., Dietz, R., *et al.* 2021. Marine mammal hotspots in the Greenland and Barents Seas. Marine Ecology Progress Series, 659: 3–28. https://doi.org/10.3354/meps13584

Hamilton, C. D., Lydersen, C., Ims, R. A., and Kovacs, K. M. 2015b. Predictions replaced by facts: a keystone species' behavioural responses to declining Arctic sea-ice. Biology Letters, 11(11): 20150803. https://doi.org/10.1098/rsbl.2015.0803

Hamilton, C., Lydersen, C., Ims, R., and Kovacs, K. 2016. Coastal habitat use by ringed seals *Pusa hispida* following a regional sea-ice collapse: importance of glacial refugia in a changing Arctic. Marine Ecology Progress Series, 545: 261–277. https://doi.org/10.3354/meps11598

Han, D., Joo, J., Son, W., Cho, K. H., Choi, J. W., Yang, E. J., Kim, J., *et al.* 2021. Effects of Geophony and Anthrophony on the Underwater Acoustic Environment in the East Siberian Sea, Arctic Ocean. Geophysical Research Letters, 48(12): e2021GL093097. https://doi.org/10.1029/2021GL093097

Hancke, K., Kristiansen, S., and Lund-Hansen, L. C. 2022. Highly Productive Ice Algal Mats in Arctic Melt Ponds: Primary Production and Carbon Turnover. Frontiers in Marine Science, 9: 841720. https://doi.org/10.3389/fmars.2022.841720

Hannah, L., Thornborough, K., Murray, C. C., Nelson, J., Locke, A., Mortimor, J., and Thornborough, K. 2020. Pathways of Effects Conceptual Models for Marine Commercial Shipping in Canada: Biological and Ecological Effects. No. 2020/077, Canadian Science Advisory Secretariat Research Documents. Canadian Science Advisory Secretariat. Ottawa, Canada.

Hänninen, J., Weckström, M., Pawłowska, J., Szymańska, N., Uurasjärvi, E., Zajaczkowski, M., Hartikainen, S., *et al.* 2021. Plastic debris composition and concentration in the Arctic Ocean, the North Sea and the Baltic Sea. Marine Pollution Bulletin, 165: 112150. https://doi.org/10.1016/j.marpolbul.2021.112150

Hardge, K., Peeken, I., Neuhaus, S., Lange, B. A., Stock, A., Stoeck, T., Weinisch, L., *et al.* 2017. The importance of sea ice for exchange of habitat-specific protist communities in the Central Arctic Ocean. Journal of Marine Systems, 165: 124–138. https://doi.org/10.1016/j.jmarsys.2016.10.004

Harris, I., Osborn, T. J., Jones, P. D., and Lister. D. 2014. Updated high-resolution grids of monthly climatic observations—The CRU TS3.10 Dataset. International Journal of Climatology, 34(3): 623–642. https://doi.org/10.1002/joc.3711

Harris, R. E., Miller, G. W., and Richardson, W. J. 2001. Seal response to airgun sounds during the summer seismic surveys in the Alaskan Beaufort Sea. Marine Mammal Science, 17(4): 795–812. https://doi.org/10.1111/j.1748-7692.2001.tb01299.x

Harrison, W. G., Børsheim, K. Y., Li, W. K. W., Maillet, G. L., Pepin, P., Sakshaug, E., Skogen, M. D., *et al.* 2013. Phytoplankton production and growth regulation in the Subarctic North Atlantic: A comparative study of the Labrador Sea–Labrador/Newfoundland shelves and Barents/Norwegian/Greenland seas and shelves. Progress in Oceanography, 114: 26–45. https://doi.org/10.1016/j.pocean.2013.05.003

Haug, T., Bogstad, B., Chierici, M., Gjøsæter, H., Hallfredsson, E. H., Høines, Å. S., Hoel, A. H., *et al.* 2017. Future harvest of living resources in the Arctic Ocean north of the Nordic and Barents Seas: A review of possibilities and constraints. Fisheries Research, 188: 38–57. https://doi.org/10.1016/j.fishres.2016.12.002

Hauser, D. D. W., Laidre, K. L., Stern, H. L., Suydam, R. S., and Richard, P. R. 2018. Indirect effects of sea ice loss on summer-fall habitat and behaviour for sympatric populations of an Arctic marine predator. Diversity and Distributions, 24(6): 791–799. https://doi.org/10.1111/ddi.12722

Hauser, D. D. W., Laidre, K. L., Suydam, R. S., and Richard, P. R. 2014. Population-specific home ranges and migration timing of Pacific Arctic beluga whales (*Delphinapterus leucas*). Polar Biology, 37(8): 1171–1183. https://doi.org/10.1007/s00300-014-1510-1

He, M., Yan, M., Chen, X., Wang, X., Gong, H., Wang, W., and Wang, J. 2022. Bioavailability and toxicity of microplastics to zooplankton. Gondwana Research, 108: 120–126. https://doi.org/10.1016/j.gr.2021.07.021

Hegseth, E. N., and Sundfjord, A. 2008. Intrusion and blooming of Atlantic phytoplankton species in the high Arctic. Journal of Marine Systems, 74(1–2): 108–119. https://doi.org/10.1016/j.jmarsys.2007.11.011

Hegseth, E. N., and von Quillfeldt, C. 2022. The Sub-Ice Algal Communities of the Barents Sea Pack Ice: Temporal and Spatial Distribution of Biomass and Species. Journal of Marine Science and Engineering, 10(2): 164. https://doi.org/10.3390/jmse10020164

Heide-Jørgensen, M. P., Blackwell, S. B., Tervo, O. M., Samson, A. L., Garde, E., Hansen, R. G., Ngô, M. C., *et al.* 2021. Behavioral Response Study on Seismic Airgun and Vessel Exposures in Narwhals. Frontiers in Marine Science, 8: 658173. https://doi.org/10.3389/fmars.2021.658173

Heide-Jørgensen, M. P., Blackwell, S. B., Williams, T. M., Sinding, M. H. S., Skovrind, M., Tervo, O. M., Garde, E., *et al.* 2020. Some like it cold: Temperature-dependent habitat selection by narwhals. Ecology and Evolution, 10(15): 8073–8090. https://doi.org/10.1002/ece3.6464

Heide-Jørgensen, M. P., Nielsen, N. H., Hansen, R. G., Schmidt, H. C., Blackwell, S. B., and Jørgensen, O. A. 2015. The predictable narwhal: satellite tracking shows behavioural similarities between isolated subpopulations. Journal of Zoology, 297(1): 54–65. https://doi.org/10.1111/jzo.12257

Helal, K. M., Fragasso, J., and Moro, L. 2024. Effectiveness of ocean gliders in monitoring ocean acoustics and anthropogenic noise from ships: A systematic review. Ocean Engineering, 295: 116993. https://doi.org/10.1016/j.oceaneng.2024.116993

HELCOM. 2018. The Sixth Pollution Load Compilation (PLC-6). Baltic Marine Environment Protection Commission, Helsinki. https://helcom.fi/post_type_publ/plc-6-executive-summary/

HELCOM. 2019. Noise sensitivity of animals in the Baltic Sea. No. 167, Baltic Sea Environment Underwater Noise Proceedings. Baltic Marine Environment Protection Commission, Helsinki.

Heldal, H. E., Gwynn, J., Teien, H-C., Volynkin, A., Jensen, L. K., Scheibener, S., and Epifanov, A. 2019. Cruise report: Investigation of the marine environment around the nuclear submarine "Komsomolets" 6–10 July 2019, Toktrapport. Havforskningsinstituttet.

Helm, R. C., Costa, D. P., DeBruyn, T. D., O'Shea, T. J., Wells, R. S., and Williams, T. M. 2014. Overview of Effects of Oil Spills on Marine Mammals. *In* Handbook of Oil Spill Science and Technology, pp. 455–475. Ed. by M. Fingas. Wiley. https://doi.org/10.1002/9781118989982.ch18

Herzke, D., Ghaffari, P., Sundet, J. H., Tranang, C. A., and Halsband, C. 2021. Microplastic Fiber Emissions from Wastewater Effluents: Abundance, Transport Behavior and Exposure Risk for Biota in an Arctic Fjord. Frontiers in Environmental Science, 9: 662168. https://doi.org/10.3389/fenvs.2021.662168

Hess-Erga, O-K., Moreno-Andrés, J., Enger, Ø., and Vadstein, O. 2019. Microorganisms in ballast water: Disinfection, community dynamics, and implications for management. Science of The Total Environment, 657: 704–716. https://doi.org/10.1016/j.scitotenv.2018.12.004

Hirai, H., Takada, H., Ogata, Y., Yamashita, R., Mizukawa, K., Saha, M., Kwan, C., *et al.* 2011. Organic micropollutants in marine plastics debris from the open ocean and remote and urban beaches. Marine Pollution Bulletin, 62(8): 1683–1692. https://doi.org/10.1016/j.marpolbul.2011.06.004

Ho, Q. T., Bank, M. S., Azad, A. M., Nilsen, B. M., Frantzen, S., Boitsov, S., Maage, A., *et al.* 2021. Co-occurrence of contaminants in marine fish from the North East Atlantic Ocean: Implications for human risk assessment. Environment International, 157: 106858. https://doi.org/10.1016/j.envint.2021.106858

Hobbs, L., Banas, N. S., Cohen, J. H., Cottier, F. R., Berge, J., and Varpe, Ø. 2021. A marine zooplankton community vertically structured by light across diel to interannual timescales. Biology Letters, 17(2): rsbl.2020.0810, 20200810. https://doi.org/10.1098/rsbl.2020.0810

Hobbs, R. C., Reeves, R. R., Prewitt, J. S., Desportes, G., Breton-Honeyman, K., Christensen, T., Citta, J. J., *et al.* 2019. Global Review of the Conservation Status of Monodontid Stocks. Marine Fisheries Review, No. 81. NOAA Fisheries. https://doi.org/10.7755/MFR.81.3–4.1

Hoekstra, P. F., O'Hara, T. M., Teixeira, C., Backus, S., Fisk, A. T., and Muir, D. C. G. 2002. Spatial trends and bioaccumulation of organochlorine pollutants in marine zooplankton from the Alaskan and Canadian Arctic. Environmental Toxicology and Chemistry, 21(3): 575–583. https://doi.org/10.1002/etc.5620210316

Hoffmann, L., Eggers, S. L., Allhusen, E., Katlein, C., and Peeken, I. 2020. Interactions between the ice algae *Fragillariopsis cylindrus* and microplastics in sea ice. Environment International, 139: 105697. https://doi.org/10.1016/j.envint.2020.105697

Holbech, H., and Pedersen, K. L. 2018. Ballast Water and Invasive Species in the Arctic. *In* Arctic Marine Resource Governance and Development, pp. 115–137. Ed. by N. Vestergaard, B. A. Kaiser, L. Fernandez, and J. Nymand Larsen. Springer International Publishing. https://doi.org/10.1007/978-3-319-67365-3_7

Hollowed, A. B., Planque, B., and Loeng, H. 2013. Potential movement of fish and shellfish stocks from the sub-Arctic to the Arctic Ocean. Fisheries Oceanography, 22(5): 355–370. https://doi.org/10.1111/fog.12027

Holte, B., Dahle, S., Gulliksen, B., and Næs, K. 1996. Some macrofaunal effects of local pollution and glacier-induced sedimentation, with indicative chemical analyses, in the sediments of two Arctic fjords. Polar Biology, 16(8): 549–557. https://doi.org/10.1007/BF02329051

Homeland Security. 2023. Military Operations Other Than War. Chapter 8. Homeland Security Digital Library. Department of Homeland Security, Washington, DC. (https://www.hsdl.org/?view&did=437411).

Hop, H., Assmy, P., Wold, A., Sundfjord, A., Daase, M., Duarte, P., Kwasniewski, S., *et al.* 2019. Pelagic Ecosystem Characteristics across the Atlantic Water Boundary Current from Rijpfjorden, Svalbard, to the Arctic Ocean during Summer (2010–2014). Frontiers in Marine Science, 6: 181. https://doi.org/10.3389/fmars.2019.00181

Hop, H., Borgå, K., Gabrielsen, G. W., Kleivane, L., and Skaare, J. U. 2002. Food Web Magnification of Persistent Organic Pollutants in Poikilotherms and Homeotherms from the Barents Sea. Environmental Science & Technology, 36(12): 2589–2597. https://doi.org/10.1021/es010231l

Hop, H., Poltermann, M., Lønne, O. J., Falk-Petersen, S., Korsnes, R., and Budgell, W. P. 2000. Ice amphipod distribution relative to ice density and under-ice topography in the northern Barents Sea. Polar Biology, 23(5): 357–367. https://doi.org/10.1007/s003000050456

Hop, H., Vihtakari, M., Bluhm, B. A., Assmy, P., Poulin, M., Gradinger, R., Peeken, I., *et al.* 2020. Changes in Sea-Ice Protist Diversity with Declining Sea Ice in the Arctic Ocean from the 1980s to 2010s. Frontiers in Marine Science, 7: 243. https://doi.org/10.3389/fmars.2020.00243

Hop, H., Vihtakari, M., Bluhm, B. A., Daase, M., Gradinger, R., and Melnikov, I. A. 2021a. Ice-Associated Amphipods in a Pan-Arctic Scenario of Declining Sea Ice. Frontiers in Marine Science, 8: 743152. https://doi.org/10.3389/fmars.2021.743152

Hop, H., Wold, A., Meyer, A., Bailey, A., Hatlebakk, M., Kwasniewski, S., Leopold, P., *et al.* 2021b. Winter-Spring Development of the Zooplankton Community Below Sea Ice in the Arctic Ocean. Frontiers in Marine Science, 8: 609480. https://doi.org/10.3389/fmars.2021.609480

Hopcroft, R. R., Clarke, C., Nelson, R. J., and Raskoff, K. A. 2005. Zooplankton communities of the Arctic's Canada Basin: the contribution by smaller taxa. Polar Biology, 28(3): 198–206. https://doi.org/10.1007/s00300-004-0680-7

Hoppe, C. J. M. 2022. Always ready? Primary production of Arctic phytoplankton at the end of the polar night. Limnology and Oceanography Letters, 7(2): 167–174. https://doi.org/10.1002/lol2.10222

Huang, Y., Zhang, W., Zhang, S., Jin, F., Fang, C., Ma, X., Wang, J., *et al.* 2022. Systematical insights into distribution and characteristics of microplastics in near-surface waters from the East Asian Seas to the Arctic Central Basin. Science of The Total Environment, 815: 151923. https://doi.org/10.1016/j.scitotenv.2021.151923

Hughes, K. A., and Ashton, G. V. 2017. Breaking the ice: the introduction of biofouling organisms to Antarctica on vessel hulls. Aquatic Conservation: Marine and Freshwater Ecosystems, 27(1): 158–164. https://doi.org/10.1002/aqc.2625

Hunt, G. L., Drinkwater, K. F., Arrigo, K., Berge, J., Daly, K. L., Danielson, S., Daase, M., *et al.* 2016. Advection in polar and sub-polar environments: Impacts on high latitude marine ecosystems. Progress in Oceanography, 149: 40–81. https://doi.org/10.1016/j.pocean.2016.10.004

Huntington, A., Corcoran, P. L., Jantunen, L., Thaysen, C., Bernstein, S., Stern, G. A., and Rochman, C. M. 2020. A first assessment of microplastics and other anthropogenic particles in Hudson Bay and the surrounding eastern Canadian Arctic waters of Nunavut. FACETS, 5(1): 432–454. https://doi.org/10.1139/facets-2019-0042

Huserbråten, M. B. O., Hattermann, T., Broms, C., and Albretsen, J. 2022. Trans-polar drift-pathways of riverine European microplastic. Scientific Reports, 12(1): 3016. https://doi.org/10.1038/s41598-022-07080-z

IASC (International Arctic Science Committee). 2022. https://iasc.info/ (accessed 2024).

IASSA (International Arctic Social Sciences Association). 2025. https://iassa.org/ (accessed 2024).

Ibarbalz, F. M., Henry, N., Mahé, F., Ardyna, M., Zingone, A., Scalco, E., Lovejoy, C., *et al.* 2023. Pan-Arctic plankton community structure and its global connectivity. Elementa: Science of the Anthropocene, 11(1): 00060. https://doi.org/10.1525/elementa.2022.00060

ICES. 1964. Convention for the International Council for the Exploration of the Sea. https://doi.org/10.17895/ices.pub.7533

ICES. 2020. ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean (WGICA). ICES Scientific Reports, No. 2:33. https://doi.org/10.17895/ices.pub.6001

ICES. 2021a. ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean (WGICA). ICES Scientific Reports, No. 2:79. http://doi.org/10.17895/ices.pub.8007

ICES. 2021b. Working Group on Shipping Impacts in the Marine Environment (WGSHIP). ICES Scientific Reports, No. 3:118. https://doi.org/10.17895/ices.pub.9672

ICES 2021c. Technical guidelines - ICES ecosystem overviews. *ICES technical Guidelines*. https://doi.org/10.17895/ices.advice.7916

ICES 2021d. Workshop on methods and guidelines to link human activities, pressures and state of the ecosystem in ecosystem overviews (WKTRANSPARENT; outputs from 2020 meeting). https://doi.org/10.17895/ices.pub.7930

ICES. 2022. Central Arctic Ocean ecoregion – Ecosystem Overview. In Report of the ICES Advisory Committee, 2022. ICES Advice 2022, Section 2.1. https://doi.org/10.17895/ices.advice.21731240

ICES. 2023a. ICES Ecosystem Overviews Technical Guidelines. Version 4. ICES Guidelines and Policies - Advice Technical Guidelines. 24 pp. https://doi.org/10.17895/ices.pub.22059803

ICES. 2023b. Integrated Ecosystem Assessment Steering Group. International Council for the Exploration of the Sea. Copenhagen. https://www.ices.dk/community/groups/Pages/IEASG.aspx

Iglesias-Merchan, C., Diaz-Balteiro, L., and Soliño, M. 2015. Transportation planning and quiet natural areas preservation: Aircraft overflights noise assessment in a National Park. Transportation Research Part D: Transport and Environment, 41: 1–12. https://doi.org/10.1016/j.trd.2015.09.006

Iken, K., Bluhm, B., and Gradinger, R. 2005. Food web structure in the high Arctic Canada Basin: evidence from δ^{13}C and $\boldsymbol{\delta^{15}}$**N** analysis. Polar Biology, 28(3): 238–249. https://doi.org/10.1007/s00300-004-0669-2

IMO. 1973. International Convention for the Prevention of Pollution from Ships (MARPOL). https://www.imo.org/en/about/conventions/pages/international-convention-for-the-prevention-of-pollution-from-ships-(marpol).aspx (accessed 2025)

IMO. 1974. International Convention for the Safety of Life at Sea (SOLAS). https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx (accessed 2024).

IMO. 2001. International Convention on the Control of Harmful Anti-fouling Systems on Ships. https://www.imo.org/en/About/Conventions/Pages/International-Convention-on-the-Control-of-Harmful-Anti-fouling-Systems-on-Ships-(AFS).aspx (accessed 2024).

IMO. 2004. International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM). https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Control-and-Management-of-Ships%27-Ballast-Water-and-Sediments-(BWM).aspx

IMO. 2014. International Code for Ships Operating in Polar Waters (Polar Code). https://www.imo.org/en/ourwork/safety/pages/polar-code.aspx

IMO. 2017. Global treaty to halt invasive aquatic species enters into force. International Maritime Organization. https://www.imo.org/en/MediaCentre/PressBriefings/Pages/21-BWM-EIF.aspx

IMO. 2020. IMO 2020 – cutting sulphur oxide emissions. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx

IMO. 2024. Ballast Water Management. https://www.imo.org/en/OurWork/Environment/Pages/BallastWaterManagement.aspx (accessed 2024).

Ingvaldsen, R. B., Eriksen, E., Gjøsæter, H., Engås, A., Schuppe, B. K., Assmann, K. M., Cannaby, H., *et al.* 2023. Under-ice observations by trawls and multi-frequency acoustics in the Central Arctic Ocean reveals abundance and composition of pelagic fauna. Scientific Reports, 13(1): 1000. https://doi.org/10.1038/s41598-023-27957-x

IPCC (Intergovernmental Panel on Climate Change). 2018. Summary for Policymakers — Global Warming of 1.5 °C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://www.ipcc.ch/sr15/chapter/spm/ (accessed 2024).

IPCC (Intergovernmental Panel on Climate Change). 2021. Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009157896

ITOPF. 2024. International Tanker Owners Pollution Federation Case studies. https://www.itopf.org/in-action/case-studies/.

Ivanova, S. V., Kessel, S. T., Espinoza, M., McLean, M. F., O'Neill, C., Landry, J., Hussey, N. E., *et al.* 2020. Shipping alters the movement and behavior of Arctic cod (*Boreogadus saida*), a keystone fish in Arctic marine ecosystems. Ecological Applications, 30(3): e02050. https://doi.org/10.1002/eap.2050

IWC. 2020. Report of the IWC Workshop on Marine Debris: The Way Forward, 3–5 December 2019, La Garriga, Catalonia, Spain. No. SC/68B/REP/03. https://archive.iwc.int/pages/view.php?ref=17025&k=33b414ef36 (accessed 2024).

Iyare, P. U., Vanderlip, H. L., Dias, M., Provencher, J. F., Zou, S., Lougheed, S. C., van Coeverden De Groot, P. J., *et al.* 2024. An assessment of microplastics in fecal samples from polar bears (*Ursus maritimus*) in Canada's North. Arctic Science, as-2023-0060. https://doi.org/10.1139/as-2023-0060

Jahn, A., Holland, M. M., and Kay, J. E. 2024. Projections of an ice-free Arctic Ocean. Nature Reviews Earth & Environment, 5(3): 164–176. https://doi.org/10.1038/s43017-023-00515-9

Jalkanen, J-P., Johansson, L., Liefvendahl, M., Bensow, R., Sigray, P., Östberg, M., Karasalo, I., *et al.* 2018. Modelling of ships as a source of underwater noise. Ocean Science, 14(6): 1373–1383. https://doi.org/10.5194/os-14-1373-2018

Jakobsson, M., Mayer, L. A., Bringensparr, C., Castro, C. F., Mohammad, R., Johnson, P., Ketter, T., *et al.* 2020. The International Bathymetric Chart of the Arctic Ocean Version 4.0. Scientific Data 7, 176 (2020). https://doi.org/10.1038/s41597-020-0520-9

Jalkanen, J-P., Johansson, L., Wilewska-Bien, M., Granhag, L., Ytreberg, E., Eriksson, K. M., Yngsell, D., *et al.* 2021. Modelling of discharges from Baltic Sea shipping. Ocean Science, 17(3): 699–728. https://doi.org/10.5194/os-17-699-2021

Jardine, A. M., Matthews, C. J. D., Provencher, J. F., Hornby, C., Gamberg, M., Bourdages, M. P. T., Alexander, D., *et al.* 2023. No microplastics detected in the first assessment of Atlantic walrus stomachs from Nunavut, Canada. Arctic Science, 10.1139/AS-2023-0002. https://doi.org/10.1139/as-2023-0002

Jay, C., Fischbach, A., and Kochnev, A. 2012. Walrus areas of use in the Chukchi Sea during sparse sea ice cover. Marine Ecology Progress Series, 468: 1–13. https://doi.org/10.3354/meps10057

Jensen, F. B., Kuperman, W. A., Porter, M. B., and Schmidt, H. (Eds.). 1994. Computational Ocean Acoustics, 1st ed, AIP series in modern acoustics and signal processing. AIP Press, New York, NY.

Jensen, L. K., Shpinkov, V., Heldal, H. E., Gwynn, J., Møller, B., Bulgakov, V., Katkova, M., *et al.* 2017. 10 years of joint monitoring of radioactive substances in the Barents Sea. 2006-2015. https://www.dsa.no/publikasjoner/10-years-of-joint-monitoring-of-radioactive-substances-in-the-barents-sea/10%20years%20of%20joint%20monitoring%20of%20radioactive%20substances%20in%20the%20Barents%20Sea.pdf

Jensen, S. K., Aars, J., Lydersen, C., Kovacs, K. M., and Åsbakk, K. 2010. The prevalence of *Toxoplasma gondii* in polar bears and their marine mammal prey: evidence for a marine transmission pathway? Polar Biology, 33(5): 599–606. https://doi.org/10.1007/s00300-009-0735-x

Jin, M., Fu, J., Xue, B., Zhou, S., Zhang, L., and Li, A. 2017. Distribution and enantiomeric profiles of organochlorine pesticides in surface sediments from the Bering Sea, Chukchi Sea and adjacent Arctic areas. Environmental Pollution, 222: 109–117. https://doi.org/10.1016/j.envpol.2016.12.075

Joerss, H., Xie, Z., Wagner, C. C., Von Appen, W. J., Sunderland, E. M. and Ebinghaus, R. 2020. Transport of Legacy Perfluoroalkyl Substances and the Replacement Compound HFPO-DA through the Atlantic Gateway to the Arctic Ocean—Is the Arctic a Sink or a Source?. Environmental science & technology, 54(16): 9958–9967.

Johannesen, E., Jørgensen, L. L., Fossheim, M., Primicerio, R., Greenacre, M., Ljubin, P. A., Dolgov, A. V., *et al.* 2017. Large-scale patterns in community structure of benthos and fish in the Barents Sea. Polar Biology, 40(2): 237–246. https://doi.org/10.1007/s00300-016-1946-6

Johansen, S., Larsen, O. N., Christensen-Dalsgaard, J., Seidelin, L., Huulvej, T., Jensen, K., Lunneryd, S-G., *et al.* 2016. In-Air and Underwater Hearing in the Great Cormorant (*Phalacrocorax carbo sinensis*). *In* The Effects of Noise on Aquatic Life II, pp. 505–512. Ed. by A. N. Popper, and A. Hawkins. Advances in Experimental Medicine and Biology. Springer New York, New York, NY. https://doi.org/10.1007/978-1-4939-2981-8_61

Johnson, A. C., and Derocher, A. E. 2020. Variation in habitat use of Beaufort Sea polar bears. Polar Biology, 43(9): 1247–1260. https://doi.org/10.1007/s00300-020-02705-3

Johnson, H. J., and Koshy, A. A. 2020. Latent Toxoplasmosis Effects on Rodents and Humans: How Much is Real and How Much is Media Hype? mBio, 11(2): e02164-19. https://doi.org/10.1128/mBio.02164-19

Jones, D. O. B., Kaiser, S., Sweetman, A. K., Smith, C. R., Menot, L., Vink, A., Trueblood, D., *et al.* 2017. Biological responses to disturbance from simulated deep-sea polymetallic nodule mining. PLOS One, 12(2): e0171750. https://doi.org/10.1371/journal.pone.0171750

Jones, J. M. 2021. Underwater soundscape and radiated noise from ships in Eclipse Sound, NE Canadian Arctic. Report prepared for the Nunavut Impact Review Board (NIRB) and submitted to the NIRB by Oceans North on January 18, 2021. No. MPLTM651, Marine Physical Laboratory Technical Memorandum. Scripps Institution of Oceanography, LaJolla, CA, USA. https://thenarwhal.ca/wp-content/uploads/2021/02/JJONES_EclipseSound_Soundscape-and-ship-noise-compressed.pdf

Jonsson, S., Mastromonaco, M.N., Wang, F., Bravo, A.G., Cairns, W.R., Chételat, J., Douglas, T.A., Lescord, G., Ukonmaanaho, L. and Heimbürger-Boavida, L.E., 2022. Arctic methylmercury cycling. Science of the Total Environment, 850, p.157445. https://doi.org/10.1016/j.scitotenv.2022.157445

Joo, H. M., Lee, S. H., Jung, S. W., Dahms, H-U., and Lee, J. H. 2012. Latitudinal variation of phytoplankton communities in the western Arctic Ocean. Deep-Sea Research II, 81–84: 3–17. https://doi.org/10.1016/j.dsr2.2011.06.004

Jordà-Molina, È., Sen, A., Bluhm, B. A., Renaud, P. E., Włodarska-Kowalczuk, M., Legeżyńska, J., Oleszczuk, B., *et al.* 2023. Lack of strong seasonality in macrobenthic communities from the northern Barents Sea shelf and Nansen Basin. Progress in Oceanography, 219: 103150. https://doi.org/10.1016/j.pocean.2023.103150

Josefson, A. B., Hansen, J. L. S., Asmund, G., and Johansen, P. 2008. Threshold response of benthic macrofauna integrity to metal contamination in West Greenland. Marine Pollution Bulletin, 56(7): 1265–1274. https://doi.org/10.1016/j.marpolbul.2008.04.028

Jæger, I., Hop, H., and Gabrielsen, G. W. 2009. Biomagnification of mercury in selected species from an Arctic marine food web in Svalbard. Science of The Total Environment, 407(16): 4744–4751. https://doi.org/10.1016/j.scitotenv.2009.04.004

Jørgensen, L. L., *et al.* Submitted. Ecosystem risks from human activities in the fast-changing Central Arctic Ocean.

Jørgensen, L. L., Bakke, G., and Hoel, A. H. 2020. Responding to global warming: New fisheries management measures in the Arctic. Progress in Oceanography, 188: 102423. https://doi.org/10.1016/j.pocean.2020.102423

Jørgensen, L.L., Planque, B., Thangstad, T.H. and Certain, G. 2016. Vulnerability of megabenthic species to trawling in the Barents Sea. ICES Journal of Marine Science, 73(suppl. 1): i84–i97. https://doi.org/10.1093/icesjms/fsv107

Jørgensen, L., Primicerio, R., Ingvaldsen, R., Fossheim, M., Strelkova, N., Thangstad, T., Manushin, I., *et al.* 2019. Impact of multiple stressors on sea bed fauna in a warming Arctic. Marine Ecology Progress Series, 608: 1–12. https://doi.org/10.3354/meps12803

Kahkashan, S., Wang, X., Chen, J., Bai, Y., Ya, M., Wu, Y., Cai, Y., *et al.* 2019. Concentration, distribution and sources of perfluoroalkyl substances and organochlorine pesticides in surface sediments of the northern Bering Sea, Chukchi Sea and adjacent Arctic Ocean. Chemosphere, 235: 959–968. https://doi.org/10.1016/j.chemosphere.2019.06.219

Kanhai, L. D. K., Gardfeldt, K., Krumpen, T., Thompson, R. C., and O'Connor, I. 2020. Microplastics in sea ice and seawater beneath ice floes from the Arctic Ocean. Scientific Reports, 10(1): 5004. https://doi.org/10.1038/s41598-020-61948-6

Kanhai, L. D. K., Johansson, C., Frias, J. P. G. L., Gardfeldt, K., Thompson, R. C., and O'Connor, I. 2019. Deep sea sediments of the Arctic Central Basin: A potential sink for microplastics. Deep Sea Research Part I: Oceanographic Research Papers, 145: 137–142. https://doi.org/10.1016/j.dsr.2019.03.003

Kapsar, K., Gunn, G., Brigham, L., Liu, J. 2023. Mapping vessel traffic patterns in the ice-covered waters of the Pacific Arctic. Climatic Change 176: 94.

Karl, H., Kamman, U., Aust, M-O., Manthey-Karl, M., Lüth, A., and Kanisch, G. 2016. Large scale distribution of dioxins, PCBs, heavy metals, PAH-metabolites and radionuclides in cod (*Gadus morhua*) from the North Atlantic and its adjacent seas. Chemosphere, 149: 294–303. https://doi.org/10.1016/j.chemosphere.2016.01.052

Karlsen, J., Bisther, A., Lydersen, C., Haug, T., and Kovacs, K. 2002. Summer vocalisations of adult male white whales (*Delphinapterus leucas*) in Svalbard, Norway. Polar Biology, 25(11): 808–817. https://doi.org/10.1007/s00300-002-0415-6

Karpovich, S. A., Skinner, J. P., Mondragon, J. E., and Blundell, G. M. 2015. Combined physiological and behavioral observations to assess the influence of vessel encounters on harbor seals in glacial fjords of southeast Alaska. Journal of Experimental Marine Biology and Ecology, 473: 110–120. https://doi.org/10.1016/j.jembe.2015.07.016

Katsuki, K., Takahashi, K., Onodera, J., Jordan, R. W., and Suto, I. 2009. Living diatoms in the vicinity of the North Pole, summer 2004. Micropaleontology, 55(2–3): 137–170. https://doi.org/10.47894/mpal.55.2.04

Kelly, B. C., Ikonomou, M. G., Blair, J. D., Surridge, B., Hoover, D., Grace, R., and Gobas, F. A. P. C. 2009. Perfluoroalkyl Contaminants in an Arctic Marine Food Web: Trophic Magnification and Wildlife Exposure. Environmental Science & Technology, 43(11): 4037–4043. https://doi.org/10.1021/es9003894

Kim, S-K., Lee, H-J., Kim, J-S., Kang, S-H., Yang, E-J., Cho, K-H., Tian, Z., *et al.* 2021. Importance of seasonal sea ice in the western Arctic ocean to the Arctic and global microplastic budgets. Journal of Hazardous Materials, 418: 125971. https://doi.org/10.1016/j.jhazmat.2021.125971

Kipp, L. E., Charette, M. A., Moore, W. S., Henderson, P. B., and Rigor, I. G. 2018. Increased fluxes of shelf-derived materials to the central Arctic Ocean. Science Advances, 4(1): 1302. https://doi.org/10.1126/sciadv.aao1302

Kirk, C. M., Amstrup, S., Swor, R., Holcomb, D., and O'Hara, T. M. 2010. Morbillivirus and Toxoplasma Exposure and Association with Hematological Parameters for Southern Beaufort Sea Polar Bears: Potential Response to Infectious Agents in a Sentinel Species. EcoHealth, 7(3): 321–331. https://doi.org/10.1007/s10393-010-0323-0

Kishida, T., and Thewissen, J. G. M. 2012. Evolutionary changes of the importance of olfaction in cetaceans based on the olfactory marker protein gene. Gene, 492(2): 349–353. https://doi.org/10.1016/j.gene.2011.11.013

Klages, M., Boetius, A., Christensen, J. P., Deubel, H., Piepenburg, D., Schewe, I., and Soltwedel, T. 2004. The Benthos of Arctic Seas and its Role for the Organic Carbon Cycle at the Seafloor. *In* The Organic Carbon Cycle in the Arctic Ocean, pp. 139–167. Ed. by R. Stein, and R. W. MacDonald. Springer, Berlin Heidelberg. https://doi.org/10.1007/978-3-642-18912-8_6

Knutsen, H., Cyvin, J. B., Totland, C., Lilleeng, Ø., Wade, E. J., Castro, V., Pettersen, A., *et al.* 2020. Microplastic accumulation by tube-dwelling, suspension feeding polychaetes from the sediment surface: A case study from the Norwegian Continental Shelf. Marine Environmental Research, 161: 105073. https://doi.org/10.1016/j.marenvres.2020.105073

Koch, C. W., Brown, T. A., Amiraux, R., Ruiz-Gonzalez, C., MacCorqucodale, M., Yunda-Guarin, G. A., Kohlback, D., *et al.* 2023, Year-round utilization of sea ice-associated carbon in Arctic ecosystems. Nature Communications, 14, 1964 (2023). https://doi.org/10.1038/s41467-023-37612-8

Koelmans, A. A., Besseling, E., and Shim, W. J. 2015. Nanoplastics in the Aquatic Environment. Critical Review. *In* Marine Anthropogenic Litter, pp. 325–340. Ed. by M. Bergmann, L. Gutow, and M. Klages. Springer International Publishing. https://doi.org/10.1007/978-3-319-16510-3_12

Kohlbach, D., Graeve, M., A. Lange, B., David, C., Peeken, I., and Flores, H. 2016. The importance of ice algae-produced carbon in the central Arctic Ocean ecosystem: Food web relationships revealed by lipid and stable isotope analyses: Ice algal carbon in Arctic food web. Limnology and Oceanography, 61(6): 2027–2044. https://doi.org/10.1002/lno.10351

Kohlbach, D., Schaafsma, F. L., Graeve, M., Lebreton, B., Lange, B. A., David, C., Vortkamp, M., *et al.* 2017. Strong linkage of polar cod (*Boreogadus saida*) to sea ice algae-produced carbon: Evidence from stomach content, fatty acid and stable isotope analyses. Progress in Oceanography, 152: 62–74. https://doi.org/10.1016/j.pocean.2017.02.003

Kohler, S. G., Heimbürger-Boavida, L. E., Petrova, M. V., Digernes, M. G., Sanchez, N., Dufour, A., Simić, A., *et al.* 2022. Arctic Ocean's wintertime mercury concentrations limited by seasonal loss on the shelf. Nature Geoscience, 1–6. https://doi.org/10.1038/s41561-022-00986-3

Kortsch, S., Primicerio, R., Fossheim, M., Dolgov, A. V., and Aschan, M. 2015. Climate change alters the structure of arctic marine food webs due to poleward shifts of boreal generalists. Proceedings of the Royal Society B: Biological Sciences, 282(1814): 20151546. https://doi.org/10.1098/rspb.2015.1546

Koski, W. R., Funk, D. W., and Ireland, D. S. 2009. An update on feeding by bowhead whales near an offshore seismic survey in the Central Beaufort Sea. No. SC/61/BRG3. https://www.north-slope.org/wp-content/uploads/2022/03/feeding-bowhead-whales-near-Offshore-Seismic-in-Beaufort-Sea.pdf

Kosobokova, K., and Hirche, H-J. 2000. Zooplankton distribution across the Lomonosov Ridge, Arctic Ocean: species inventory, biomass and vertical structure. Deep Sea Research Part I: Oceanographic Research Papers, 47(11): 2029–2060. https://doi.org/10.1016/S0967-0637(00)00015-7

Kosobokova, K. N. 2003. Regional Features of Quantitative Distribution of Zooplankton in the Arctic Basin. Doklady Earth Sciences, 392(2): 986–989.

Kosobokova, K. N., Hanssen, H., Hirche, H-J., and Knickmeier, K. 1997. Composition and distribution of zooplankton in the Laptev Sea and adjacent Nansen Basin during summer, 1993. Polar Biology, 19(1): 63–76. https://doi.org/10.1007/s003000050216

Kosobokova, K. N., Hopcroft, R. R., and Hirche, H-J. 2011. Patterns of zooplankton diversity through the depths of the Arctic's central basins. Marine Biodiversity, 41(1): 29–50. https://doi.org/10.1007/s12526-010-0057-9

Kovacs, K. M., Lydersen, C., Vacquiè-Garcia, J., Shpak, O., Glazov, D., and Heide-Jørgensen, M. P. 2020. The endangered Spitsbergen bowhead whales' secrets revealed after hundreds of years in hiding. Biology Letters, 16(6): 20200148. https://doi.org/10.1098/rsbl.2020.0148

Krapp, R. H., Bassinet, T., Berge, J., Pampanin, D. M., and Camus, L. 2009. Antioxidant responses in the polar marine sea-ice amphipod *Gammarus wilkitzkii* to natural and experimentally increased UV levels. Aquatic Toxicology, 94(1): 1–7. https://doi.org/10.1016/j.aquatox.2009.05.005

Kröncke, I. 1994. Macrobenthos composition, abundance and biomass in the Arctic Ocean along a transect between Svalbard and the Makarov Basin. Polar Biology, 14(8). https://doi.org/10.1007/BF00238221

Kröncke, I., Vanreusel, A., Vincx, M., Wollenburg, J., Mackensen, A., Liebezeit, G., and Behrends, B. 2000. Different benthic size-compartments and their relationship to sediment chemistry in the deep Eurasian Arctic Ocean. Marine Ecology Progress Series, 199: 31–41. https://doi.org/10.3354/meps199031

Krüger, L., V. H. Paiva, M. V. Petry, and J. A. Ramos. 2017.Strange lights in the nights: using abnormal peaks of light in geolocator data to infer interaction of seabirds with nocturnal fishing vessels. *Polar Biology* 40:221-226. https://doi.org/10.1007/

Krumpen, T., Belter, H. J., Boetius, A., Damm, E., Haas, C., Hendricks, S., Nicolaus, M., *et al.* 2019. Arctic warming interrupts the Transpolar Drift and affects long-range transport of sea ice and ice-rafted matter. Scientific Reports, 9(1): 5459. https://doi.org/10.1038/s41598-019-41456-y

Kühn, S., Bravo Rebolledo, E. L., and van Franeker, J. A. 2015. Deleterious Effects of Litter on Marine Life. *In* Marine Anthropogenic Litter, pp. 75–116. Ed. by M. Bergmann, L. Gutow, and M. Klages. Springer International Publishing. https://doi.org/10.1007/978-3-319-16510-3_4

Kühn, S., Schaafsma, F. L., Van Werven, B., Flores, H., Bergmann, M., Egelkraut-Holtus, M., Tekman, M. B., *et al.* 2018. Plastic ingestion by juvenile polar cod (*Boreogadus saida*) in the Arctic Ocean. Polar Biology, 41(6): 1269–1278. https://doi.org/10.1007/s00300-018-2283-8

Kühn, S., and van Franeker, J. A. 2020. Quantitative overview of marine debris ingested by marine megafauna. Marine Pollution Bulletin, 151: 110858. https://doi.org/10.1016/j.marpolbul.2019.110858

Kuletz, K., Cushing, D., and Labunski, E. 2020. Distributional shifts among seabird communities of the Northern Bering and Chukchi seas in response to ocean warming during 2017–2019. Deep Sea Research Part II: Topical Studies in Oceanography, 181–182: 104913. https://doi.org/10.1016/j.dsr2.2020.104913

Kunisch, E. H., Bluhm, B. A., Daase, M., Gradinger, R., Hop, H., Melnikov, I. A., Varpe, Ø., *et al.* 2020. Pelagic occurrences of the ice amphipod *Apherusa glacialis* throughout the Arctic. Journal of Plankton Research, 42(1): 73–86. https://doi.org/10.1093/plankt/fbz072

Kunz, K. L., Claireaux, G., Pörtner, H-O., Knust, R., and Mark, F. C. 2018. Aerobic capacities and swimming performance of Polar cod (*Boreogadus saida* Lepechin) under ocean acidification and warming conditions. Journal of Experimental Biology, jeb.184473. https://doi.org/10.1242/jeb.184473

Kunz, K. L., Frickenhaus, S., Hardenberg, S., Johansen, T., Leo, E., Pörtner, H-O., Schmidt, M., *et al.* 2016. New encounters in Arctic waters: a comparison of metabolism and performance of polar cod (*Boreogadus saida*) and Atlantic cod (*Gadus morhua*) under ocean acidification and warming. Polar Biology, 39(6): 1137–1153. https://doi.org/10.1007/s00300-016-1932-z

Kutschale, H. 1969. Arctic Hydroacoustics. ARCTIC, 22(3): 246–264. https://doi.org/10.14430/arctic3218

Kvadsheim, P. H., Forland, T. N., de Jong, K., Nyqvist, D., Grimsbø, E., and Sivle L. D. 2020. Effekter av støyforurensning på havmiljø – kunnskapsstatus og forvaltningsrådgiving. No. 20/01015, FFI-RAPPORT. Kjeller, Norway: Forsvarets forskningsinstitutt/Havforskningsinstituttet. https://www.miljodirektoratet.no/globalassets/publikasjoner/m1670/m1670.pdf

Kvadsheim, P. H., Sevaldsen, E. M., Folkow, L. P., and Blix, A. S. 2010. Behavioural and Physiological Responses of Hooded Seals (*Cystophora cristata*) to 1 to 7 kHz Sonar Signals. Aquatic Mammals, 36(3): 239–247. https://doi.org/10.1578/AM.36.3.2010.239

Kvernvik, A. C., Rokitta, S. D., Leu, E., Harms, L., Gabrielsen, T. M., Rost, B., and Hoppe, C. J. M. 2020. Higher sensitivity towards light stress and ocean acidification in an Arctic sea-ice-associated diatom compared to a pelagic diatom. New Phytologist, 226(6): 1708–1724. https://doi.org/10.1111/nph.16501

Kylin, H., and Haglund, K. 2010. Screening of Antifouling Biocides around a Pleasure Boat Marina in the Baltic Sea After Legal Restrictions. Bulletin of Environmental Contamination and Toxicology, 85(4): 402–406. https://doi.org/10.1007/s00128-010-0094-x

La Sorte, F. A., and Jetz, W. 2010. Avian distributions under climate change: towards improved projections. Journal of Experimental Biology, 213(6): 862–869. https://doi.org/10.1242/jeb.038356

Labunski, E. A., Kuletz, K. J., Lanctot, R., Saalfeld, S., Morgan, T. C., McGuire, R. L., and Gall, A. E. 2022. Marine Bird Distribution and Abundance in the Northern Bering and Chukchi Seas: Final Report. No. AK-17-03, BOEM Environmental Studies. Bureau of Ocean Energy Management, Anchorage, AK. https://espis.boem.gov/Final%20Reports/BOEM_2022-067.pdf

Laget, F. 2017. Transport of potentially non-native dinoflagellate species to the Canadian Arctic following ballast water discharge from a domestic vessel. Dissertation. University of Quebec at Rimouski, Rimouski Institute of Marine Sciences. 138 pp. https://semaphore.uqar.ca/id/eprint/1342/1/Frederic_Laget_octobre2017.pdf

Lagerström, M., Ferreira, J., Ytreberg, E., and Eriksson-Wiklund, A-K. 2020a. Flawed risk assessment of antifouling paints leads to exceedance of guideline values in Baltic Sea marinas. Environmental Science and Pollution Research, 27(22): 27674–27687. https://doi.org/10.1007/s11356-020-08973-0

Lagerström, M., Ytreberg, E., Wiklund, A-K. E., and Granhag, L. 2020b. Antifouling paints leach copper in excess – study of metal release rates and efficacy along a salinity gradient. Water Research, 186: 116383. https://doi.org/10.1016/j.watres.2020.116383

Laidre, K. L., and Stirling, I. 2020. Grounded icebergs as maternity denning habitat for polar bears (*Ursus maritimus*) in North and Northeast Greenland. Polar Biology, 43(7): 937–943. https://doi.org/10.1007/s00300-020-02695-2

Laiolo, P. 2010. The emerging significance of bioacoustics in animal species conservation. Biological Conservation, 143(7): 1635–1645. https://doi.org/10.1016/j.biocon.2010.03.025

Laney, H., and Cavanagh, R. C. 2000. Supersonic Aircraft Noise at and beneath the Ocean Surface: Estimation of Risk for Effects on Marine Mammals. Interim Report for the Period October 1996 to April 2000. No. AFRL-HE-WP-TR-2000-0167. United States Air Force Research Laboratory. https://apps.dtic.mil/sti/tr/pdf/ADA395062.pdf

Larsson, P., Andersson, A., Broman, D., Nordbäck, J., and Lundberg, E. 2000. Persistent Organic Pollutants (POPs) in Pelagic Systems. AMBIO: A Journal of the Human Environment, 29(4): 202–209. https://doi.org/10.1579/0044-7447-29.4.202

Last, K. S., Hobbs, L., Berge, J., Brierley, A. S., and Cottier, F. 2016. Moonlight Drives Ocean-Scale Mass Vertical Migration of Zooplankton during the Arctic Winter. Current Biology, 26(2): 244–251. https://doi.org/10.1016/j.cub.2015.11.038

Lavrentyev, P. J., Franzè, G., and Moore, F. B. 2019. Microzooplankton Distribution and Dynamics in the Eastern Fram Strait and the Arctic Ocean in May and August 2014. Frontiers in Marine Science, 6: 264. https://doi.org/10.3389/fmars.2019.00264

Lawrence, M. J., Stemberger, H. L., Zolderdo, A. J., Struthers, D. P., and Cooke, S. J. 2015. The effects of modern war and military activities on biodiversity and the environment. Environmental Reviews, 23(4). https://doi.org/10.1139/er-2015-0039

Lee, J., and Chown, S. 2009. Temporal development of hull-fouling assemblages associated with an Antarctic supply vessel. Marine Ecology Progress Series, 386: 97–105. https://doi.org/10.3354/meps08074

Lee, K., Alava, J. J., Cottrell, P., Cottrell, L., Grace, R., Zysk, I., and Ravert, S. 2023. Emerging Contaminants and New POPs (PFAS and HBCDD) in Endangered Southern Resident and Bigg's (Transient) Killer Whales (*Orcinus orca*): *In Utero* Maternal Transfer and Pollution Management Implications. *Environmental Science & Technology*, 57: 360–374. https://doi.org/10.1021/acs.est.2c04126

Lefebvre, K. A., Quakenbush, L., Frame, E., Huntington, K. B., Sheffield, G., Stimmelmayr, R., Bryan, A., *et al.* 2016. Prevalence of algal toxins in Alaskan marine mammals foraging in a changing arctic and subarctic environment. Harmful Algae, 55: 13–24. https://doi.org/10.1016/j.hal.2016.01.007

Lefort, K. J., Garroway, C. J., and Ferguson, S. H. 2020. Killer whale abundance and predicted narwhal consumption in the Canadian Arctic. Global Change Biology, 26(8): 4276–4283. https://doi.org/10.1111/gcb.15152

Lemelin, H., Dawson, J., Stewart, E. J., Maher, P., and Lueck, M. 2010. Last-chance tourism: the boom, doom, and gloom of visiting vanishing destinations. Current Issues in Tourism, 13(5): 477–493. https://doi.org/10.1080/13683500903406367

Leopold, P., Renaud, P. E., Ambrose, W. G., and Berge, J. 2019. High Arctic *Mytilus* spp.: occurrence, distribution and history of dispersal. Polar Biology, 42(1): 237–244. https://doi.org/10.1007/s00300-018-2415-1

Leu, E., Mundy, C. J., Assmy, P., Campbell, K., Gabrielsen, T. M., Gosselin, M., Juul-Pedersen, T., *et al.* 2015. Arctic spring awakening – Steering principles behind the phenology of vernal ice algal blooms. Progress in Oceanography, 139: 151–170. https://doi.org/10.1016/j.pocean.2015.07.012

Lewis, P. N., Riddle, M. J., and Hewitt, C. L. 2004. Management of exogenous threats to Antarctica and the sub-Antarctic Islands: balancing risks from TBT and non-indigenous marine organisms. Marine Pollution Bulletin, 49(11–12): 999–1005. https://doi.org/10.1016/j.marpolbul.2004.07.001

Li, W. K. W., McLaughlin, F. A., Lovejoy, C., and Carmack, E. C. 2009. Smallest Algae Thrive As the Arctic Ocean Freshens. Science, 326(5952): 539–539. https://doi.org/10.1126/science.1179798

Li, Y., Wang, Z., and Lin, X. 2016. Microbial community structure of Arctic seawater as revealed by pyrosequencing. Acta Oceanologica Sinica, 35(6): 78–84. https://doi.org/10.1007/s13131-015-0742-4

Lim, S. M., Payne, C. M., Van Dijken, G. L., and Arrigo, K. R. 2022. Increases in Arctic sea ice algal habitat, 1985–2018. Elementa: Science of the Anthropocene, 10(1): 00008. https://doi.org/10.1525/elementa.2022.00008

Lischka, S., Büdenbender, J., Boxhammer, T., and Riebesell, U. 2011. Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod *Limacina helicina*: mortality, shell degradation, and shell growth. Biogeosciences, 8(4): 919–932. https://doi.org/10.5194/bg-8-919-2011

Lischka, S., and Riebesell, U. 2012. Synergistic effects of ocean acidification and warming on overwintering pteropods in the Arctic. Global Change Biology, 18(12): 3517–3528. https://doi.org/10.1111/gcb.12020

Liu, F-F., Wang, S-C., Zhu, Z-L., and Liu, G-Z. 2021. Current Progress on Marine Microplastics Pollution Research: A Review on Pollution Occurrence, Detection, and Environmental Effects. Water, 13(12): 1713. https://doi.org/10.3390/w13121713

Loeng, H., Brander, K., and Carmack, E. 2005. Marine Systems. *In* Arctic climate impact assessment, pp. 453–538. Ed. by J. Berner, C. Symon, L. Arris, and O. W. Heal. Cambridge University Press, Cambridge.

Lohman, R. 2017. Microplastics are not important for the cycling and bioaccumulation of organic pollutants in the oceans—but should microplastics be considered POPs themselves? Integrated Environmental Assessment and Management, 13( ): 460–465. https://doi.org/10.1002/ieam.1914

Lone, K., Kovacs, K. M., Lydersen, C., Fedak, M., Andersen, M., Lovell, P., and Aars, J. 2018. Aquatic behaviour of polar bears (*Ursus maritimus*) in an increasingly ice-free Arctic. Scientific Reports, 8(1): 9677. https://doi.org/10.1038/s41598-018-27947-4

Long, W. C., Swiney, K. M., and Foy, R. J. 2013. Effects of ocean acidification on the embryos and larvae of red king crab, *Paralithodes camtschaticus*. Marine Pollution Bulletin, 69(1–2): 38–47. https://doi.org/10.1016/j.marpolbul.2013.01.011

Louis, M., Skovrind, M., Samaniego Castruita, J. A., Garilao, C., Kaschner, K., Gopalakrishnan, S., Haile, J. S., *et al.* 2020. Influence of past climate change on phylogeography and demographic history of narwhals, *Monodon monoceros*. Proceedings of the Royal Society B: Biological Sciences, 287(1925): 20192964. https://doi.org/10.1098/rspb.2019.2964

Lovejoy, C., Legendre, L., Martineau, M-J., Bâcle, J., and von Quillfeldt, C. H. 2002. Distribution of phytoplankton and other protists in the North Water. Deep Sea Research Part II: Topical Studies in Oceanography, 49(22–23): 5027–5047. https://doi.org/10.1016/S0967-0645(02)00176-5

Lovejoy, C., Quillfeldt, C. H., Hopcroft, R., Poulin, M., Thaler, M., Arendt, K., Debes, H., *et al.* 2017. Plankton. *In* State of the Arctic Marine Biodiversity Report, pp. 63–84. Conservation of Arctic Flora and Fauna, Akureyri, Iceland. http://hdl.handle.net/11374/1945

Lowry, L., Reeves, R., and Laidre, K. 2017. *Delphinapterus leucas*: The IUCN Red List of Threatened Species 2017: e.T6335A50352346. https://doi.org/10.2305/IUCN.UK.2017-3.RLTS.T6335A50352346.en

Lowther, A. D., Kovacs, K. M., Griffiths, D., and Lydersen, C. 2015. Identification of motivational state in adult male Atlantic walruses inferred from changes in movement and diving behavior. Marine Mammal Science, 31(4): 1291–1313. https://doi.org/10.1111/mms.12224

Lucia, M., Verboven, N., Strøm, H., Miljeteig, C., Gavrilo, M. V., Braune, B. M., Boertmann, D., *et al.* 2015. Circumpolar contamination in eggs of the high-Arctic ivory gull *Pagophila eburnea*. Environmental Toxicology and Chemistry, 34(7): 1552–1561. https://doi.org/10.1002/etc.2935

Ludvigsen, M., Berge, J., Geoffroy, M., Cohen, J. H., De La Torre, P. R., Nornes, S. M., Singh, H., *et al.* 2018. Use of an Autonomous Surface Vehicle reveals small-scale diel vertical migrations of zooplankton and susceptibility to light pollution under low solar irradiance. Science Advances, 4(1): eaap9887. https://doi.org/10.1126/sciadv.aap9887

Lukina, O., Kurochkina, A., and Karmanova, A. 2020. Assessment of tourism development in Arctic entities. E3S Web of Conferences, 175: 10010. https://doi.org/10.1051/e3sconf/202017510010

Lundberg, J. 2021. Undocumented oil leakages: A study about stern tube seals and leakages. Kalmar Maritime Academy. urn:nbn:se:lnu:diva-103570

Lunde Hermansson, A. L., Hassellöv, I-M., Grönholm, T., Jalkanen, J-P., Fridell, E., Parsmo, R., Hassellöv, J., *et al.* 2024. Strong economic incentives of ship scrubbers promoting pollution. Nature Sustainability. https://doi.org/10.1038/s41893-024-01347-1

Lunde Hermansson, A. L., Hassellöv, I-M., Moldanová, J., and Ytreberg, E. 2021. Comparing emissions of polyaromatic hydrocarbons and metals from marine fuels and scrubbers. Transportation Research Part D: Transport and Environment, 97: 102912. https://doi.org/10.1016/j.trd.2021.102912

Lund-Hansen, L. C., Markager, S., Hancke, K., Stratmann, T., Rysgaard, S., Ramløv, H., and Sorrell, B. K. 2015. Effects of sea-ice light attenuation and CDOM absorption in the water below the Eurasian sector of central Arctic Ocean (>88°N). Polar Research, 34(1): 23978. https://doi.org/10.3402/polar.v34.23978

Lusher, A. L., Provencher, J. F., Baak, J. E., Hamilton, B. M., Vorkamp, K., Hallanger, I. G., Pijogge, L., *et al.* 2022. Monitoring litter and microplastics in Arctic mammals and birds. Arctic Science, as-2021-0058. https://doi.org/10.1139/as-2021-0058

Lusher, A. L., Tirelli, V., O'Connor, I., and Officer, R. 2015. Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. Scientific Reports, 5(1): 14947. https://doi.org/10.1038/srep14947

Lønne, O. J., and Gulliksen, B. 1989. Size, age and diet of polar cod, *Boreogadus saida* (Lepechin 1773), in ice covered waters. Polar Biology, 9(3): 187–191. https://doi.org/10.1007/BF00297174

Ma, Y., Adelman, D. A., Bauerfeind, E., Cabrerizo, A., McDonough, C. A., Muir, D., Soltwedel, T., *et al.* 2018. Concentrations and Water Mass Transport of Legacy POPs in the Arctic Ocean. Geophysical Research Letters, 45(23). https://doi.org/10.1029/2018GL078759

MacDonald, I. R., Bluhm, B. A., Iken, K., Gagaev, S., and Strong, S. 2010. Benthic macrofauna and megafauna assemblages in the Arctic deep-sea Canada Basin. Deep Sea Research Part II: Topical Studies in Oceanography, 57(1–2): 136–152. https://doi.org/10.1016/j.dsr2.2009.08.012

MacIntyre, K. Q., Stafford, K. M., Berchok, C. L., and Boveng, P. L. 2013. Year-round acoustic detection of bearded seals (*Erignathus barbatus*) in the Beaufort Sea relative to changing environmental conditions, 2008–2010. Polar Biology, 36(8): 1161–1173. https://doi.org/10.1007/s00300-013-1337-1

Mallory, M.L. and Braune, B.M., 2012. Tracking contaminants in seabirds of Arctic Canada: temporal and spatial insights. Marine Pollution Bulletin, 64:1475-1484. https://doi.org/10.1016/j.marpolbul.2012.05.012

Marangoni, L. F. B., Davies, T., Smyth, T., Rodríguez, A., Hamann, M., Duarte, C., Pendoley, K., *et al.* 2022. Impacts of artificial light at night in marine ecosystems—A review. Global Change Biology, 28(18): 5346–5367. https://doi.org/10.1111/gcb.16264

Marquardt, M., Goraguer, L., Assmy, P., Bluhm, B. A., Aaboe, S., Down, E., Patrohay, E., *et al.* 2023. Seasonal dynamics of sea-ice protist and meiofauna in the northwestern Barents Sea. Progress in Oceanography, 218: 103128. https://doi.org/10.1016/j.pocean.2023.103128

Martin, M. J., Halliday, W. D., Citta, J. J., Quakenbush, L., Harwood, L., Lea, E. V., Juanes, F., *et al.* 2023. Exposure and behavioural responses of tagged bowhead whales (*Balaena mysticetus*) to vessels in the Pacific Arctic. Arctic Science, as-2022-0052. https://doi.org/10.1139/as-2022-0052

Martin, M. J., Halliday, W. D., Storrie, L., Citta, J. J., Dawson, J., Hussey, N. E., Juanes, F., *et al.* 2022. Exposure and behavioral responses of tagged beluga whales (*Delphinapterus leucas*) to ships in the Pacific Arctic. Marine Mammal Science, 39(2): 387–421. https://doi.org/10.1111/mms.12978

Matishov, G. G., Makarevich, P. R., and Ishkulov, D. G. 2011. "Invaders" and "non-invaders": Causes and consequences of their appearance. Izvestia of Samara Scientific Center of the Russian Academy of Sciences, 13.

Matley, J. K., Crawford, R. E., and Dick, T. A. 2012. Summer foraging behaviour of shallow-diving seabirds and distribution of their prey, Arctic cod (*Boreogadus saida*), in the Canadian Arctic. Polar Research, 31(1): 15894. https://doi.org/10.3402/polar.v31i0.15894

Matthews, C. J. D., Breed, G. A., LeBlanc, B., and Ferguson, S. H. 2020. Killer whale presence drives bowhead whale selection for sea ice in Arctic seascapes of fear. Proceedings of the National Academy of Sciences, 117(12): 6590–6598. https://doi.org/10.1073/pnas.1911761117

Matthias, V., Bewersdorff, I., Aulinger, A., and Quante, M. 2010. The contribution of ship emissions to air pollution in the North Sea regions. Environmental Pollution, 158(6): 2241–2250. https://doi.org/10.1016/j.envpol.2010.02.013

Mayer, A. C., Mayer, J., Wyser, M., Legerer, F., Czerwinski, J., Lutz, T. W., Johnson, T. V., *et al.* 2024. Particulate filters for combustion engines to mitigate global warming. estimating the effects of a highly efficient but underutilized tool. Emission Control Science and Technology, *10* (1): 10–21.

Mayer, M., and Piepenburg, D. 1996. Epibenthic community patterns on the continental slope off East Greenland at 75 N. Marine Ecology Progress Series, 143(1–3): 151–164. 10.3354/meps143151

Mayette, A., Marcoux, M., Iacozza, J., Ferguson, M., Brower, A., and Loseto, L. 2023. Summer distribution and habitat preference of beluga whale social groups in the Eastern Beaufort Sea. Arctic Science, as-2022-0035. https://doi.org/10.1139/as-2022-0035

McConnell, A., Routledge, R., and Connors, B. 2010. Effect of artificial light on marine invertebrate and fish abundance in an area of salmon farming. Marine Ecology Progress Series, 419: 147–156. https://doi.org/10.3354/meps08822

McDonald, T. L., Richardson, W. J., Greene Jr., C. R., Blackwell, S. B., Nations, C. S., Nielson, R. M., and Streever, B. 2012. Detecting changes in the distribution of calling bowhead whales exposed to fluctuating anthropogenic sounds. Journal of Cetacean Research and Management, 12(1): 91–106. https://doi.org/10.47536/jcrm.v12i1.596

McElhany, P. 2017. CO_2 sensitivity experiments are not sufficient to show an effect of ocean acidification. ICES Journal of Marine Science, 74(4): 926–928. https://doi.org/10.1093/icesjms/fsw085

McKeon, C. S., Weber, M. X., Alter, S. E., Seavy, N. E., Crandall, E. D., Barshis, D. J., Fechter-Leggett, E., *et al.* 2016. Melting barriers to faunal exchange across ocean basins. Global Change Biology, 22(2): 465–473. https://doi.org/10.1111/gcb.13116

McKinney, M. A., Iverson, S. J., Fisk, A. T., Sonne, C., Rigét, F. F., Letcher, R. J., Arts, M. T., *et al.* 2013. Global change effects on the long-term feeding ecology and contaminant exposures of East Greenland polar bears. Global Change Biology, 19(8): 2360–2372. https://doi.org/10.1111/gcb.12241

Mecklenburg, C. W., Lynghammar, A., Johannesen, E., Byrkjedal, I., Christiansen, J. S., Dolgov, A. V., Karamushko, O. V., *et al.* 2018. Marine Fishes of the Arctic Region: Volume 1 and 2. Conservation of Arctic Flora and Fauna. http://hdl.handle.net/11374/2116 (accessed 2024).

Meier, S., and Hillebrand, H. 2012. Dominance of the invasive diatom *Mediopyxis helysia* (Kuhn *et al.*, 2006) irrespective of prevailing Si:N ratios. Presented at the 97th Annual Meeting of the Ecological Society of America (ESA 2012).

Meier, S., Muijsers, F., Beck, M., Badewien, T. H., and Hillebrand, H. 2015. Dominance of the non-indigenous diatom *Mediopyxis helysia* in Wadden Sea phytoplankton can be linked to broad tolerance to different Si and N supplies. Journal of Sea Research, 95: 36–44. https://doi.org/10.1016/j.seares.2014.10.001

Melnikov, I. A. 1997. The Arctic sea ice ecosystem. Gordon and Branch Science Publisher, Amsterdam.

Melnikov, I. A. 2018. Characterization of the Biodiversity of Modern Sea Ice in the North Pole Region. Doklady Earth Sciences, 480(2): 792–795. https://doi.org/10.1134/S1028334X18060132

Melnikov, I. A., and Chernova, N. V. 2013. Characteristics of under-ice swarming of polar cod *Boreogadus saida* (Gadidae) in the Central Arctic Ocean. Journal of Ichthyology, 53(1): 7–15. https://doi.org/10.1134/S0032945213010086

Melnikov, I. A., Zhitina, L. S., Ivanov, V. V., and Timofeeva, A. B. 2022. Ice algae in current water-ice environmental condition of the Arctic Ocean. Arctic and Antarctic Research, 68(2): 191–207. https://doi.org/10.30758/0555-2648-2022-68-2-191-207

Meltofte, H., Barry, T., and Berteaux, D. 2013. Synthesis: Implications for Conservation. *In* Arctic Biodiversity Assessment 2013, pp. 22–67. Ed. by H. Meltofte. Conservation of Arctic Flora and Fauna, Akureyri. Iceland. http://hdl.handle.net/11374/223

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., *et al.* 2019. Polar Regions. *In* IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, Ed. by H-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, *et al.* Intergovernmental Panel on Climate Change.

Merkel, F. R., and Johansen, K. L. 2011. Light-induced bird strikes on vessels in Southwest Greenland. Marine Pollution Bulletin, 62(11): 2330–2336. https://doi.org/10.1016/j.marpolbul.2011.08.040

Merrill, G. B., Hermabessiere, L., Rochman, C. M., and Nowacek, D. P. 2023. Microplastics in marine mammal blubber, melon, & other tissues: Evidence of translocation. Environmental Pollution, 335: 122252. https://doi.org/10.1016/j.envpol.2023.122252

Meyer-Kaiser, K. S., Schrage, K. R., Von Appen, W.-J., Hoppmann, M., Lochthofen, N., Sundfjord, A., and Soltwedel, T. 2022. Larval dispersal and recruitment of benthic invertebrates in the Arctic Ocean. Progress in Oceanography, 203: 102776. https://doi.org/10.1016/j.pocean.2022.102776

Michel, C., Bluhm, B., Ford, V., Gallucci, V., Gaston, A. J., Gordillo, F. J. L., Gradinger, R., *et al.* 2013. Chapter 14: Marine Ecosystems. *In* Arctic Biodiversity Assessment. Status and Trends in Arctic Biodiversity, pp. 486–527. Ed. by H. Meltofte. Conservation of Arctic Flora and Fauna (CAFF), Akureyri, Iceland. https://www.arcticbiodiversity.is/index.php/the-report/chapters/marine-ecosystems

Miljeteig, C., Gabrielsen, G. W., Strøm, H., Gavrilo, M. V., Lie, E., and Jenssen, B. M. 2012. Eggshell thinning and decreased concentrations of vitamin E are associated with contaminants in eggs of ivory gulls. Science of The Total Environment, 431: 92–99. https://doi.org/10.1016/j.scitotenv.2012.05.018

Miljeteig, C., Strøm, H., Gavrilo, M. V., Volkov, A., Jenssen, B. M., and Gabrielsen, G. W. 2009. High Levels of Contaminants in Ivory Gull *Pagophila eburnea* Eggs from the Russian and Norwegian Arctic. Environmental Science & Technology, 43(14): 5521–5528. https://doi.org/10.1021/es900490n

Miller, M., Miller, W., Conrad, P., James, E., Melli, A., Leutenegger, C., Dabritz, H., *et al.* 2008. Type X *Toxoplasma gondii* in a wild mussel and terrestrial carnivores from coastal California: New linkages between terrestrial mammals, runoff and toxoplasmosis of sea otters. International Journal for Parasitology, 38(11): 1319–1328. https://doi.org/10.1016/j.ijpara.2008.02.005

Miller, P. J. O., Isojunno, S., Siegal, E., Lam, F-P. A., Kvadsheim, P. H., and Curé, C. 2022. Behavioral responses to predatory sounds predict sensitivity of cetaceans to anthropogenic noise within a soundscape of fear. Proceedings of the National Academy of Sciences, 119(13): e2114932119. https://doi.org/10.1073/pnas.2114932119

Miller, P. K., Waghiyi, V., Welfinger-Smith, G., Byrne, S. C., Kava, J., Gologergen, J., Eckstein, L., *et al.* 2013. Community-based participatory research projects and policy engagement to protect environmental health on St Lawrence Island, Alaska. International Journal of Circumpolar Health, 72(1): 21656. https://doi.org/10.3402/ijch.v72i0.21656

Mironov, A. N., Dilman, A. B., and Krylova, E. M. 2013. Global distribution patterns of genera occurring in the Arctic Ocean deeper 2000 m. Invertebrate Zoology, 10(1): 167–194. https://doi.org/10.15298/invertzool.10.1.08

Moldanová, J., Hassellöv, I-M., Matthias, V., Fridell, E., Jalkanen, J-P., Ytreberg, E., Quante, M., *et al.* 2022. Framework for the environmental impact assessment of operational shipping. Ambio, 51(3): 754–769. https://doi.org/10.1007/s13280-021-01597-9

Molnár, P. K., Bitz, C. M., Holland, M. M., Kay, J. E., Penk, S. R., and Amstrup, S. C. 2020. Fasting season length sets temporal limits for global polar bear persistence. Nature Climate Change, 10(8): 732–738. https://doi.org/10.1038/s41558-020-0818-9

Moore, R. C., Noel, M., Etemadifar, A., Loseto, L., Posacka, A. M., Bendell, L., and Ross, P. S. 2022. Microplastics in beluga whale (*Delphinapterus leucas*) prey: An exploratory assessment of trophic transfer in the Beaufort Sea. Science of The Total Environment, 806: 150201. https://doi.org/10.1016/j.scitotenv.2021.150201

Moore, S. E., George, J. C., and Reeves, R. R. 2021. Bowhead whale ecology in changing high-latitude ecosystems. *In* The Bowhead Whale, pp. 417–427. Elsevier. https://doi.org/10.1016/B978-0-12-818969-6.00027-3

Moore, S. E., and Grebmeier, J. M. 2018. The Distributed Biological Observatory: Linking Physics to Biology in the Pacific Arctic Region. ARCTIC, 71(5). https://doi.org/10.14430/arctic4606

Moore, S. E., Haug, T., Víkingsson, G. A., and Stenson, G. B. 2019. Baleen Whale Ecology in Arctic and Subarctic Seas in an era of Rapid Habitat Alteration. Progress in Oceanography, 176: 102118. https://doi.org/10.1016/j.pocean.2019.05.010

Morganti, T. M., Slaby, B. M., de Kluijver, A., Busch, K., Hentschel, U., Middelburg, J. J., Grotheer, H., *et al.* 2022. Giant sponge grounds of Central Arctic seamounts are associated with extinct seep life. Nature Communications, 13, 638 (2022). https://doi.org/10.1038/s41467-022-28129-7

MOSAiC Expedition. 2022. MOSAiC Expedition. https://mosaic-expedition.org/ (accessed 2024).

MOSJ. 2019. Walrus., MOSJ. https://mosj.no/en/indikator/fauna/marine-fauna/walrus/ (accessed 2024).

MOSJ. 2024. Polar bear., MOSJ. https://mosj.no/en/indikator/fauna/marine-fauna/polar-bear/ (accessed 2024).

Muir, D. C. G., and Norstrom, R. J. 2000. Geographical differences and time trends of persistent organic pollutants in the Arctic. Toxicology Letters, 112–113: 93–101. https://doi.org/10.1016/S0378-4274(99)00255-6

Murray, J. L., Gregor, D. J., Loeng, H., and Hacquebord, L. 1998. Physical/Geographical Characteristics of the Arctic. *In* AMAP Assessment Report: Arctic Pollution Issues, pp. 9–24. Ed. by J. L. Murray. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Muto, M. M. 2021. Alaska marine mammal stock assessments, 2020. NOAA Technical Memorandum NMFS-AFSC, No. 421. https://doi.org/10.25923/yn3s-n786

Nahrgang, J., Dubourg, P., Frantzen, M., Storch, D., Dahlke, F., and Meador, J. P. 2016. Early life stages of an Arctic keystone species (*Boreogadus saida*) show high sensitivity to a water-soluble fraction of crude oil. Environmental Pollution, 218: 605–614. https://doi.org/10.1016/j.envpol.2016.07.044

NAMMCO. 2019. Report of the *Ad hoc* Working Group on Narwhal in East Greenland. September 2019, Copenhagen, Denmark. North Atlantic Marine Mammal Commission.

NAMMCO. 2022. Disturbance Workshop of the Joint NAMMCO–JCNB Working Group on Narwhal and Beluga, December 2022, Copenhagen, Denmark.

NAMMCO. 2023. The *Ad hoc* Working Group on Narwhal in East Greenland, December 2023, Copenhagen, Denmark.

NAMMCO Agreement. 1992. https://nammco.no/nammco-agreement/ (accessed 2024).

NATO. 2022a. Multi-Domains Operations Conference – What We Are Learning. NATO's ACT. https://www.act.nato.int/article/multi-domains-operations-conference-what-we-are-learning/ (accessed 2024).

NATO. 2022b. Joint press conference with NATO Secretary General Jens Stoltenberg and the Prime Minister of Canada, Justin Trudeau., NATO. https://www.nato.int/cps/en/natohq/opinions_206908.htm (accessed 2024).

NATO. 2023. Allied Command Operations (ACO). NATO. https://www.nato.int/cps/en/natohq/topics_52091.htm (accessed 2024).

NATO. 2024. NATO will defend Allied interests in the Arctic" say Chair of NATO Military Committee. 19 October 2024. https://www.nato.int/cps/en/natohq/news_229940.htm

NATO. 2025. National Exercises and Activities. North Atlantic Treaty Organization (NATO). https://shape.nato.int/exercises/allied-national-exercises

Nava, V., and Leoni, B. 2021. A critical review of interactions between microplastics, microalgae and aquatic ecosystem function. Water Research, 188: 116476. https://doi.org/10.1016/j.watres.2020.116476

NEAFC. 1980. Convention on Future Multilateral Cooperation in Northeast Atlantic Fisheries (NEAFC Convention). https://www.neafc.org/basictexts (accessed 2024).

New, L. F., Hall, A. J., Harcourt, R., Kaufman, G., Parsons, E. C. M., Pearson, H. C., Cosentino, A. M., *et al.* 2015. The modelling and assessment of whale-watching impacts. Ocean & Coastal Management, 115: 10–16. https://doi.org/10.1016/j.ocecoaman.2015.04.006

Niemi, A., Michel, C., Hille, K., and Poulin, M. 2011. Protist assemblages in winter sea ice: setting the stage for the spring ice algal bloom. Polar Biology, 34(12): 1803–1817. https://doi.org/10.1007/s00300-011-1059-1

Nikishin, A. M., Petrov, E. I., Cloetingh, S., Korniychuk, A. V., Morozov, A. F., Petrov, O. V., Poselov, V. A., *et al.* 2021. Arctic Ocean Mega Project: Paper 1 - Data collection. Earth-Science Reviews, 217: 103559. https://doi.org/10.1016/j.earscirev.2021.103559

Nilsen, T. 2020a. North Pole Barneo camp cancelled., The Independent Barents Observer. https://thebarentsobserver.com/en/arctic/2020/03/north-pole-barneo-camp-cancelled (accessed 2024).

Nilsen, T. 2020b. More than 20 bulldozers, one aircraft, and tons of other gear spread around the Arctic seafloor by Russia's ice base. The Independent Barents Observer. https://thebarentsobserver.com/en/arctic/2020/02/about-20-bulldozers-have-sunk-arctic-seafloor-one-more-coming-soon (accessed 2024).

Nilssen, E. M., and Sundet, J. H. 2006. The introduced species red king crab (*Paralithodes camtschaticus*) in the Barents Sea II. Growth increments and moulting probability. Fisheries Research, 82: 319–326. https://doi.org/10.1016/j.fishres.2006.05.008

NSIDC. 2024. Arctic sea ice: Walking on sunshine. National Snow and Ice Data Center News. 23 April 2024. https://nsidc.org/sea-ice-today/analyses/arctic-sea-ice-walking-sunshine

Nong, D., Warziniack, T., Countryman, A. M., and Grey, E. K. 2019. Melting Arctic sea ice: Implications for nonindigenous species (NIS) spread in the United States. Environmental Science & Policy, 91: 81–91. https://doi.org/10.1016/j.envsci.2018.10.013

North Pole Quark Expeditions. 2024. https://www.quarkexpeditions.com/blog/arctic/north-pole (accessed 2024).

North Pole Dreaming: Journey to the Top of the World | Quark Expeditions. 2024. https://www.quarkexpeditions.com/blog/north-pole-dreaming-journey-to-the-top-of-the-world (accessed 2024).

Norwegian Ministry of the Environment. 2009. Ballast Water Regulation. https://www.bimco.org/~/media/News/2010/Ports/Norwegian_Ballast_Water.ashx

Nöthig, E-M., Ramondenc, S., Haas, A., Hehemann, L., Walter, A., Bracher, A., Lalande, C., *et al.* 2020. Summertime Chlorophyll a and Particulate Organic Carbon Standing Stocks in Surface Waters of the Fram Strait and the Arctic Ocean (1991–2015). Frontiers in Marine Science, 7: 350. https://doi.org/10.3389/fmars.2020.00350

Novikov, M. A., Gorbacheva, E. A., Prokhorova, T. A., and Kharlamova, M. N. 2021. Composition and Distribution of Marine Anthropogenic Litter in the Barents Sea. Oceanology, 61(1): 48–57. https://doi.org/10.1134/S0001437021010148

NSIDC. 2022. Ain't no sunshine when she's gone. Arctic Sea Ice News and Analysis. http://nsidc.org/arcticseaicenews/2022/10/ (accessed 2024).

Oak, T. G. 2020. Oil and gas exploration and production activities in areas with defined benthic conservation objectives: a review of potential impacts and mitigation measures. Research Document No. 2020/040. Canadian Science Advisory Secretariat. publications.gc.ca/pub?id=9.890986&sl=0 (accessed 2024).

O'Corry-Crowe, G., Mahoney, A. R., Suydam, R., Quakenbush, L., Whiting, A., Lowry, L., and Harwood, L. 2016. Genetic profiling links changing sea-ice to shifting beluga whale migration patterns. Biology Letters, 12(11): 20160404. https://doi.org/10.1098/rsbl.2016.0404

O'Hara, T. M., Krahn, M. M., Boyd, D., Becker, P. R., and Philo, L. M. 1999. Organochlorine contaminant levels in Eskimo harvested bowhead whales of Arctic Alaska. Journal of Wildlife Diseases, 35(4): 741–752. https://doi.org/10.7589/0090-3558-35.4.741

Olenin, S., Gollasch, S., Lehtiniemi, M., Sapota, M., and Zaiko, A. 2017. Biological invasions. *In* Biological oceanography of the Baltic Sea, pp. 193–232. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-0668-2_5

Oleszczuk, B., Silberberger, M. J., Grzelak, K., Winogradow, A., Dybwad, C., Peeken, I., Wiedmann, I., *et al.* 2023. Macrofauna and meiofauna food-web structure from Arctic fjords to deep Arctic Ocean during spring: A stable isotope approach. Ecological Indicators, 154: 110487. https://doi.org/10.1016/j.ecolind.2023.110487

Olson, J., Rode, K., Eggett, D., Smith, T., Wilson, R., Durner, G., Fischbach, A., *et al.* 2017. Collar temperature sensor data reveal long-term patterns in southern Beaufort Sea polar bear den distribution on pack ice and land. Marine Ecology Progress Series, 564: 211–224. https://doi.org/10.3354/meps12000

Ortman, K. 2009. Radioactive Waste Impacts Mitigated by the Arctic Military Environmental Cooperation Program: Lessons in International Cooperation. Masters Thesis, University of Cambridge, Scott Polar Research Institute.

Osmundsen, L. 2023. Port reception facilities and a regional approach: A bridge for abating plastic pollution in the arctic? Marine Policy, 148: 105436. https://doi.org/10.1016/j.marpol.2022.105436

OSPAR. 2017. Offshore Oil and Gas. https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-human-activities/trends-discharges-spills-and-emissions-offshore-oil-and-gas-inst/ (accessed 2024).

OSPAR. 1992. OSPAR Commission. Protecting and conserving the North-East Atlantic and its resources.https://www.ospar.org/ (accessed 2024).

Östlund, H. G., and Hut, G. 1984. Arctic Ocean water mass balance from isotope data. Journal of Geophysical Research: Oceans, 89(C4): 6373–6381. https://doi.org/10.1029/JC089iC04p06373

Overview. 1994. Agreement relating to the implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982. https://www.un.org/Depts/los/convention_agreements/convention_overview_part_xi.htm (accessed 2024).

Oziel, L., Baudena, A., Ardyna, M., Massicotte, P., Randelhoff, A., Sallée, J-B., Ingvaldsen, R. B., *et al.* 2020. Faster Atlantic currents drive poleward expansion of temperate phytoplankton in the Arctic Ocean. Nature Communications, 11(1): 1705. https://doi.org/10.1038/s41467-020-15485-5

Paasche, Ø., Olsen, A., Årthun, M., Anderson, L., Wängberg, S., Ashjian, C., Grebmeier, J., *et al.* 2019. Addressing Arctic Challenges Requires a Comprehensive Ocean Survey. Eos 100(1): 13–15. https://doi.org/10.1029/2019EO136200

Pakhomova, S., Berezina, A., Lusher, A. L., Zhdanov, I., Silvestrova, K., Zavialov, P., Van Bavel, B., *et al.* 2022. Microplastic variability in subsurface water from the Arctic to Antarctica. Environmental Pollution, 298: 118808. https://doi.org/10.1016/j.envpol.2022.118808

PAME. 2019a. PAME Desktop Study on Marine Litter including Microplastics in the Arctic.

PAME. 2019b. Underwater Noise in the Arctic: A State of Knowledge Report, Roveniemi, May 2019. Protection of the Arctic Marine Environment (PAME) Secretariat, Akureyri, Iceland.

PAME. 2020. Arctic Shipping Status Report. No. 1, Arctic Shipping Status Report. PAME Secretariat/USA. https://storymaps.arcgis.com/stories/592bfe70251741b48b0a9786b75ff5d0

PAME. 2021a. PAME Regional Action Plan on Marine Litter in the Arctic.

PAME. 2021b. Underwater Noise Pollution from Shipping in the Arctic, Protection of the Arctic Marine Environment Working Group (PAME), May 2021. Protection of the Arctic Marine Environment (PAME) Secretariat.

PAME. 2021c. PAME Modelling Arctic Oceanographic Connectivity. Protection of the Arctic Marine Environment, Akureyri, Iceland.

Pan, M., and Huntington, H. P. 2016. A precautionary approach to fisheries in the Central Arctic Ocean: Policy, science, and China. Marine Policy, 63: 153–157. https://doi.org/10.1016/j.marpol.2015.10.015

Panigada, S., Pesante, G., Zanardelli, M., Capoulade, F., Gannier, A., and Weinrich, M. T. 2006. Mediterranean fin whales at risk from fatal ship strikes. Marine Pollution Bulletin, 52(10): 1287–1298. https://doi.org/10.1016/j.marpolbul.2006.03.014

Parga Martínez, K. B., Tekman, M. B., and Bergmann, M. 2020. Temporal Trends in Marine Litter at Three Stations of the HAUSGARTEN Observatory in the Arctic Deep Sea. Frontiers in Marine Science, 7: 321. https://doi.org/10.3389/fmars.2020.00321

Patenaude, N. J., Richardson, W. J., Smultea, M. A., Koski, W. R., Miller, G. W., Würsig, B., and Greene, C. R. Jr. 2002. Aircraft Sound and Disturbance to Bowhead and Beluga Whales during Spring Migration in the Alaskan Beaufort Sea. Marine Mammal Science, 18(2): 309–335. https://doi.org/10.1111/j.1748-7692.2002.tb01040.x

Paul, A. Z., and Menzies, R. J. 1974. Benthic ecology of the high Arctic deep sea. Marine Biology, 27(3): 251–262. https://doi.org/10.1007/BF00391950

PBSG (Polar Bear Specialist Group). 2023. Status Report on the World's Polar Bear Subpopulations. No. 2023 Status Report. https://www.iucn-pbsg.org/wp-content/uploads/2024/01/PBSG-Status-Criteria-and-Report_Final_2023Oct17.pdf

Pedersen, A. F., Bayen, S., Liu, L., Dietz, R., Sonne, C., Rosing-Asvid, A., Ferguson, S. H., *et al.* 2024. Nontarget and suspect screening reveals the presence of multiple plastic-related compounds in polar bear, killer whale, narwhal and long-finned pilot whale blubber from East Greenland. Environmental Pollution, 357: 124417.

Pedreschi, D., Niiranen, S., Skern-Mauritzen, M. and Reid, D.G., 2023. Operationalising ODEMM risk assessment for Integrated Ecosystem Assessment scoping: Complexity vs. manageability. Frontiers in Marine Science, *9*, p.1037878

Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C., Krumpen, T., Bergmann, M., *et al.* 2018. Arctic sea ice is an important temporal sink and means of transport for microplastic. Nature Communications, 9(1): 1505. https://doi.org/10.1038/s41467-018-03825-5

Peterson, C. H., Rice, S. D., Short, J. W., Esler, D., Bodkin, J. L., Ballachey, B. E., and Irons, D. B. 2003. Long-Term Ecosystem Response to the Exxon Valdez Oil Spill. Science, 302(5653): 2082–2086. https://doi.org/10.1126/science.1084282

Pickart, R. S., Schulze, L. M., Moore, G. W. K., Charette, M. A., Arrigo, K. R., van Dijken, G., and Danielson, S. L. 2013. Long-term trends of upwelling and impacts on primary productivity in the Alaskan Beaufort Sea. Deep Sea Research Part I: Oceanographic Research Papers, 79: 106–121. https://doi.org/10.1016/j.dsr.2013.05.003

Pine, M. K., Hannay, D. E., Insley, S. J., Halliday, W. D., and Juanes, F. 2018. Assessing vessel slowdown for reducing auditory masking for marine mammals and fish of the western Canadian Arctic. Marine Pollution Bulletin, 135: 290–302. https://doi.org/10.1016/j.marpolbul.2018.07.031

Pinzone, M., Nordøy, E. S., Eppe, G., Malherbe, C., Das, K., and Collard, F. 2021. First record of plastic debris in the stomach of a hooded seal pup from the Greenland Sea. Marine Pollution Bulletin, 167: 112350. https://doi.org/10.1016/j.marpolbul.2021.112350

Polar Code (International Code for Ships Operating in Polar Waters). 2014. https://www.imo.org/en/MediaCentre/HotTopics/Pages/polar-default.aspx (accessed 2024).

Polasek, L., Bering, J., Kim, H., Neitlich, P., Pister, B., Terwilliger, M., Nicolato, K., *et al.* 2017. Marine debris in five national parks in Alaska. Marine Pollution Bulletin, 117(1–2): 371–379. https://doi.org/10.1016/j.marpolbul.2017.01.085

Polyakov, I. V., Alkire, M. B., Bluhm, B. A., Brown, K. A., Carmack, E. C., Chierici, M., Danielson, S. L., *et al.* 2020. Borealization of the Arctic Ocean in Response to Anomalous Advection from Sub-Arctic Seas. Frontiers in Marine Science, 7: 491. https://doi.org/10.3389/fmars.2020.00491

Polyakov, I. V., Alkire, M. B., Bluhm, B. A., Brown, K. A., Carmack, E. C., Chierici, M., Danielson, S. L., *et al.* 2021. Corrigendum: Borealization of the Arctic Ocean in Response to Anomalous Advection from Sub-Arctic Seas. Frontiers in Marine Science, 8: 667007. https://doi.org/10.3389/fmars.2021.667007

Polyakov, I. V., Pnyushkov, A. V., Alkire, M. B., Ashik, I. M., Baumann, T. M., Carmack, E. C., Goszczko, I., *et al.* 2017. Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. Science, 356(6335): 285–291. https://doi.org/10.1126/science.aai8204

Poulin, M., Daugbjerg, N., Gradinger, R., Ilyash, L., Ratkova, T., and Von Quillfeldt, C. 2011. The pan-Arctic biodiversity of marine pelagic and sea-ice unicellular eukaryotes: a first-attempt assessment. Marine Biodiversity, 41(1): 13–28. https://doi.org/10.1007/s12526-010-0058-8

Poulsen, A. J., and Schmidt, H. 2016. Acoustic noise properties in the rapidly changing Arctic Ocean. Proceedings of Meetings on Acoustics, 28(1): 070005 (2016) https://doi.org/10.1121/2.0000552

Prestrud, K. W., Åsbakk, K., Fuglei, E., Mørk, T., Stien, A., Ropstad, E., Tryland, M., *et al.* 2007. Serosurvey for *Toxoplasma gondii* in Arctic foxes and possible sources of infection in the high Arctic of Svalbard. Veterinary Parasitology, 150(1–2): 6–12. https://doi.org/10.1016/j.vetpar.2007.09.006

Proshutinsky, A. Y., and Johnson, M. A. 1997. Two circulation regimes of the wind-driven Arctic Ocean. Journal of Geophysical Research, Oceans, 102: 12493–12514. https://doi.org/10.1029/97JC00738

Provencher, J. F., Gaston, A. J., Mallory, M. L., O'hara, P. D., and Gilchrist, H. G. 2010. Ingested plastic in a diving seabird, the thick-billed murre (*Uria lomvia*), in the eastern Canadian Arctic. Marine Pollution Bulletin, 60(9): 1406–1411. https://doi.org/10.1016/j.marpolbul.2010.05.017

Provencher, J., Gaston, A., O'Hara, P., and Gilchrist, H. 2012. Seabird diet indicates changing Arctic marine communities in eastern Canada. Marine Ecology Progress Series, 454: 171–182. https://doi.org/10.3354/meps09299

Quakenbush, L. T., Suydam, R. S., Brown, A. L., Lowry, L. F., Frost, K. J., and Mahoney, B. A. 2015. Diet of beluga whales, *Delphinapterus leucas*, in Alaska from stomach contents, March-November. Marine Fisheries Review, 77(1): 70–84. https://doi.org/10.7755/MFR.77.1.7

Quigley, G., Brinkman, T. J., Wilson, R., and Christ, A. 2024. Behavioral response of polar bears to aircraft activity on the northern coast of Alaska. The Journal of Wildlife Management, 88(3): e22554. https://doi.org/10.1002/jwmg.22554

Ramirez-Llodra, E., Meyer, H. K., Bluhm, B. A., Brix, S., Brandt, A., Dannheim, J., and Downey, R. V. 2024. The emerging picture of a diverse deep Arctic Ocean seafloor: from habitats to ecosystems. Elementa – Science of the Anthropocene, (2024) 12 (1): 00140. https://online.ucpress.edu/elementa/article/12/1/00140/203384/The-emerging-picture-of-a-diverse-deep-Arctic

Randelhoff, A., Sundfjord, A., and Reigstad, M. 2015. Seasonal variability and fluxes of nitrate in the surface waters over the Arctic shelf slope. Geophysical Research Letters, 42(9): 3442–3449. https://doi.org/10.1002/2015GL063655

Rapp, J. 2014. Bacterial diversity in sea ice, melt ponds, water column, ice algal aggregates and deep-sea sediments of the Central Arctic Ocean. Master's Thesis, University of Bremen, Bremen, Germany. https://hdl.handle.net/21.11116/0000-0001-C5CE-9

Raskoff, K. A., Hopcroft, R. R., Kosobokova, K. N., Purcell, J. E., and Youngbluth, M. 2010. Jellies under ice: ROV observations from the Arctic 2005 hidden ocean expedition. Deep Sea Research Part II: Topical Studies in Oceanography, 57(1–2): 111–126. https://doi.org/10.1016/j.dsr2.2009.08.010

Rayfuse, R. 2019. The role of law in the regulation of fishing activities in the Central Arctic Ocean. Marine Policy, 110: 103562. https://doi.org/10.1016/j.marpol.2019.103562

Reiling, S., and Dixon, B. 2019. *Toxoplasma gondii*: How an Amazonian parasite became an Inuit health issue. Canada Communicable Disease Report, 45(7/8): 183–190. https://doi.org/10.14745/ccdr.v45i78a03

Reimer, J. R., Caswell, H., Derocher, A. E., and Lewis, M. A. 2019. Ringed seal demography in a changing climate. Ecological Applications, 29(3): e01855. https://doi.org/10.1002/eap.1855

Renaud, P. E., Ambrose, W. G., Vanreusel, A., and Clough, L. M. 2006. Nematode and macrofaunal diversity in central Arctic Ocean benthos. Journal of Experimental Marine Biology and Ecology, 330(1): 297–306. https://doi.org/10.1016/j.jembe.2005.12.035

Renaut, S., Devred, E., and Babin, M. 2018. Northward Expansion and Intensification of Phytoplankton Growth During the Early Ice-Free Season in Arctic. Geophysical Research Letters, 45(19). https://doi.org/10.1029/2018GL078995

Rey, F. 2012. Declining silicate concentrations in the Norwegian and Barents Seas. ICES Journal of Marine Science, 69(2): 208–212. https://doi.org/10.1093/icesjms/fss007

Ribeiro, C. G., Dos Santos, A. L., Trefault, N., Marie, D., Lovejoy, C., and Vaulot, D. 2022. Arctic phytoplankton spring bloom diversity across the marginal ice zone in Baffin Bay. preprint. Microbiology. https://doi.org/10.1101/2022.03.14.484350

Ricciardi, A. 2006. Patterns of invasion in the Laurentian Great Lakes in relation to changes in vector activity. Diversity and Distributions, 12(4): 425–433. https://doi.org/10.1111/j.1366-9516.2006.00262.x

Richardson, W. J., and Malme, C. I. 1993. Man-made noise and behavioral responses. *In* The Bowhead Whale, pp. 631–700. Ed. by J. J. Burns. Society for Marine Mammalogy, Lawrence, Kansas.

Richardson, W. J., Miller, G. W., and Greene, C. R. 1999. Displacement of migrating bowhead whales by sounds from seismic surveys in shallow waters of the Beaufort Sea. The Journal of the Acoustical Society of America, 106(4_Supplement): 2281–2281. https://doi.org/10.1121/1.427801

Richter-Menge, J., Overland, J. E., Mathis, J. T., and Osborne, E. (Eds.). 2017. Arctic Report Card 2017. http://www.arctic.noaa.gov/Report-Card

Rigét, F., Bignert, A., Braune, B., Dam, M., Dietz, R., Evans, M., Green, N., *et al.* 2019. Temporal trends of persistent organic pollutants in Arctic marine and freshwater biota. Science of The Total Environment, 649: 99–110. https://doi.org/10.1016/j.scitotenv.2018.08.268

Rigét, F., Braune, B., Bignert, A., Wilson, S., Aars, J., Born, E., Dam, M., *et al.* 2011a. Temporal trends of Hg in Arctic biota, an update. Science of The Total Environment, 409(18): 3520–3526. https://doi.org/10.1016/j.scitotenv.2011.05.002

Rigét, F., Tamstorf, M. P., Larsen, M. M., Søndergaard, J., Asmund, G., Falk, J. M., and Sigsgaard, C. 2011b. Mercury (Hg) Transport in a High Arctic River in Northeast Greenland. Water, Air, & Soil Pollution, 222(1–4): 233–242. https://doi.org/10.1007/s11270-011-0819-4

Robertson, F., Koski, W., and Trites, A. 2016. Behavioral responses affect distribution analyses of bowhead whales in the vicinity of seismic operations. Marine Ecology Progress Series, 549: 243–262. https://doi.org/10.3354/meps11665

Rodríguez, A., Burgan, G., Dann, P., Jessop, R., Negro, J. J., and Chiaradia, A. 2014. Fatal Attraction of Short-Tailed Shearwaters to Artificial Lights. PLOS One, 9(10): e110114. https://doi.org/10.1371/journal.pone.0110114

Rodríguez, A., Rodríguez, B., Acosta, Y., and Negro, J. J. 2022. Tracking Flights to Investigate Seabird Mortality Induced by Artificial Lights. Frontiers in Ecology and Evolution, 9: 786557. https://doi.org/10.3389/fevo.2021.786557

Rosenhaim, I. L., Riemann-Campe, K., Sumata, H., Koeberle, C., Brauner, R., Herber, A., and Gerdes, R. 2019. Simulated ballast water accumulation along Arctic shipping routes. Marine Policy, 103: 9–18. https://doi.org/10.1016/j.marpol.2019.02.013

Ross, P. S., Chastain, S., Vassilenko, E., Etemadifar, A., Zimmermann, S., Quesnel, S. A., Eert, J., *et al.* 2021. Pervasive distribution of polyester fibres in the Arctic Ocean is driven by Atlantic inputs. Nature Communications, 12(1): 1–9. https://doi.org/10.1038/s41467-020-20347-1

Rossland, H., Johnsen, A., Kvadsheim, P. H., and Bjerketveit, B. 2018. Sluttrapport fra demoleringen av torpedoer fra vraket av KNM Helge Ingstad. No. 18/00901, FFI-RAPPORT. Forsvarets forskningsinstitut.

Roth, E. H., Schmidt, V., Hildebrand, J. A., and Wiggins, S. M. 2013. Underwater radiated noise levels of a research icebreaker in the central Arctic Ocean. The Journal of the Acoustical Society of America, 133(4): 1971–1980. https://doi.org/10.1121/1.4790356

Rothrock, D. A., Yu, Y., and Maykut, G. A. 1999. Thinning of the Arctic sea-ice cover. Geophysical Research Letters, 26(23): 3469–3472. https://doi.org/10.1029/1999GL010863

Routti, H., Atwood, T. C., Bechshoft, T., Boltunov, A., Ciesielski, T. M., Desforges, J-P., Dietz, R., *et al.* 2019a. State of knowledge on current exposure, fate and potential health effects of contaminants in polar bears from the circumpolar Arctic. Science of The Total Environment, 664: 1063–1083. https://doi.org/10.1016/j.scitotenv.2019.02.030

Routti, H., Berg, M. K., Lille-Langøy, R., Øygarden, L., Harju, M., Dietz, R., Sonne, C., *et al.* 2019b. Environmental contaminants modulate the transcriptional activity of polar bear (*Ursus maritimus*) and human peroxisome proliferator-activated receptor alpha (PPARA). Scientific Reports, 9(1): 6918. https://doi.org/10.1038/s41598-019-43337-w

Routti, H., Harju, M., Lühmann, K., Aars, J., Ask, A., Goksøyr, A., Kovacs, K. M., *et al.* 2021. Concentrations and endocrine disruptive potential of phthalates in marine mammals from the Norwegian Arctic. Environment International, 152: 106458. https://doi.org/10.1016/j.envint.2021.106458

Roux, M. J., and Pedreschi, D. (Eds.). 2024. ICES Framework for Ecosystem-Informed Science and Advice (FEISA). ICES Cooperative Research Reports Vol. 359. https://doi.org/10.17895/ices.pub.25266790

Royo-Llonch, M., Sánchez, P., Ruiz-González, C., Salazar, G., Pedrós-Alió, C., Sebastián, M., Labadie, K., *et al.* 2021. Compendium of 530 metagenome-assembled bacterial and archaeal genomes from the polar Arctic Ocean. Nature Microbiology, 6(12): 1561–1574. https://doi.org/10.1038/s41564-021-00979-9

Ruberg, E. J., Elliott, J. E., and Williams, T. D. 2021. Review of petroleum toxicity and identifying common endpoints for future research on diluted bitumen toxicity in marine mammals. Ecotoxicology, 30(4): 537–551. https://doi.org/10.1007/s10646-021-02373-x

Rudels, B. 2015. Arctic Ocean circulation, processes and water masses: A description of observations and ideas with focus on the period prior to the International Polar Year 2007-2009. Progress in Oceanography, 132: 22–67. https://doi.org/10.1016/j.pocean.2013.11.006

Rudels, B., and Carmack, E. 2022. Arctic Ocean Water Mass Structure and Circulation. Oceanography, . https://doi.org/10.5670/oceanog.2022.116

Rudels, B., Jones, E. P., Schauer, U., and Eriksson, P. 2004. Atlantic sources of the Arctic Ocean surface and halocline waters. Polar Research, 23(2): 181–208. https://doi.org/10.3402/polar.v23i2.6278

Ruiz, G. M., and Hewitt, C. 2009. Latitudinal Patterns of Biological Invasions in Marine Ecosystems: A Polar Perspective. *In* Smithsonian at the Poles: Contributions to International Polar Year Science, pp. 347–358. Smithsonian Institution Scholarly Press. https://doi.org/10.5479/si.097884601X.26

Runge, C. A., Daigle, R. M., and Hausner, V. H. 2020. Quantifying tourism booms and the increasing footprint in the Arctic with social media data. PLOS One, 15(1): e0227189. https://doi.org/10.1371/journal.pone.0227189

Ryan, P. G., Ryan, E. M., and Glass, J. P. 2021. Dazzled by the light: the impact of light pollution from ships on seabirds at Tristan da Cunha. Ostrich, 92(3): 218–224. https://doi.org/10.2989/00306525.2021.1984998

Rybakova, E., Kremenetskaia, A., Vedenin, A., Boetius, A., and Gebruk, A. 2019. Deep-sea megabenthos communities of the Eurasian Central Arctic are influenced by ice-cover and sea-ice algal falls. PLOS One, 14(7): e0211009. https://doi.org/10.1371/journal.pone.0211009

Rødlista. 2021. Artsdatabanken. 2021. https://artsdatabanken.no/lister/rodlisteforarter/2021/ (accessed 2024).

Sakshaug, E. 2004. Primary and Secondary Production in the Arctic Seas. *In* The Organic Carbon Cycle in the Arctic Ocean, pp. 57–81. Ed. by R. Stein, and R. W. MacDonald. Springer, Berlin Heidelberg. https://doi.org/10.1007/978-3-642-18912-8_3

Salvadó, J. A., Sobek, A., Carrizo, D., and Gustafsson, Ö. 2016. Observation-based assessment of PBDE loads in Arctic Ocean waters. Environmental Science & Technology, 50(5): 2236–2245. https://doi.org/10.1021/acs.est.5b05687

Sawhill, S. G. 2000. Cleaning-up the Arctic's Cold War Legacy: Nuclear Waste and Arctic Military Environmental Cooperation. Cooperation and Conflict, 35(1): 5–36. https://doi.org/10.1177/00108360021961986

Sayinli, B., Dong, Y., Park, Y., Bhatnagar, A., and Sillanpää, M. 2022. Recent progress and challenges facing ballast water treatment – A review. Chemosphere, 291: 132776. https://doi.org/10.1016/j.chemosphere.2021.132776

Schauer, U., Muench, R. D., Rudels, B., and Timokhov, L. 1997. Impact of eastern Arctic shelf waters on the Nansen Basin intermediate layers. Journal of Geophysical Research: Oceans, 102(C2): 3371–3382. https://doi.org/10.1029/96JC03366

Scheinin, A. P., Kerem, D., MacLeod, C. D., Gazo, M., Chicote, C. A., and Castellote, M. 2011. Gray whale (*Eschrichtius robustus*) in the Mediterranean Sea: anomalous event or early sign of climate-driven distribution change? Marine Biodiversity Records, 4: e28. https://doi.org/10.1017/S1755267211000042

Schewe, I. 2001. Small-Sized Benthic Organisms of the Alpha Ridge, Central Arctic Ocean. International Review of Hydrobiology, 86(3): 317–335. https://doi.org/10.1002/1522-2632(200106)86:3<317::AID-IROH317>3.0.CO;2-V

Schewe, I., and Soltwedel, T. 1999. Deep-sea meiobenthos of the central Arctic Ocean: distribution patterns and size-structure under extreme oligotrophic conditions. Vie et Milieu / Life & Environment, 79.

Schlindwein, V. 2023. The Expedition PS137 of the Research Vessel POLARSTERN to the Arctic Ocean in 2023 *In* Berichte zur Polar- und Meeresforschung = Reports on polar and marine research, 781. Ed. by H. Bornemann, and S. Amir Sawadkuhi. Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven. https://doi.org/10.57738/BzPM_0781_2023

Schmidtko, S., Stramma, L., and Visbeck, M. 2017. Decline in global oceanic oxygen content during the past five decades. Nature, 542(7641): 335–339. https://doi.org/10.1038/nature21399

Schröder, C., Reimer, N., and Jochmann, P. 2017. Environmental impact of exhaust emissions by Arctic shipping. Ambio, 46(S3): 400–409. https://doi.org/10.1007/s13280-017-0956-0

Schulz, M., Bergmann, M., von Juterzenka, K., and Soltwedel, T. 2010. Colonisation of hard substrata along a channel system in the deep Greenland Sea. Polar Biology, 33(10): 1359–1369. https://doi.org/10.1007/s00300-010-0825-9

SDWG. 2019. Best Waste Management Practices for Small and Remote Arctic Communities: A study of best waste management practices used in remote Arctic communities in Alaska, Canada, and Finland. Interim Project Report, Meeitng Documents. Arctic Council, Tromsö, Norway. http://hdl.handle.net/11374/2297

Seinfeld, J. H., and Pandis, S. N. 2006. Atmospheric chemistry and physics: from air pollution to climate change, 2nd ed. John Wiley, Hoboken, NJ.

Selck, H., Drouillard, K., Eisenreich, K., Koelmans, A. A., Palmqvist, A., Ruus, A., Salvito, D., *et al.* 2012. Explaining differences between bioaccumulation measurements in laboratory and fi eld data through use of a probabilistic modeling approach. Integrated Environmental Assessment and Management, 8(1): 42–63.

Selz, V., Saenz, B. T., van Dijken, G. L., and Arrigo, K. R. 2018. Drivers of Ice Algal Bloom Variability between 1980 and 2015 in the Chukchi Sea. Journal of Geophysical Research: Oceans, 123(10): 7037–7052. https://doi.org/10.1029/2018JC014123

Shapiro, K., Bahia-Oliveira, L., Dixon, B., Dumètre, A., de Wit, L. A., VanWormer, E., and Villena, I. 2019. Environmental transmission of *Toxoplasma gondii*: Oocysts in water, soil and food. Food and Waterborne Parasitology, 15: e00049. https://doi.org/10.1016/j.fawpar.2019.e00049

Sharma, R., Loseto, L. L., Ostertag, S. K., Tomaselli, M., Bredtmann, C. M., Crill, C., Rodríguez-Pinacho, C., *et al.* 2018. Qualitative risk assessment of impact of *Toxoplasma gondii* on health of beluga whales, *Delphinapterus leucas* from the Eastern Beaufort Sea, Northwest Territories. Arctic Science, AS-2017-0037. https://doi.org/10.1139/AS-2017-0037

Sharma, R., Nath, B. N., Parthiban, G., and Sankar, S. J. 2001. Sediment redistribution during simulated benthic disturbance and its implications on deep seabed mining. Deep-Sea Research Part II: Topical Studies in Oceanography, 48(16): 3363–3380.

Sheffield, G., Ahmasuk, A., Ivanoff, F., Noongwook, A., and Koonooka, J. 2021. 2020 Foreign Marine Debris Event—Bering Strait. *In* Arctic Report Card 2021. Ed. by T. A. Moon, M. L. Druckenmiller, and R. L. Thoman. https://doi.org/10.25923/jwag-eg41

Shpak, O. V., Kuznetsova, D. M., and Rozhnov, V. V. 2013. Observation of the gray whale (*Eschrichtius robustus*) in the Laptev Sea. Biology Bulletin, 40(9): 797–800. https://doi.org/10.1134/S1062359013090100

Silber, G. K., and Adams, J. D. 2019. Vessel Operations in the Arctic, 2015–2017. Frontiers in Marine Science, 6: 573. https://doi.org/10.3389/fmars.2019.00573

Simon, A., Chambellant, M., Ward, B. J., Simard, M., Proulx, J. F., Levesque, B., Bigras-Poulin, M., *et al.* 2011. Spatio-temporal variations and age effect on *Toxoplasma gondii* seroprevalence in seals from the Canadian Arctic. Parasitology, 138(11): 1362–1368. https://doi.org/10.1017/S0031182011001260

Simon-Lledó, E., Bett, B. J., Huvenne, V. A. I., Köser, K., Schoening, T., Greinert, J., and Jones, D. O. B. 2019. Biological effects 26 years after simulated deep-sea mining. Scientific Reports, 9(1): 8040. https://doi.org/10.1038/s41598-019-44492-w

Sirenko, B. I. (Ed.). 2001. List of species of free-living invertebrates of Eurasian Arctic Seas and adjacent deep waters. Explorations of the Fauna of the Seas, 51(59). Russian Academy of Sciences Zoological Institute, St. Petersburg. https://macrostomorpha.myspecies.info/sites/macrostomorpha.info/files/Mamkaeval2001_HQ_OPT_OCR.pdf

Sirenko, B. I., Clarke, C., Hopcroft, R. R., Huettmann, F., Bluhm, B. A., and Gradinger, R. (Eds.). 2024. The Arctic Register of Marine Species (ARMS) compiled by the Arctic Ocean Diversity (ArcOD). https://www.marinespecies.org/arms on 2024-05-22 (accessed 2024).

Skjerdal, H., Heldal, H. E., Rand, A., Gwynn, J., Jensen, L. K., Volynkin, A., Haanes, H., *et al.* 2020. Radioactivity in the Marine Environment 2015, 2016 and 2017. Results from the Norwegian Marine Monitoring Programme RAME, DSA Report. Norwegian Radiation and Nuclear Safety Authority, Østerås.

Skjoldal, H. R. (ed.). 2022. Ecosystem assessment of the Central Arctic Ocean: Description of the ecosystem. ICES Cooperative Research Reports Vol. 355. 341 pp. https://doi.org/10.17895/ices.pub.20191787

Slabbekoorn, H., Bouton, N., van Opzeeland, I., Coers, A., Ten Cate, C., and Popper, A. N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fish. Trends in Ecology & Evolution, 25(7): 419–427. https://doi.org/10.1016/j.tree.2010.04.005

Smith, C. E., Sykora-Bodie, S. T., Bloodworth, B., Pack, S. M., Spradlin, T. R., and LeBoeuf, N. R. 2016. Assessment of known impacts of unmanned aerial systems (UAS) on marine mammals: data gaps and recommendations for researchers in the United States. Journal of Unmanned Vehicle Systems, 4(1): 31–44. https://doi.org/10.1139/juvs-2015-0017

Smith, L. C., and Stephenson, S. R. 2013. New Trans-Arctic shipping routes navigable by midcentury. Proceedings of the National Academy of Sciences, 110(13). https://doi.org/10.1073/pnas.1214212110

Smith, T. S., Derocher, A. E., Mazur, R. L., York, G., Owen, M. A., Obbard, M., Richardson, E. S., *et al.* 2023. Anthropogenic food: an emerging threat to polar bears. Oryx, 57(4): 425–434. https://doi.org/10.1017/S0030605322000278

Smultea, M. A., Brueggman, J., and Ferti, D. 2010. Polar bear reactions to icebreakers: poster. Presented at the Alaska Marine Sciences Symposium. Anchorage, Alaska.

Smythe, T. A., Loseto, L. L., Bignert, A., Rosenberg, B., Budakowski, W., Halldorson, T., Pleskach, K., *et al.* 2018. Temporal Trends of Brominated and Fluorinated Contaminants in Canadian Arctic Beluga *Delphinapterus leucas*. Arctic Science, AS-2017-0044. https://doi.org/10.1139/AS-2017-0044

Snoeijs-Leijonmalm, P., Flores, H., Sakinan, S., Hildebrandt, N., Svenson, A., Castellani, G., Vane, K., *et al.* 2022. Unexpected fish and squid in the central Arctic deep scattering layer. Science Advances, 8(7): eabj7536. https://doi.org/10.1126/sciadv.abj7536

Snoeijs-Leijonmalm, P., Flores, H., Volckaert, F., Schaafsma, F. L., Niehoff, B., Hjelm, J., Hentati-Sundberg, J., *et al.* 2020. Review of the research knowledge and gaps on fish populations, fisheries and linked ecosystems in the Central Arctic Ocean (CAO). Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2826/387890 (accessed 2024).

Snoeijs-Leijonmalm, P., Gjøsæter, H., Ingvaldsen, R. B., Knutsen, T., Korneliussen, R., Ona, E., Skjoldal, H. R., *et al.* 2021. A deep scattering layer under the North Pole pack ice. Progress in Oceanography, 194: 102560. https://doi.org/10.1016/j.pocean.2021.102560

Sobek, A., and Gustafsson, Ö. 2014. Deep water masses and sediments are main compartments for polychlorinated biphenyls in the Arctic Ocean. Environmental Science & Technology, 48(12): 6719–6725. https://doi.org/10.1021/es500736q

Sobek, A., McLachlan, M. S., Borgå, K., Asplund, L., Lundstedt-Enkel, K., Polder, A., and Gustafsson, Ö. 2010. A comparison of PCB bioaccumulation factors between an Arctic and a temperate marine food web. Science of The Total Environment, 408(13): 2753–2760. https://doi.org/10.1016/j.scitotenv.2010.03.013

Sobek, A., Olli, K., and Gustafsson, Ö. 2006. On the relative significance of bacteria for the distribution of polychlorinated biphenyls in Arctic Ocean surface waters. Environmental Science & Technology, 40(8): 2586–2593. https://doi.org/10.1021/es0524907

Soerensen, A. L., Jacob, D. J., Schartup, A. T., Fisher, J. A., Lehnherr, I., St. Louis, V. L., Heimbürger, L., *et al.* 2016. A mass budget for mercury and methylmercury in the Arctic Ocean. Global Biogeochemical Cycles, 30(4): 560–575. https://doi.org/10.1002/2015GB005280

Soltwedel, T., Bauerfeind, E., Bergmann, M., Bracher, A., Budaeva, N., Busch, K., Cherkasheva, A., *et al.* 2016. Natural variability or anthropogenically-induced variation? Insights from 15 years of multidisciplinary observations at the Arctic marine LTER site HAUSGARTEN. Ecological Indicators, 65: 89–102. https://doi.org/10.1016/j.ecolind.2015.10.001

Soltwedel, T., Bauerfeind, E., Bergmann, M., Budaeva, N., Hoste, E., Jaeckisch, N., von Juterzenka, K., *et al.* 2005. HAUSGARTEN: Multidisciplinary Investigations at a Deep-Sea, Long-Term Observatory in the Arctic Ocean. Oceanography, 18(3): 46–61. https://doi.org/10.5670/oceanog.2005.24

Soltwedel, T., Grzelak, K., and Hasemann, C. 2020. Spatial and Temporal Variation in Deep-Sea Meiofauna at the LTER Observatory HAUSGARTEN in the Fram Strait (Arctic Ocean). *Diversity*, *12*(7), 279. **https://doi.org/10.3390/d12070279**

Søreide, J. E., Leu, A., Berge, J., Graeve, M., and Falk-Petersen, S. 2010. Timing of blooms, algal food quality and *Calanus glacialis* reproduction and growth in a changing Arctic. Global Change Biology, 16: 3154–3163.

Staalesen, A. 2021. Moscow's big plan for trans-Arctic shipping: 2,000 percent growth in 10 years., The Barents Observer. https://thebarentsobserver.com/en/arctic/2021/07/moscows-big-plan-trans-arctic-shipping-2000-percent-growth-10-years

Stafford, K. M. 2019. Increasing detections of killer whales (*Orcinus orca*), in the Pacific Arctic. Marine Mammal Science, 35(2): 696–706. https://doi.org/10.1111/mms.12551

Stafford, K. M., Citta, J. J., Okkonen, S. R., and Zhang, J. 2021. Bowhead and beluga whale acoustic detections in the western Beaufort Sea 2008–2018. PLOS One, 16(6). p.e0253929.

Stafford, K. M., Ferguson, M. C., Hauser, D. D. W., Okkonen, S. R., Berchok, C. L., Citta, J. J., Clarke, J. T., *et al.* 2018. Beluga whales in the western Beaufort Sea: Current state of knowledge on timing, distribution, habitat use and environmental drivers. Deep Sea Research Part II: Topical Studies in Oceanography, 152: 182–194. https://doi.org/10.1016/j.dsr2.2016.11.017

Stanton, D. L., and Cowart, J. R. 2024. The effects of artificial light at night (ALAN) on the circadian biology of marine animals. Frontiers in Marine Science, 11: 1372889. https://doi.org/10.3389/fmars.2024.1372889

Stavridis, J. G. 2010. Forward. *In* Environmental Security in the Arctic Ocean: Promoting Co-operation and Preventing Conflict. Ed. by P. Berkman. Routledge, London.

Steen, H. S., Wold, A., Krapp, R. H., Balto, A. K., Lenss, M. A., Daase, M., Dolinkiewicz, M. E., *et al.* 2023. Arctic Ocean - I - 2023. Cruise number 2023007009, RV Kronprins Haakon June 1 - June 21. Norwegian Polar Institute.

Steenhuisen, F. 2023. Global mercury emissions and distribution – an Arctic perspective. PhD thesis, University of Groningen.

Stein, R., Nam, S-I., Schubert, C., Vogt, C., Futterer, D., and Heinemeier, J. 1994. The Last Deglaciation Event in the Eastern Central Arctic Ocean. Science, 264(5159): 692–696. https://doi.org/10.1126/science.264.5159.692

Steinacher, M., Joos, F., Frölicher, T. L., Plattner, G-K., and Doney, S. C. 2009. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. Biogeosciences, 6(4): 515–533. https://doi.org/10.5194/bg-6-515-2009

Steiner, N. S., Bowman, J., Campbell, K., Chierici, M., Eronen-Rasimus, E., Falardeau, M., Flores, H., *et al.* 2021. Climate change impacts on sea-ice ecosystems and associated ecosystem services. Elementa: Science of the Anthropocene, 9(1): 00007. https://doi.org/10.1525/elementa.2021.00007

Steiner, N. S., Cheung, W. W. L., Cisneros-Montemayor, A. M., Drost, H., Hayashida, H., Hoover, C., Lam, J., *et al.* 2019. Impacts of the Changing Ocean-Sea Ice System on the Key Forage Fish Arctic Cod (*Boreogadus saida*) and Subsistence Fisheries in the Western Canadian Arctic—Evaluating Linked Climate, Ecosystem and Economic (CEE) Models. Frontiers in Marine Science, 6: 179. https://doi.org/10.3389/fmars.2019.00179

Stevenson, T. C., Davies, J., Huntington, H. P., and Sheard, W. 2019. An examination of trans-Arctic vessel routing in the Central Arctic Ocean. Marine Policy, 100: 83–89. https://doi.org/10.1016/j.marpol.2018.11.031

Stewart, E. J., and Dawson, J. 2011. A Matter of Good Fortune: The Grounding of the Clipper Adventurer in the Northwest Passage, Arctic Canada. Arctic, 64(2). https://doi.org/10.14430/arctic4113

Stewart, E. J., and Draper, D. 2008. The sinking of the MS Explorer: Implications for cruise tourism in Arctic Canada. Arctic, 61(2): 224–228. https://doi.org/10.14430/arctic68

Stiasny, M. H., Mittermayer, F. H., Sswat, M., Voss, R., Jutfelt, F., Chierici, M., Puvanendran, V., *et al.* 2016. Ocean Acidification Effects on Atlantic Cod Larval Survival and Recruitment to the Fished Population. PLOS One, 11(8): e0155448. https://doi.org/10.1371/journal.pone.0155448

Stimmelmayr, R., Citta, J., and Scheimreif, K. 2021. 2020-2021 Health Report for the Bering-Chukchi-Beaufort Seas Bowhead Whale. No. SC/68D/ASW/03.

Stockholm Convention. 2001. Stockholm Convention - Home page https://chm.pops.int/default.aspx (accessed 2024).

Stohl, A., Berg, T., Burkhart, J. F., Fjǽraa, A. M., Forster, C., Herber, A., Hov, Ø., *et al.* 2007. Arctic smoke – record high air pollution levels in the European Arctic due to agricultural fires in Eastern Europe in spring 2006. Atmospheric Chemistry and Physics, 7(2): 511–534. https://doi.org/10.5194/acp-7-511-2007

Stoltenberg, J. 2022. NATO is stepping up in the High North to keep our people safe. Op-ed article by NATO Secretary General Jens Stoltenberg - originally published by Canada's Globe and Mail on 24 August 2022. NATO. https://www.nato.int/cps/en/natohq/opinions_206894.htm (accessed 2024).

Stoltenberg, J., and Trudeau, J. 2022. Joint press conference with NATO Secretary General Jens Stoltenberg and the Prime Minister of Canada, Justin Trudeau, 26 August 2022. NATO. https://www.nato.int/cps/en/natohq/opinions_206908.htm (accessed 2024).

Storrie, L., Lydersen, C., Andersen, M., Wynn, R. B., and Kovacs, K. M. 2018. Determining the species assemblage and habitat use of cetaceans in the Svalbard Archipelago, based on observations from 2002 to 2014. Polar Research, 37(1): 1463065. https://doi.org/10.1080/17518369.2018.1463065

Strand, K. O., Huserbråten, M., Dagestad, K-F., Mauritzen, C., Grøsvik, B. E., Nogueira, L. A., Melsom, A., *et al.* 2021. Potential sources of marine plastic from survey beaches in the Arctic and Northeast Atlantic. Science of The Total Environment, 790: 148009. https://doi.org/10.1016/j.scitotenv.2021.148009

Stratmann, T., Mevenkamp, L., Sweetman, A. K., Vanreusel, A., and van Oevelen, D. 2018. Has phytodetritus processing by an abyssal soft-sediment community recovered 26 years after an experimental disturbance? Frontiers in Marine Science, 5: 59.

Stroeve, J. C., Veyssiere, G., Nab, C., Light, B., Perovich, D., Laliberté, J., Campbell, K., *et al.* 2024. Mapping Potential Timing of Ice Algal Blooms from Satellite. Geophysical Research Letters, 51(8): e2023GL106486. https://doi.org/10.1029/2023GL106486

Strøm, H., Boertmann, D., Gavrilo, M. V., Gilchrist, H. G., Gilg, O., Mallory, M., Mosbech, A., *et al.* 2019. Ivory gull: status, trends and new knowledge. *In* NOAA Arctic Report Card 2019. https://arctic.noaa.gov/report-card/report-card-2019/ivory-gull-status-trends-and-new-knowledge/

Sukhanova, I. N., Flint, M. V., Pautova, L. A., Stockwell, D. A., Grebmeier, J. M., and Sergeeva, V. M. 2009. Phytoplankton of the western Arctic in the spring and summer of 2002: Structure and seasonal changes. Deep Sea Research Part II: Topical Studies in Oceanography, 56(17): 1223–1236. https://doi.org/10.1016/j.dsr2.2008.12.030

Sustainable Development. 2024. Home. United Nations Department of Economic and Social Affairs. https://sdgs.un.org/ (accessed 2024).

SUDARCO (Sustainable Development of the Arctic Ocean). 2023. Framforum. https://framforum.com/2023/02/28/sustainable-development-of-the-arctic-ocean/ (accessed 2024).

Sweeney, S. O., Terhune, J. M., Frouin-Mouy, H., and Rouget, P. A. 2022. Assessing potential perception of shipping noise by marine mammals in an Arctic inlet. The Journal of the Acoustical Society of America, 151(4): 2310–2325. https://doi.org/10.1121/10.0009956

Sweetman, A., Levin, L., Rapp, H., and Schander, C. 2013. Faunal trophic structure at hydrothermal vents on the southern Mohn's Ridge, Arctic Ocean. Marine Ecology Progress Series, 473: 115–131. https://doi.org/10.3354/meps10050

Synoptic Arctic Survey. 2024. Synoptic Arctic Survey. http://synopticarcticsurvey.w.uib.no/ (accessed 2024).

Syvertsen, E. E. 1991. Ice algae in the Barents Sea: types of assemblages, origin, fate and role in the ice-edge phytoplankton bloom. Polar Research, 10(1): 277–288. https://doi.org/10.3402/polar.v10i1.6746

Szesciorka, A. R., Stafford, K. M., and Berchok, C. L. 2024. Basin-Wide Shift in Bowhead Whale Migration in the Pacific Arctic. Geophysical Research Letters, 51(4): e2023GL106416. https://doi.org/10.1029/2023GL106416

Søreide, J. E., Leu, E., Berge, J., Graeve, M., and Falk-Petersen, S. 2010. Timing of blooms, algal food quality and *Calanus glacialis* reproduction and growth in a changing Arctic. Global Change Biology, 16(11): 3154–3163. https://doi.org/10.1111/j.1365-2486.2010.02175.x

Tamburri, M. N., Soon, Z. Y., Scianni, C., Øpstad, C. L., Oxtoby, N. S., Doran, S., and Drake, L. A. 2022. Understanding the potential release of microplastics from coatings used on commercial ships. Frontiers in Marine Science, 9: 1074654. https://doi.org/10.3389/fmars.2022.1074654

Tartu, S., Aars, J., Andersen, M., Polder, A., Bourgeon, S., Merkel, B., Lowther, A. D., *et al.* 2018. Choose Your Poison—Space-Use Strategy Influences Pollutant Exposure in Barents Sea Polar Bears. Environmental Science & Technology, 52(5): 3211–3221. https://doi.org/10.1021/acs.est.7b06137

Taylor, J., Krumpen, T., Soltwedel, T., Gutt, J., and Bergmann, M. 2017. Dynamic benthic megafaunal communities: Assessing temporal variations in structure, composition and diversity at the Arctic deep-sea observatory HAUSGARTEN between 2004 and 2015. Deep Sea Research Part I: Oceanographic Research Papers, 122: 81–94. https://doi.org/10.1016/j.dsr.2017.02.008

Taylor, J., Staufenbiel, B., Soltwedel, T., and Bergmann, M. 2018. Temporal trends in the biomass of three epibenthic invertebrates from the deep-sea observatory HAUSGARTEN (Fram Strait, Arctic Ocean). Marine Ecology Progress Series, 602: 15–29. https://doi.org/10.3354/meps12654

Teichert, S., Löder, M. G. J., Pyko, I., Mordek, M., Schulbert, C., Wisshak, M., and Laforsch, C. 2021. Microplastic contamination of the drilling bivalve *Hiatella arctica* in Arctic rhodolith beds. Scientific Reports, 11(1): 14574. https://doi.org/10.1038/s41598-021-93668-w

Tekman, M. B., Gutow, L., and Bergmann, M. 2022. Marine Debris Floating in Arctic and Temperate Northeast Atlantic Waters. Frontiers in Marine Science, 9: 933768. https://doi.org/10.3389/fmars.2022.933768

Tekman, M. B., Krumpen, T., and Bergmann, M. 2017. Marine litter on deep Arctic seafloor continues to increase and spreads to the North at the HAUSGARTEN observatory. Deep Sea Research Part I: Oceanographic Research Papers, 120: 88–99. https://doi.org/10.1016/j.dsr.2016.12.011

Tekman, M. B., Wekerle, C., Lorenz, C., Primpke, S., Hasemann, C., Gerdts, G., and Bergmann, M. 2020. Tying up Loose Ends of Microplastic Pollution in the Arctic: Distribution from the Sea Surface through the Water Column to Deep-Sea Sediments at the HAUSGARTEN Observatory. Environmental Science & Technology, 54(7): 4079–4090. https://doi.org/10.1021/acs.est.9b06981

Terhaar, J., Kwiatkowski, L., and Bopp, L. 2020. Emergent constraint on Arctic Ocean acidification in the twenty-first century. Nature, 582(7812): 379–383. https://doi.org/10.1038/s41586-020-2360-3

Tervo, O. M., Blackwell, S. B., Ditlevsen, S., Conrad, A. S., Samson, A. L., Garde, E., Hansen, R. G., *et al.* 2021. Narwhals react to ship noise and airgun pulses embedded in background noise. Biology Letters, 17(11): 20210220. https://doi.org/10.1098/rsbl.2021.0220

Tetu, P., Dawson, J., and Lasserre, F. 2019. The evolution and relative competitiveness of global Arctic cruise tourism destinations. *In* Arctic Shipping: Climate Change, Commercial Traffic and Port Development, pp. 94–114. Ed. by F. Lasserre, and O. Faury. Routledge, London.

Teuten, E. L., Saquing, J. M., Knappe, D. R. U., Barlaz, M. A., Jonsson, S., Björn, A., Rowland, S. J., *et al.* 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526): 2027–2045. https://doi.org/10.1098/rstb.2008.0284

The Future We Want | Department of Economic and Social Affairs. 2024. https://sdgs.un.org/future-we-want (accessed 2024).

The Nansen Legacy. 2023. The Nansen Legacy: Annual Report 2022. No. 40/2023, The Nansen Legacy Report Series. https://doi.org/10.7557/nlrs.7069

Timmermans, M. L., and Marshall, J. 2020. Understanding Arctic Ocean circulation: A review of ocean dynamics in a changing climate. Journal of Geophysical Research: Oceans, 125(4): 2018 014378. https://doi.org/10.1029/2018JC014378

Timoshenko, D. S. 2019. Features of promotion and sustainable development of the Russian region of the Arctic as a competitive tourist destination. Theoretical and Applied Issues of Geographical Science: Demographic, Social, Legal, Economic and Ecological Aspects, 2: 186–190.

Timoshenko, D. S. 2020. Sustainable Tourism Development in the Russian Arctic: Challenges And Prospects. IOP Conference Series: Earth and Environmental Science, 539(1): 012097. https://doi.org/10.1088/1755-1315/539/1/012097

Timoshenko, D. S. 2021. Tourism branding of the Russian Arctic destinations. IOP Conference Series: Earth and Environmental Science, 625(1): 012020. https://doi.org/10.1088/1755-1315/625/1/012020

Tolstoy, M., Bohnenstieh, R. R., and Chapp, E. 2004. Long range acoustic propagation of high frequency energy in the Indian Ocean from icebergs and earthquakes. *In* Proceedings of the 26th Seismic Research Review: Trends in Nuclear Explosion Monitoring, pp. 568–578. National Nuclear Security Administration, Air Force Research Laboratory.

Tonkes, H. 2012. Phytoplankton composition of central Arctic Ocean in summer 2011: with special emphasis on pico- and nanoplankton. Masters thesis, Wageningen University and Research.

Toxværd, K., van Dinh, K., Henriksen, O., Hjorth, M., and Nielsen, T. G. 2018. Impact of Pyrene Exposure during Overwintering of the Arctic Copepod *Calanus glacialis*. Environmental Science & Technology, 52(18): 10328–10336. https://doi.org/10.1021/acs.est.8b03327

Tremblay, J-É., Bélanger, S., Barber, D. G., Asplin, M., Martin, J., Darnis, G., Fortier, L., *et al.* 2011. Climate forcing multiplies biological productivity in the coastal Arctic Ocean. Geophysical Research Letters, 38(18): n/a-n/a. https://doi.org/10.1029/2011GL048825

Tremblay, J-É., Raimbault, P., Garcia, N., Lansard, B., Babin, M., and Gagnon, J. 2014. Impact of river discharge, upwelling and vertical mixing on the nutrient loading and productivity of the Canadian Beaufort Shelf. Biogeosciences, 11(17): 4853–4868. https://doi.org/10.5194/bg-11-4853-2014

Tremblay, J-É., Robert, D., Varela, D. E., Lovejoy, C., Darnis, G., Nelson, R. J., and Sastri, A. R. 2012. Current state and trends in Canadian Arctic marine ecosystems: I. Primary production. Climatic Change, 115(1): 161–178. https://doi.org/10.1007/s10584-012-0496-3

Trevail, A. M., Gabrielsen, G. W., Kühn, S., and van Franeker, J. A. 2015. Elevated levels of ingested plastic in a high Arctic seabird, the northern fulmar (*Fulmarus glacialis*). Polar Biology, 38(7): 975–981. https://doi.org/10.1007/s00300-015-1657-4

Tyack, P. L. 2008. Implications for marine mammals of large-scale changes in the marine acoustic environment. Journal of Mammalogy, 89(3): 549–558. https://doi.org/10.1644/07-MAMM-S-307R.1

Tzu, S. 5th Century BCE. The Art of War (Oldest Military Treatise in the World).

Ubl, S., Scheringer, M., Stohl, A., Burkhart, J. F. and Hungerbuhler, K. 2012. Primary source regions of polychlorinated biphenyls (PCBs) measured in the Arctic. Atmospheric Environment, 62: 391–399.

Ulfsbo, A., Cassar, N., Korhonen, M., van Heuven, S., Hoppema, M., Kattner, G., and Anderson, L. G. 2014. Late summer net community production in the central Arctic Ocean using multiple approaches. Global Biogeochemical Cycles, 28(10): 1129–1148. https://doi.org/10.1002/2014GB004833

UN. 1995. The United Nations Fish Stocks Agreement Overview. https://www.un.org/oceancapacity/UNFSA (accessed 2024).

UN. 1995. Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks. Law of the Sea, Chapter 21. United Nations Treaty Collection, Vol. 2167, p. 3. https://treaties.un.org/pages/viewdetails.aspx?src=treaty&mtdsg_no=xxi-7&chapter=21&clang=_en

UN. 2002. World Summit on Sustainable Development, Johannesburg. https://www.un.org/en/conferences/environment/johannesburg2002 (accessed 2024).

UN. 2023. Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction. https://www.un.org/Depts/los/bbnj.htm (accessed 2024).

UNCLOS. 1982. United Nations Convention on the Law of the Sea. https://treaties.un.org/Pages/Treaties.aspx?id=21&subid=A&clang=_en

UNCTAD. 2021. Global Trade Update February 2021, Global Trade Updates. Geneva: United Nations Commission on Trade and Development. https://unctad.org/publication/global-trade-update-february-2021

UNEP. 1982. Environmental law guidelines and principles: Offshore mining and drilling. http://digitallibrary.un.org/record/42519

UNEP. 2009. Marine Litter: A Global Challenge. United Nations Environment Programme (UNEP), Nairobi.

UNEP. 2016. Marine Plastic Debris and Microplastics: Global Lessons and Research to Inspire Action and Guide Policy Change. United Nations Environment Programme (UNEP), Nairobi. https://wedocs.unep.org/20.500.11822/7720

UNEP. 2020. Global Plan of Action (GPA)., UNEP - UN Environment Programme. http://www.unep.org/explore-topics/oceans-seas/what-we-do/working-regional-seas/partners/global-plan-action-gpa (accessed 2024).

UNEP. 2021. From Pollution to Solution. A global assessment of marine litter and plastic pollution. UNITED Nations Environment Program (UNEP), Nairobi.

UNFCCC. 2015. The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement (accessed 2024).

UNFCCC. 2024. What is the United Nations Framework Convention on Climate Change? https://unfccc.int/process-and-meetings/what-is-the-united-nations-framework-convention-on-climate-change (accessed 2024).

Unger, B., Herr, H., Benke, H., Böhmert, M., Burkhardt-Holm, P., Dähne, M., Hillmann, M., *et al.* 2017. Marine debris in harbour porpoises and seals from German waters. Marine Environmental Research, 130: 77–84. https://doi.org/10.1016/j.marenvres.2017.07.009

Urick, R. J. 1983. Principles of underwater sound, 3rd ed. McGraw-Hill, Hamburg, New York.

Uryupova, E. 2023. Global interest in the Arctic region: Naval operations impacting scientific-commercial activities. Polar Record, 2023;59:e8. https://doi.org/10.1017/S0032247422000419

Vacquié-Garcia, J., Lydersen, C., Biuw, M., Haug, T., Fedak, M. A., and Kovacs, K. M. 2017. Hooded seal *Cystophora cristata* foraging areas in the Northeast Atlantic Ocean—Investigated using three complementary methods. PLOS One, 12(12): e0187889. https://doi.org/10.1371/journal.pone.0187889

Vacquié-Garcia, J., Lydersen, C., Ims, R. A., and Kovacs, K. M. 2018. Habitats and movement patterns of white whales *Delphinapterus leucas* in Svalbard, Norway in a changing climate. Movement Ecology, 6(1): 21. https://doi.org/10.1186/s40462-018-0139-z

Vacquié-Garcia, J., Lydersen, C., Marques, T., Aars, J., Ahonen, H., Skern-Mauritzen, M., Øien, N., *et al.* 2017a. Late summer distribution and abundance of ice-associated whales in the Norwegian High Arctic. Endangered Species Research, 32: 59–70. https://doi.org/10.3354/esr00791

Vacquié-Garcia, J., Lydersen, C., Marques, T., Andersen, M., and Kovacs, K. 2020. First abundance estimate for white whales *Delphinapterus leucas* in Svalbard, Norway. Endangered Species Research, 41: 253–263. https://doi.org/10.3354/esr01016

Valotto, G., and Varin, C. 2016. Characterization of hourly NOx atmospheric concentrations near the Venice International Airport with additive semi-parametric statistical models. Atmospheric Research, 167: 216–223. https://doi.org/10.1016/j.atmosres.2015.07.023

van Engeland, T., Bagøien, E., Wold, A., Cannaby, H. A., Majaneva, S., Vader, A., Rønning, J., *et al.* 2023. Diversity and seasonal development of large zooplankton along physical gradients in the Arctic Barents Sea. Progress in Oceanography, 216: 103065. https://doi.org/10.1016/j.pocean.2023.103065

van den Heuvel-Greve, M. J., Brink, A. M., Glorius, S. T., Groot, G. A., Laros, I., Renaud, P. E., Pettersen, R., *et al.* 2021. Early detection of marine non-indigenous species on Svalbard by DNA metabarcoding of sediment. Polar Biology, 44(4): 653–665. https://doi.org/10.1007/s00300-021-02822-7

van Leeuwe, M. A., Tedesco, L., Arrigo, K. R., Assmy, P., Campbell, K., Meiners, K. M., Rintala, J-M., *et al.* 2018. Microalgal community structure and primary production in Arctic and Antarctic sea ice: A synthesis. Elementa: Science of the Anthropocene, 6: 4. https://doi.org/10.1525/elementa.267

van Sebille, E., England, M. H., and Froyland, G. 2012. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environmental Research Letters, 7(4): 044040. https://doi.org/10.1088/1748-9326/7/4/044040

van Waerebeek, K., Baker, A. N., Félix, F., Gedamke, J., Iñiguez, M., Sanino, G. P., Secchi, E., *et al.* 2007. Vessel collisions with small cetaceans worldwide and with large whales in the Southern Hemisphere, an initial assessment. Latin American Journal of Aquatic Mammals, 6(1): 43–69. https://doi.org/10.5597/lajam00109

Varnajot, A., and Saarinen, J. 2021. 'After glaciers?' Towards post-Arctic tourism. Annals of Tourism Research, 91: 103205. https://doi.org/10.1016/j.annals.2021.103205

Varpe, Ø., Daase, M., and Kristiansen, T. 2015. A fish-eye view on the new Arctic lightscape. ICES Journal of Marine Science, 72(9): 2532–2538. https://doi.org/10.1093/icesjms/fsv129

Vedenin, A., Gusky, M., Gebruk, A., Kremenetskaia, A., Rybakova, E., and Boetius, A. 2018. Spatial distribution of benthic macrofauna in the Central Arctic Ocean. PLOS One, 13(10): e0200121. https://doi.org/10.1371/journal.pone.0200121

Vedenin, A. A., Mironov, A. N., Bluhm, B. A., Käß, M., Degen, R., Galkin, S. V., and Gebruk, A. V. 2022. Uniform bathymetric zonation of marine benthos on a Pan-Arctic scale. Progress in Oceanography, 202: 102764. https://doi.org/10.1016/j.pocean.2022.102764

Venn-Watson, S., Colegrove, K. M., Litz, J., Kinsel, M., Terio, K., Saliki, J., Fire, S., *et al.* 2015. Adrenal Gland and Lung Lesions in Gulf of Mexico Common Bottlenose Dolphins (*Tursiops truncatus*) Found Dead following the Deepwater Horizon Oil Spill. PLOS One, 10(5): e0126538. https://doi.org/10.1371/journal.pone.0126538

Vesman, A., Moulin, E., Egorova, A., and Zaikov, K. 2020. Marine litter pollution on the Northern Island of the Novaya Zemlya archipelago. Marine Pollution Bulletin, 150: 110671. https://doi.org/10.1016/j.marpolbul.2019.110671

Vienna Convention for the Protection of the Ozone Layer. 1987. https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-2&chapter=27&clang=_en (accessed 2024).

Vieweg, I., Bender, M. L., Semenchuk, P. R., Hop, H., and Nahrgang, J. 2021. Effects of chronic crude oil exposure on the fitness of polar cod (*Boreogadus saida*) through changes in growth, energy reserves and survival. Marine Environmental Research, 174: 105545. https://doi.org/10.1016/j.marenvres.2021.105545

Villanger, G. D., Lydersen, C., Kovacs, K. M., Lie, E., Skaare, J. U., and Jenssen, B. M. 2011. Disruptive effects of persistent organohalogen contaminants on thyroid function in white whales (*Delphinapterus leucas*) from Svalbard. Science of The Total Environment, 409(13): 2511–2524. https://doi.org/10.1016/j.scitotenv.2011.03.014

Visalli, M. E., Best, B. D., Cabral, R. B., Cheung, W. W. L., Clark, N. A., Garilao, C., Kaschner, K., *et al.* 2020. Data-driven approach for highlighting priority areas for protection in marine areas beyond national jurisdiction. Marine Policy, 122: 103927. https://doi.org/10.1016/j.marpol.2020.103927

von Benda-Beckmann, A. M., Aarts, G., Sertlek, H. Ö., Lucke, K., Verboom, W. C., Kastelein, R. A., Ketten, D. R., *et al.* 2015. Assessing the Impact of Underwater Clearance of Unexploded Ordnance on Harbour Porpoises (*Phocoena phocoena*) in the Southern North Sea. Aquatic Mammals, 41(4): 503–523. https://doi.org/10.1578/AM.41.4.2015.503

von Duyke, A. L., Douglas, D. C., Herreman, J. K., and Crawford, J. A. 2020. Ringed seal (*Pusa hispida*) seasonal movements, diving, and haul-out behavior in the Beaufort, Chukchi, and Bering Seas (2011–2017). Ecology and Evolution, 10(12): 5595–5616. https://doi.org/10.1002/ece3.6302

van Franeker, J. A., Kühn, S., Anker-Nilssen, T., Edwards, E. W. J., Gallien, F., Guse, N., Kakkonen, J. E., *et al.* 2021. New tools to evaluate plastic ingestion by northern fulmars applied to North Sea monitoring data 2002–2018. Marine Pollution Bulletin, 166: 112246. https://doi.org/10.1016/j.marpolbul.2021.112246

von Quillfeldt, C. H. 2000. Common Diatom Species in Arctic Spring Blooms: Their Distribution and Abundance. Botanica Marina, 43(6). https://doi.org/10.1515/BOT.2000.050

Votier, S. C., Archibald, K., Morgan, G. and Morgan, L., 2011. The use of plastic debris as nesting material by a colonial seabird and associated entanglement mortality. Marine Pollution Bulletin, 62:168-172.

Vylegzhanin, A. N., Young, O. R., and Berkman, P. A. 2020. The Central Arctic Ocean Fisheries Agreement as an element in the evolving Arctic Ocean governance complex. Marine Policy, 118: 104001. https://doi.org/10.1016/j.marpol.2020.104001

Wadhams, P., and Davis, N. R. 2000. Further evidence of ice thinning in the Arctic Ocean. Geophysical Research Letters, 27(24): 3973–3975. https://doi.org/10.1029/2000GL011802

Walker, T. R., Adebambo, O., Del Aguila Feijoo, M. C., Elhaimer, E., Hossain, T., Edwards, S. J., Morrison, C. E., *et al.* 2019. Environmental Effects of Marine Transportation. *In*: World Seas: An Environmental Evaluation, pp. 505–530. . Elsevier. https://doi.org/10.1016/B978-0-12-805052-1.00030-9

Walther, B. A., and Bergmann, M. 2022. Plastic pollution of four understudied marine ecosystems: a review of mangroves, seagrass meadows, the Arctic Ocean and the deep seafloor. Emerging Topics in Life Sciences, 6(4): 371–387. https://doi.org/10.1042/ETLS20220017

Wang, Y., Chen, X., Guo, W., and Zhou, H. 2018. Distinct bacterial and archaeal diversities and spatial distributions in surface sediments of the Arctic Ocean. FEMS Microbiology Letters, 365(24). https://doi.org/10.1093/femsle/fny273

Wang, Z., Na, G., Gao, H., Wang, Y. and Yao, Z., 2014. Atmospheric concentration characteristics and gas/particle partitioning of PCBs from the North Pacific to the Arctic Ocean. Acta Oceanologica Sinica, 33(12), pp.32-39.

Ware, C., Berge, J., Jelmert, A., Olsen, S. M., Pellissier, L., Wisz, M., Kriticos, D., *et al.* 2016. Biological introduction risks from shipping in a warming Arctic. Journal of Applied Ecology, 53: 340–349. https://doi.org/10.1111/1365-2664.12566

Ware, C., Berge, J., Sundet, J. H., Kirkpatrick, J. B., Coutts, A. D. M., and Jelmert, A. 2014. Climate change, non-indigenous species, and shipping: Assessing the risk of species introduction to a high-Arctic Archipelago. Diversity and Distributions, 20: 10–19. https://doi.org/10.1111/ddi.12117

Warren, S. D., and Büttner, R. 2006. Documentation of disturbance-dependent threatened and endangered species on US Army-Europe training areas in Bavaria. No. 06–05, CMML TPS. Center for Environmental Management of Military Lands, Fort Collins, CO, USA.

Warren, S. D., Holbrook, S. W., Dale, D. A., Whelan, N. L., Elyn, M., Grimm, W., and Jentsch, A. 2007. Biodiversity and the Heterogeneous Disturbance Regime on Military Training Lands. Restoration Ecology, 15(4): 606–612. https://doi.org/10.1111/j.1526-100X.2007.00272.x

Wartzok, D., Watkins, W. A., Wursig, B., and Malme, C. I. 1989. Movements and behaviors of bowhead whales in response to repeated exposures to noises associated with industrial activities in the Beaufort Sea. Report from Purdue University, Fort Wayne, IN, for Amoco Production Co., P.O. Box 800, Denver, CO 80201.

Washburn, T. W., Turner, P. J., Durden, J. M., Jones, D. O. B., Weaver, P., and Van Dover, C. L. 2019. Ecological risk assessment for deep-sea mining. Ocean & Coastal Management, 176: 24–39. https://doi.org/10.1016/j.ocecoaman.2019.04.014

Wassmann, P., Carmack, E. C., Bluhm, B. A., Duarte, C. M., Berge, J., Brown, K., Grebmeier, J. M., *et al.* 2020. Towards a unifying pan-arctic perspective: A conceptual modelling toolkit. Progress in Oceanography, 189: 102455. https://doi.org/10.1016/j.pocean.2020.102455

Wassmann, P., Duarte, C. M., Agustí, S., and Sejr, M. K. 2011. Footprints of climate change in the Arctic marine ecosystem. Global Change Biology, 17(2): 1235–1249. https://doi.org/10.1111/j.1365-2486.2010.02311.x

Wassmann, P., Kosobokova, K. N., Slagstad, D., Drinkwater, K. F., Hopcroft, R. R., Moore, S. E., Ellingsen, I., *et al.* 2015. The contiguous domains of Arctic Ocean advection: Trails of life and death. Progress in Oceanography, 139: 42–65. https://doi.org/10.1016/j.pocean.2015.06.011

Wassmann, P., and Reigstad, M. 2011. Future Arctic Ocean Seasonal Ice Zones and Implications for Pelagic-Benthic Coupling. Oceanography, 24(3): 220–231. https://doi.org/10.5670/oceanog.2011.74

Watt, C. A., Heide-Jørgensen, M. P., and Ferguson, S. H. 2013. How adaptable are narwhal? A comparison of foraging patterns among the world's three narwhal populations. Ecosphere, 4(6): 1–15. https://doi.org/10.1890/ES13-00137.1

Wei, C-L., Rowe, G. T., Escobar-Briones, E., Boetius, A., Soltwedel, T., Caley, M. J., Soliman, Y., *et al.* 2010. Global Patterns and Predictions of Seafloor Biomass Using Random Forests. PLOS One, 5(12): e15323. https://doi.org/10.1371/journal.pone.0015323

Welch, H., Clavelle, T., White, T. D., Cimino, M. A., van Osdel, J., Hochberg, T., Kroodsma, D., *et al.* 2022. Hot spots of unseen fishing vessels. Science Advances, 8(44): eabq2109. https://doi.org/10.1126/sciadv.abq2109

Werth, A. J., Blakeney, S. M., and Cothren, A. I. 2019. Oil adsorption does not structurally or functionally alter whale baleen. Royal Society Open Science, 6(5): 182194. https://doi.org/10.1098/rsos.182194

Werth, A. J., Kahane-Rapport, S. R., Potvin, J., Goldbogen, J. A., and Savoca, M. S. 2024. Baleen–Plastic Interactions Reveal High Risk to All Filter-Feeding Whales from Clogging, Ingestion, and Entanglement. Oceans, 5(1): 48–70. https://doi.org/10.3390/oceans5010004

Węsławski, J. M., and Kotwicki, L. 2018. Macro-plastic litter, a new vector for boreal species dispersal on Svalbard. Polish Polar Research, 39(1): 165–174. https://doi.org/10.24425/118743

Westing, A. H. 1971. Ecological Effects of Military Defoliation on the Forests of South Vietnam. BioScience, 21(17): 893–898. https://doi.org/10.2307/1295667

WGICA. 2023. ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean. (https://www.ices.dk/community/groups/Pages/WGICA.aspx).

Williams, T. M., Blackwell, S. B., Tervo, O., Garde, E., Sinding, M. S., Richter, B., and Heide-Jørgensen, M. P. 2022. Physiological responses of narwhals to anthropogenic noise: A case study with seismic airguns and vessel traffic in the Arctic. Functional Ecology, 36(9): 2251–2266. https://doi.org/10.1111/1365-2435.14119

Wilson Center. 2023. Deterring Russia at Sea in the High North. https://www.wilsoncenter.org/event/deterring-russia-sea-high-north

Wolkers, H., Lydersen, C., Kovacs, K. M., Burkow, I., and van Bavel, B. 2006. Accumulation, metabolism, and food-chain transfer of chlorinated and brominated contaminants in subadult white whales (*Delphinapterus leucas*) and narwhals (*Monodon monoceros*) from Svalbard, Norway. Archives of Environmental Contamination and Toxicology, 50: 69–78.

Wood, H. L., Spicer, J. I., and Widdicombe, S. 2008. Ocean acidification may increase calcification rates, but at a cost. Proceedings of the Royal Society B: Biological Sciences, 275(1644): 1767–1773. https://doi.org/10.1098/rspb.2008.0343

Woodgate, R., Stafford, K., and Prahl, F. 2015. A Synthesis of Year-Round Interdisciplinary Mooring Measurements in the Bering Strait (1990–2014) and the RUSALCA Years (2004–2011). Oceanography, 28(3): 46–67. https://doi.org/10.5670/oceanog.2015.57

Woody, C. 2022. The US Coast Guard's biggest ship made a rare trip to the North Pole amid warnings about Russian and Chinese moves in the Arctic. Business Insider. https://www.businessinsider.com/coast-guard-icebreaker-healy-visits-north-pole-amid-arctic-activity-2022-10 (accessed 2024).

Yakushev, E., Gebruk, A., Osadchiev, A., Pakhomova, S., Lusher, A., Berezina, A., van Bavel, B., *et al.* 2021. Microplastics distribution in the Eurasian Arctic is affected by Atlantic waters and Siberian rivers. Communications Earth & Environment, 2(1): 23. https://doi.org/10.1038/s43247-021-00091-0

Yamaguchi, A., Ashjian, C. J., and Campbell, R. G. 2022. Comparison of population structure, vertical distribution and growth of sympatric, carnivorous, mesopelagic copepods, *Paraeuchaeta glacialis* and *Heterorhabdus norvegicus*, in the western Arctic Ocean. Journal of Plankton Research, 44(3): 443–453. https://doi.org/10.1093/plankt/fbac019

Yamamoto-Kawai, M., McLaughlin, F. A., Carmack, E. C., Nishino, S., Shimada, K., and Kurita, N. 2009. Surface freshening of the Canada Basin, 2003–2007: River runoff versus sea ice meltwater. Journal of Geophysical Research: Oceans, 114(C1): 2008JC005000. https://doi.org/10.1029/2008JC005000

Yamashita, R., Hiki, N., Kashiwada, F., Takada, H., Mizukawa, K., Hardesty, B. D., Roman, L., *et al.* 2021. Plastic additives and legacy persistent organic pollutants in the preen gland oil of seabirds sampled across the globe. Environmental Monitoring and Contaminants Research, 1(0): 97–112. https://doi.org/10.5985/emcr.20210009

Yamazaki, E., Taniyasu, S., Wang, X. and Yamashita, N., 2021. Per-and polyfluoroalkyl substances in surface water, gas and particle in open ocean and coastal environment. Chemosphere, 272, p.129869.

Yang, H., Ma, M., Thompson, J. R., and Flower, R. J. 2018. Transport expansion threatens the Arctic. In: Science, 359(6376): 646–647. https://doi.org/10.1126/science.aar5443

Yang, Q., Dixon, T. H., Myers, P. G., Bonin, J., Chambers, D., van den Broeke, M. R., Ribergaard, M. H., *et al.* 2016. Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic overturning circulation. Nature Communications, 7(1): 10525. https://doi.org/10.1038/ncomms10525

Yeung, L. W., Dassuncao, C., Mabury, S., Sunderland, E. M., Zhang, X., and Lohmann, R. 2017. Vertical profiles, sources, and transport of PFASs in the Arctic Ocean. Environmental Science & Technology, 51(12): 6735–6744. https://doi.org/10.1021/acs.est.7b00788

Ytreberg, E., Hansson, K., Lunde Hermansson, A.., Parsmo, R., Lagerström, M., Jalkanen, J-P., and Hassellöv, I-M. 2022. Metal and PAH loads from ships and boats, relative other sources, in the Baltic Sea. Marine Pollution Bulletin, 182: 113904. https://doi.org/10.1016/j.marpolbul.2022.113904

Ytreberg, E., Åström, S., and Fridell, E. 2021. Valuating environmental impacts from ship emissions – The marine perspective. Journal of Environmental Management, 282: 111958. https://doi.org/10.1016/j.jenvman.2021.111958

Zakharov, D. V., Manushin, I. E., Nosova, T. B., Strelkova, N. A., and Pavlov, V. A. 2021. Diet of snow crab in the Barents Sea and macrozoobenthic communities in its area of distribution. ICES Journal of Marine Science, 78: 545–556. https://doi.org/10.1093/icesjms/fsaa132

Zantis, L. J., Carroll, E. L., Nelms, S. E., and Bosker, T. 2021. Marine mammals and microplastics: A systematic review and call for standardisation. Environmental Pollution, 269: 116142. https://doi.org/10.1016/j.envpol.2020.116142

Zhang, X., Zhang, Y., Dassuncao, C., Lohmann, R., and Sunderland, E. M. 2017. North Atlantic Deep Water formation inhibits high Arctic contamination by continental perfluorooctane sulfonate discharges. Global Biogeochemical Cycles, 31(8): 1332–1343. https://doi.org/10.1002/2017GB005624

Zhulay, I., Bluhm, B. A., Renaud, P. E., Degen, R., and Iken, K. 2015. Functional Pattern of Benthic Epifauna in the Chukchi Borderland, Arctic Deep Sea. Frontiers in Marine Science, 8. https://doi.org/10.3389/fmars.2021.609956

Zhulay, I., Iken, K., Renaud, P. E., and Bluhm, B. A. 2019. Epifaunal communities across marine landscapes of the deep Chukchi Borderland (Pacific Arctic). Deep Sea Research Part I: Oceanographic Research Papers, 151: 103065. https://doi.org/10.1016/j.dsr.2019.06.011

Zhulay, I., Iken, K., Renaud, P. E., Kosobokova, K., and Bluhm, B. A. 2023. Reduced efficiency of pelagic–benthic coupling in the Arctic deep sea during lower ice cover. Scientific Reports, 13(1): 6739. https://doi.org/10.1038/s41598-023-33854-0

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Annex 2: List of abbreviations

CAO	Central Arctic Ocean
ABNJ	Area beyond national jurisdictions
ACAP	Arctic Contaminants Action Program working group of the Arctic Council
ACGF	Arctic Coast Guard Forum
ACIA	Arctic Climate Impact Assessment report of the Arctic Council
AIS	Automatic identification system
ALOIS	The Arctic lithosphere-ocean interaction study
AMAP	Arctic Monitoring and Assessment Programme working group of the Arctic Council
AMEC	Arctic military environmental cooperation
ArDWL	Arctic deep-water layer
ASTD	Arctic ship traffic data
ATBA	Areas to be avoided
ATV	All-terrain vehicles
AtWL	Intermediate Atlantic water layer
BAH	Bahamas-flagged vessels
Basel Convention	Basel Convention on the Control of Transboundary Movements of Wastes and Other Hazardous Wastes and their Disposal
BBNJ	Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction
BC	Black carbon
BR	Body residue
BWM	Ballast water and sediments
BWMC	International Convention for the Control and Management of Ships' Ballast Water and Sediments
CAFF	Conservation of Arctic Flora and Fauna working group of the Arctic Council
CAN	Canadian-flagged vessels
CAO	Central Arctic Ocean
CAOFA	The International Agreement to Prevent Unregulated Fishing in the High Seas of the Central Arctic Ocean
CB	Critical body residue
CBD	Convention on biological diversity
CH_4	Methane

CHR	Chinese-flagged vessels
CI	Confidence Interval
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CLSC	Commission on the Limits of the Continental Shelf
CMS	Convention on the Conservation of Migratory Species of Wild Animals
CO	Carbon monoxide
CO_2	Carbon dioxide
COLREG	Convention on International Regulations for Preventing Collisions at Sea
Consultative Process	United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea
COP	Conference of the Parties
COVID-19	Coronavirus disease 2019
Cu	Copper
dB	Decibel
DLS	Deep-scattering layer
DVM	Diel vertical migration
dw	Dry weight
EA	Ecosystem approach
EBM	Ecosystem-based management
ECAs	Emission control areas
ECE	Economic Commission for Europe of the United Nations
EcoQO	Ecological quality objective
EEZ	Exclusive economic zones
EPPR	Emergency Prevention, Preparedness, and Response working group of the Arctic Council
ESPOO	Espoo city in Finland where the Convention on Environmental Impact Assessments was signed
FAO	Food and Agriculture Organization of the United Nations
FRA	French-flagged vessels
FSA	Sector-specific fish stocks agreement
FYI	First-year ice
GER	German-flagged vessels
GO-SHIP	The Global Ocean Ship-Based Hydrographic Investigations Program
GPA	Global Programme of Action for the Protection of the Marine Environment from Land-based Activities

HACON	Hot Vents in an Ice-Covered Ocean
HFO	Heavy fuel oil
Hg	Mercury
Hz	Hertz
IASSA	International Arctic Social Sciences Association
ICES	The International Council for the Exploration of the Sea
ICEX	Ice exercise
IEA	Integrated ecosystem assessment
IMO	International Maritime Organization
IOC	Intergovernmental Oceanographic Commission
ISAC	International Arctic Science Committee
IWC	International Whaling Commission
JOIS-BGOS	The Joint Ocean Ice Study (JOIS)-Beaufort Gyre Observing System (BGOS)
JPSRM	Joint Program of Scientific Research and Monitoring under the Scientific Coordinating Group of CAOFA
KOR	Republic of Korea-flagged vesssels
LME	Large marine ecosystems
London Convention	Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter
LRTAP	Convention on Long-range Transboundary Air Pollution
MAI	Marshall Islands-flagged vessels
MARPOL	International Convention for Prevention of Pollution from Ships
MeHg	Methylmercury
MLAE	Russian Marine Live-Ice Automobile Expedition
MOSAiC	Multidisciplinary drifting observatory for the Study of Arctic Climate
MP	Marine litter particles
MYI	Multi-year ice
N2O	Nitrous oxide
NABOS	Nansen and Amundsen Basin Observing System
NAMMCO	North Atlantic Marine Mammal Commission
NATO	North Atlantic Treaty Organization
NEAFC	Northeast Atlantic Fisheries Commission
NIS	Non-indigenous species
nmi	Nautical miles
NOR	Norwegian-flagged vessels

NO_x	Nitrogen oxides
NTH	Netherland-flagged vessels
OC	Organic carbon
ODEMM	Options for Delivering Ecosystem-Based Marine Management
OHCs	Organohalogenated compounds
OPRC	International Convention on Oil Preparedness, Response and Co-operation
OSPAR	Convention for the Protection of the Marine Environment of the Northeast Atlantic (Combining Oslo Convention on Dumping
PAME	Protection of the Marine Environment working group of the Arctic Council
PAN	Panama-flagged
PASSION	Pan-Arctic Observing System of Systems Implementing Observations for Societal Needs
PBDE	Polybrominated diphenyl ether
PBSG	Polar Bear Specialist Group (Under IUCN)
PCB	Polychlorinated biphenyl
PFAS	Per- and polyfluoroalkyl substances
PICES	North Pacific Marine Science Organization
PM	Particulate matter
PML	Polar mixed layer
Polar Code	International Code for Navigation in Polar Waters
POP	Persistent organic pollutant
PSSA	Particularly sensitive sea srea
RFMA	Regional Fishery Management Arrangement
RFMO	Regional Fishery Management Organization
RQ	Risk quotient (RQ = BR / CBR)
RUS	Russian-flagged vessels
S-AIS	Satellite
SDWG	Sustainable Development Working Group of the Arctic Council
SHEBA	Surface Heat Budget of the Arctic Ocean study
SOLAS	International Convention for the Safety of Life at Sea
SO_x	Sulfur oxides
spp.	Multiple species within a genus (plural of sp.)
SUDARCO	Sustainable Development of the Arctic Ocean
SUIT	Special surface and under-ice trawl

SWD	Swedish-flagged vessels
THg	Total mercury
TSS	Traffic separation schemes
UFP	Ultrafine particle
UNCED	United Nations Conference on Environment and Development
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United Nations Environment Program
UNFCCC	United Nations Convention Framework Convention on Climate Change
UNFSA	United Nations Fish Stock Agreement
UNGA	United Nations General Assembly
US	USA-flagged vessels
UXO	Unexploded ordnance
VAN	Vanuatu-flagged vessels
WGICA	ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean
ww	Wet weight
XBT	Expendable bathythermograph
Zn	Zinc

Annex 3: Global sources – additional papers on contaminants

Some additional information was found for other contaminant types, such as organochlorine pesticides (Table A3.1).

Table A3.1. Reported concentrations of other contaminants in several compartments of the CAO.

Compound	Sample type	Location	Sampling year	Reported concentrations	Reference
Organochlorine pesticides (DDT)	Seawater	CAO	2001–2005	0.10–66 pg L^{-1}	Carrizo *et al.*, 2017
Organochlorine pesticides (DDTs, HCHs, and CHLs)	Sediment	Bering Strait, Chuckchi Sea, border CAO	2008	Sum DDTs: 0.64–3.17 ng g^{-1} DW Sum HCHs: 0.19–0.65 ng g^{-1} DW SumCHLs: 0.03–0.16 ng g^{-1} DW	Jin *et al.*, 2017

Additionally, information on contaminant studies in the adjacent areas was compiled (Table A3.2).

Table A3.2. Contaminant concentrations in compartments surrounding the CAO.

Compound	Sample type	Location	Sampling year	Reference
Hg	Seawater, sediment, biota (amphipods, clams, snow crabs, polar cod and whelks)	Northeastern Chukchi Sea	2009, 2010	Fox *et al.*, 2014
PCBs, pesticides	Seawater	Fram Strait		Ma *et al.*, 2018
PCBs	Air, seawater	North Atlantic, Fram Strait, border of Eurasian shelf	2004	Gioia *et al.* 2008
PFAS	Seawater	North Atlantic to Fram Strait	2018	Joerss *et al.*, 2020
PFAS	Seawater	Western Arctic Ocean – on border of Amerasian shelf (R/V "Mirai") – Bering Strait	2013	Yamazaki *et al.*, 2021
PCBs, pesticides	Seawater	Fram Strait		Ma *et al.*, 2018
PCBs, PBDEs, and pesticides	River water	Arctic rivers: Ob and Yenisey	2003, 2005	Carroll *et al.*, 2008
PCBs	River water	Pan-Arctic		Carrizo and Gustafsson, 2011b
PCBs, PBDEs and pesticides	River water	Arctic rivers: Ob and Yenisey	2003, 2005	Carroll *et al.*, 2008
PCBs	Air	Monitoring stations around the CAO	Long-term	Carlsson *et al.*, 2018
PCBs	Air	North Pacific to Arctic Ocean	2012	Wang *et al.*, 2014
PCBs	Air	Monitoring stations around the CAO		Ubl *et al.*, 2012