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Ecosystem Assessment of the Central Arctic Ocean: Description of Human activities, its Pressures and Vulnerability of the Ecosystem.

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Picture: Polar bear on the sea-ice. Used by the permission of - Research cruises - Institute of Marine Research

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I Summary

Pressures occurring in the Central Arctic Ocean (CAO) are both a result of human activities that take place locally in the CAO, such as research, tourist and military ship-traffic and people on the icecap, or far away and arriving the CAO by global sources such as air, rivers and ocean current.

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/sea-ice disturbance, Artificial light pollution, Unintended injury and mortality in open water, Human presence on ice, are the 11 pressures that was recognised as relevant for the CAO. The impact of climate change originated from human activity (the Pressure "heating") are not included in this work because Climate change is not a local activity that can be managed locally, and neither does the pressure" "heating" comes from any other of the human activities in the CAO.

Ice prokaryotes and viruses, Water column and seafloor prokaryotes and viruses, Ice algae, Phytoplankton, Ice invertebrates, Zooplankton, Pelagic squid, Softbottom and hardbottom benthos, Sympagic-, Mesopelagic-, and Demersal/benthos-pelagic fish, Polar bear, Ringed seal, Bowhead whale, Narwhals/Beluga whale, Transients-, Seasonal Resident- and Ice obligates sea birds were the group/species of relevant ecosystem components of the CAO. Most groups were considered with a population that were widely distributed across the entire CAO, while some few groups had limited distribution on the seafloor (Hardbottom benthos), in the water column (the whales), or along the ice-edge (ice obligate seabirds and ringed seal). While most ecosystem components were present inside the CAO year-round, some few components (whales, Transients-, Seasonal Resident seabirds) were only present for some few months.

Some of the relevant pressures introduced by sources in the CAO are anticipated to have an impact on all (e.g., Contaminants), some (e.g., Artificial noise pollution) or few/non (e.g., Nutrient and organic enrichment) of the ecosystem component in the CAO.

II Foreword

The ICES-PICES-PAME Working Group on Integrated Ecosystem Assessment of the Central Arctic Ocean (WGICA) is to conduct integrated ecosystem assessments (IEA) of the Central Arctic Ocean (CAO). The assessment of the CAO is a 3 step process:

- compiling all relevant information on the biology, human activities and sources, the pressures and the vulnerability of the ecosystem necessary – here we used definitions, methods, and glossaries already in use by ICES ref <u>https://ices-</u><u>library.figshare.com/articles/report/ICES_Ecosystem_Overviews_Technical_Guidelines/22059803</u> and adopted these to the CAO (see Report 1, 2 and the Ecosystem Overview of the CAO, ICES 2021),
- the scoring process (online workshops) with the multiple disciplinary groups of scientists
 evaluating/scoring the spatial, temporal overlap of the pressures from each of the sources with
 the ecosystem component population, the degree of vulnerability of each of the ecosystem
 component, the longevity of the longest living species within the ecosystem component and the
 persistence of the pressures when released in the environment,
- the ranking and evaluation of the risk-scoring resulting in the final assessment for the CAO (see Ecosystem Overview of the CAO, Jørgensen et al in prep, and future regularly produced assessments in the WGICA)

This report 2 builds on *the description of the ecosystem* in Report 1 (Skjoldal et al 2022) and provides a description of the human activities and global sources, what pressures they produce, and how these pressure impact ecosystem components in the Central Arctic Ocean, or CAO. Beside the global sources bringing in pressures via air, rivers and ocean currents, the relevant human activity for the CAO includes science-, tourist-, and military ship traffic and a limited amount of people on the icecap, arrived by air og by ships. A set of 11 pressures derived from these sources are identified and described. Furthermore, are the entire CAO ecosystem, from the smallest bacteria to the largest sea mammals, divided into 19 ecosystem components and described for their spatial distribution and temporal occurrences in the CAO. Each of these are also described for their vulnerability toward relevant pressures from human activities and global sources. These information's is the foundation for ongoing and future assessment of the CAO that have (Ecosystem Overview, Jørgensen et al in prep) or will evaluate the risk of human activities on the ecosystem components.

Why are we doing an IEA for the CAO? It 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 Central Arctic Ocean (CAO) (Figure 1.1) mostly comprises high seas areas remote from any landmass, including deep basins and slopes up to depths of approximately 500 m, as well as some shallower shelf areas of the bordering Beaufort/Chukchi and East Siberian/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 parallel or the 200-mile Exclusive Economic Zones (EEZs) in the Beaufort/Chukchi seas. The Central Arctic Ocean ecoregion seabed consists of two large deep basins (between 3800 and 4500 m deep), the Eurasian Basin, and the Amerasian Basin, separated by the Lomonosov Ridge. This ~1300 m deep ridge consists of steep slopes rising about 3000 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 Advice 2022).



The Northern Sea Route is anticipated to become a major Arctic shipping lane, and the Russian government intends to boost annual transit volumes on the Northern Sea Route from 1,3 million tons in 2020 to 30 million tons in 2030 (Barents Observer 2021). The shipping activity will give rise to a range of different pressures on the environment, both related to accidents (collisions, groundings and sinking of ships), and from normal ship operations resulting in various emissions (including energy and noise) and discharges from the ships (Jalkanen et al. 2018, Hannah et al 2020; Jalkanen et al. 2021, Moldanová et al. 2021). While the frequency of accidental oil spills has steadily decreased since the 1970s (ITOPF 2017), 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, these constitute floating towns, and they give rise to a range of waste streams to the marine environment.

Cruise ship accidents have happened in the past (discussed in Stewart and Draper 2008; Stewart and Dawson 2011). It is thus not a question whether they will occur again, but when these events will occur. There is a large body of evidence that all stresses caused by ship traffic and human activity are already impacting on the Arctic ecosystem (e.g. Nahrgang et al. 2016; Kühn et al. 2018; Peeken et al. 2018), but the available data are not suitable to disentangle the effect of cruise ships from other anthropogenic sources.

Additional disturbances associated with tourism are disturbance include landing operations with small boats, and air operations, e.g., helicopter tours (Hagen et al. 2012). These activities cause microplastics pollution, among other emissions into air and water. Finally, the prospects of modern military activities, extending to the point of military conflict, cause dramatic habitat alteration, environmental pollution, and disturbance that contribute to population declines and biodiversity losses arising from both acute and chronic effects in terrestrial and aquatic systems (Lawrence et al. 2015). The degree to which warfare can exert an impact upon an ecosystem and its constituent populations rests entirely on the nature of the disturbance, the sensitivity of the biological system (including resilience), and the timescale of the impacts (Westing 1971; Demarais et al. 1999; Dudley et al. 2002; Warren and Büttner 2006; Warren et al. 2007).

the Arctic sea-ice diminishes, the CAO is likely to become an increasingly important last resort for high-Arctic species that depend on summer ice. There has been a large loss in sea ice since the 1990s in what is termed the "Great melt", with a pronounced change from heavier multiyear pack ice to thinner annual ice.

Stress can be caused to ecosystem components in the CAO by the effects of human activities on the seabed, in the pelagic zone or on/within the resort of the shrinking ice habitat. This report will advance on identifying the most vulnerable ecosystem components toward the pressures from the variety of relevant sources of the CAO. The intention is, along with Report 1, to provide all the background necessary to do an assessment of what risk "pressures" from all the sources poses to the ecosystem components.

We will follow the ODEMM approach and definitions:

Contaminants (70): Introduction of pesticides, antifoulants, pharmaceuticals, heavy metals and hydrocarbons into marine waters.

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

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

Artificial noise pollution: Underwater sound from anthropogenic sources (e.g. shipping, fishing, geological investigations, harbour operations).

Nutrient and organic enrichment: Organic enrichment e.g. from industrial and sewage effluent input and/or fertilisers, and other nitrogen & phosphorous rich substances into rivers and coastal areas. Include organic discards e.g. from aquaculture or fishing discards.

Extraction of species: Targeted extraction of species.

Physical seabed or sea-ice disturbance: Physical interaction of human activities with the seafloor and with seabed fauna/flora causing physical damage and/or mortality (e.g. from trawling or anchoring), excluding death or injury due to collision. Abrasion may cause damage to spawning grounds. Artificial light pollution Not defoned 8.9 Unintended injury 8.10 Human presence on ice

This will, in a following step, prepare a set of science based advise to guid national authorities surrounding the CAO, as well as international processes such as the Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean (CAO-FA) and Marine Biodiversity of Areas Beyond National Jurisdiction (BBNJ).

2 Global sources of pressures

2.1 Introduction routes into the CAO

Martine van den Heuvel-Greve, Bjørn Einar Grøsvik, Lis Lindal Jørgensen Haakon Hop, Tom Christensen; Hilde Elise Heldal, Randi Ingvaldsen,

Some pressures occurring in the Central Arctic Ocean can be a result of human activities that take place outside the CAO, sometimes even far away. This is partly the case for the following pressures: non-indigenous species (NIS), contaminants and marine litter. They reach the CAO via ocean currents, rivers and atmospheric deposition (Figure 2.1). Details of these pressures will be described in this chapter, organized per pressure. Several processes exist that influence the inflow in 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, UNEP/GRID-Arendal From AMAP collection: <u>https://www.grida.no/resources/7021</u>)

The Arctic Ocean is an enclosed ocean that communicates with the North Atlantic through the Fram Strait (2600 m) and the Barents Sea, and with the Pacific Ocean through the shallow (50 m) and narrow (85 km) Bering Strait. The Fram Strait is the only gateway allowing for a two-way deep exchange (Rudels, 2015). The Central Arctic Ocean 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 to 79% of the water in the Arctic Ocean, while the inflow through the Bering Strait is estimated to contribute to 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 the 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 sub-surface 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 (> 1000 m) Arctic Ocean (Schauer et al., 1997; Rudels et al., 2004; Rudels et al., 2015). With this, contaminants and marine litter brought into the Arctic can be transferred to great depths where it stays for a considerable amount of time, with only little escape out of the system through the Fram Strait.

The Arctic is under the influence of the Beaufort High centered over the Canadian Basin 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 Central Arctic Ocean and further towards the Fram Strait.

Many rivers flow from the massive, surrounding continents into the CAO (Rudels and Carmack, 2022), which leads to the ocean receiving some 11% of the globe's fresh water (Yakushev et al., 2021). The flow of freshwater between the land, the atmosphere, and the ocean is increasing. Besides fresh water, Arctic rivers are pouring enormous quantities of sediment, nutrients, and organic carbon into the Arctic Ocean every year (AMAP, 2017). An intensification of shelf-derived material inputs to the central basin may be a source to 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 light absorbing airborne pollutants (Black Carbon aerosols) in quantities that well exceed the background levels (Backman et al., 2021), of 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 of microplastic particles produced by road traffic (tire wear particles and brake wear particles) modeled to be of similar magnitude as the total estimated direct and riverine transport of such particles to the ocean (Evangeliou et al., 2020).

Air pollution resulting from agricultural waste burning in Eastern Europe (mostly Russia, the Baltic countries, Belorussia, and the Ukraine) took 3-4 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 a travel time of 3-4 weeks (Stohl et al., 2006). Unusually high concentrations of PCBs, far away from the sources, were also proposed to be caused by such biomass burning emissions (Eckhardt et al., 2007), further showing that long distance atmospheric transport of contaminants towards the Arctic region is happening.

2.2 Non-indigenous species

2.2.1 What is "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 does it occur in the CAO

There are currently no records of NIS in the CAO.

In case NIS are brought into the CAO, 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 is currently limited to a few research vessels, tourist icebreakers, and military vessels. In addition, ice stations have been used for both research and tourist purposes. Because of the ongoing decline in sea ice extent and volume, and opening of northern sea routes, shipping will be further increasing in the next decades (Rosenhaim et al., 2019), hereby 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 non-native marine organisms (Ware et al., 2014, 2016). The IMO regulation (see Chapter 5) allows ballast water to be exchanged in open sea (hence the CAO) but encourages the ships to install special equipment for treatment of ballast water (IMO, 2004). There are also national ballast water regulations in e.g. Norway (Norwegian Ministry of the Environment, 2009). Biofouling, which includes the undesirable accumulation of marine organisms on submerged structures, such as the hull of ships, may also be a vector for spreading of non-indigenous species to the CAO. However, when ships enter and sail through sea ice, the hulls are typically cleaned by abrasion for most of the attached organisms. Non-binding IMO Biofouling Guidelines have been developed to encourage the control and management of ships' biofouling to minimize the transfer of invasive aquatic species.

Floating macro-plastic (e.g., litter) can also transport (boreal) species to the Arctic, for example gooseneck barnacles *Lepas* sp., blue mussels, 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 can probably not establish populations in the deep basin of the CAO.

In the coastal areas surrounding the CAO, so far, only species related to hard substrate have been recorded, and as stated above, these species are not likely to find a suitable habitat in the deep CAO basins. These coastal marine invaders (located in the Svalbard archipelago) include e.g. the barnacles *Amphibalanus improvisus* and *Austrominius modestus*, the blue mussel *Mytilus edulis*, the crab species *Carcinus maenas*, *Paralithodes camtschaticus*, and *Chionoecetes opilio*, and potentially the tunicates *Botrylloides violaceus* and *Molgula manhattensis* (Nilssen & Sundet, 2006; Ware et al., 2016; Leopold et al., 2019; Van den Heuvel-Greve et al., 2021; Zakharov et al., 2021).

2.2.3 When does it occur in the CAO

There are currently no records of NIS in the CAO.

2.3 Contaminants

2.3.1 What are "contaminants"

Contaminants are chemical elements or compounds that may be naturally occurring or manmade.

The current focus in this report is placed on the available information on levels of mercury (Hg), polychlorinated biphenyls (PCBs), polybrominated biphenylethers (PBDEs), per- and polyfluoroalkyl substances (PFAS) in sea water, sediment and biota in the CAO. PCBs, PBDEs and PFAS are man-made or industrial-made chemicals. Mercury (Hg) and radioactive compounds can origin from both natural and industrial sources. Data on additional contaminant types are compiled in tables.

Radioactivity is discussed in a separate section.

Bioaccumulation of contaminants

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

2.3.2 Where does it occur in the CAO

Contaminants can be transported to the Arctic region via air currents, rivers and ocean currents (see Figure 1 of 2.1; AMAP, 1998). The North East Atlantic Current transports water masses northwards together with nutrients, plankton and other marine organisms, but also 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, sediment, snow, sea-ice and biota in the CAO, and these data are not recent. 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 some old, archived samples for biota (1983-1998).

Contaminant concentrations in sea water

The latest assessment of status and trends of **mercury (Hg)** in the Arctic was performed in 2021 (AMAP, 2021). Rivers and coastal erosion were identified to be dominant transport pathways for the delivery of methylmercury (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 CAO. Methylmercury that accumulates in Arctic food webs is produced within the Arctic (AMAP, 2021). 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 food webs (AMAP, 2021).

The major pathways of **PCBs** into the CAO seemed to be river discharge, atmospheric deposition and ocean currents. Highest concentrations were found in the shelf seas and lower concentrations in the Central Arctic Basin (Figure 2.2, Carrizo & Gustafsson, 2011). 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 Basin, indicating a predominant atmospheric source, whereas hexachlorinated PCBs were more abundant in the western sector, pointing at a larger contribution from waterborne transport from North America and Europe (Figure 2.2, Carrizo & Gustafsson, 2011). PCB concentrations were increasing with depth in the water column of the CAO Nansen, Amundsen, and Makarov basins (Figure 2.3; Sobek & Gustafsson 2014, Table 2.1). Highest concentrations were observed in the deep water and lowest in the upper Polar Mixed Layer (PML). Smaller chlorinated PCBs (tri-, tetra- and pentachlorinated PCBs) dominated in water, whereas larger chlorinated PCBs (penta- and hexachlorinated PCBs) dominated in sediment (Sobek & Gustafsson, 2014).



Figure 2.2 Left: Total concentration of Σ 13PCBs in surface seawater of the seven pan-Arctic shelf seas and the interior basin (pg/L), based on data from three expeditions in 2001, 2005, and 2008. Right: Σ 13PCBs inventories (kilograms) and relative congener distribution based on the degree of chlorination for each of the seven Arctic shelf seas and for the Central Interior Basin. Both figures are derived from Carrizo & Gustafsson, 2011.



Figure 2.3. Extrapolated Σ 7PCB concentration in the Arctic Ocean (pg/L) in A) surface water, and B) depth profile along a section in the CAO (see black arrow in the left figure) (Sobek & Gustafsson, 2014).

PBDEs were observed in sea water samples from the CAO (Salvadó et al. 2016) with Σ 14PBDE concentrations ranging from 0.3-11.2 pg/L in the upper Polar Mixed Layer (PML) (Table 2.1). Lower levels were observed in the interior basin compared with the surrounding shelf seas (Figure 2.4). Σ 14PBDE concentrations in the deeper water masses were up to one order of magnitude higher than those in the surface water. Lower brominated congeners, particularly BDE-47 and BDE-99, increased with increasing depth. Also, the concentration of BDE-71 increased with depth (Table 2.2). As this congener is not present in any PBDE commercial mixture, this was thought to be the result of debromination of the BDE-209.



Figure 2.4. Left: Spatial distribution of Σ 14PBDE concentrations (pg/L) in the Arctic Polar Mixed Layer. Right: Relative abundance of the tri- to deca-BDE congeners in the Polar Mixed Layer of the different Pan-Arctic shelf seas and the CAO. (Salvadó et al. 2016).

Table 2.1. The concentration of the Polybrominated diphenyl ether BDE-71 in three different waterbodie	S
of the Central Arctic Ocean (CAO) (Salvadó et al. 2016).	

Waters of the CAO	BDE-71 concentration
Polar Mixed Layer	158 ± 77 kg
Intermediate Atlantic Water Layer	6320 ± 235 kg
Arctic Deep Water Layer	30800 ± 3100 kg

PFAS were observed in sea water samples collected from the Eurasian Basin of the CAO (Yeung et al. 2017), in concentrations of 11–174 pg/L S13PFAS (Table 2.2). PFAS was mainly limited to the PML and halocline (150 m below the surface). Main PFAS compounds observed were PFOA, PFOS, PFBS, PFNA, PFHxA, PFHpA, PFDS, PFHxS, and PFUnDA. PFAS profiles varied with location and depth. This may point at different sources for PFAS (atmosphere, ocean currents and rivers) and ocean circulation patterns. Higher concentrations of PFAS were observed in PML water than those of PCBs as these 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 and is predicted to continue to increase to 2038 (Yeung et al. 2017). This was also found in modelling studies, in which it was estimated that in 2015 30% of the PFOS discharges from North America and Europe had reached the CAO, 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, the deeper waters below 1000 m were thought to have increased PFOS concentrations (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 SPFAS concentrations in snow and melt ponds were 403 ± 405 pg/L. Atmospheric deposition is thought to be an important source for PFAS in the Eurasian part of the CAO, especially due to the proximity to Eurasian continental atmospheric emissions (Yeung et al. 2017).

Compound	Sample type	Location	Sampling year	Reported concentrations	Reference
Mercury (Hg)	Sea water	CAO and wider Arctic			AMAP, 2021. AMAP Assessment 2021: Mercury in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. viii + 324pp.
PCBs	Sea water	CAO	2001 (Oden expedition)	Concentrations of the sum of the seven PCB congeners (Σ7PCB) in the Nansen Basin increased from 0.7 pg/L in the surface polar mixed layer to 3.6 pg/L and 4.5 pg/L in the Atlantic water layer and Arctic deep water layer, respectively. POC concentrations decreased accordingly by a	Sobek, A. & Gustafsson, O., 2014. Deep water masses and sediments are main compartments for polychlorinated biphenyls in the Arctic Ocean. Environmental science & technology, 48(12), pp.6719-6725.

				factor of 10–30 from the polar mixed layer to the Arctic deep water layer, supporting a strong particle dissolution/mineralization- influence on the vertical distribution of PCBs.	
PCBs	Sea water	CAO and surrounding shelf seas	2001, 2005, 2008	Concentrations of the Sum- 13PCB were 0.13-21 pg/L, with higher concentrations in the shelf seas and lower concentrations in the Central Arctic Basin.	Carrizo, D., & Gustafsson, O., 2011. 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.
PBDEs	Sea water	CAO	2001 (Oden SWEDARCTIC expedition), 2005 (Oden SWEDARCTIC expedition)	Σ14PBDE concentrations in the Polar Mixed Layer range from 0.3 to 11.2 pg/L. In deep-water masses, Σ14PBDE concentrations are up to 1 order of magnitude higher than in the Polar Mixed Layer.	Salvadó, J.A., Sobek, A., Carrizo, D. and Gustafsson, O., 2016. Observation-based assessment of PBDE loads in Arctic Ocean waters. Environmental science & technology, 50(5), pp.2236-2245.
PFAS	Sea water, snow, melt pond water	CAO (and Beaufort Chuckchi shelf)	2012 (Polarstern ARK-XXII/3 expedition, August- September)	In sea water: Surface water concentrations of total PFASs in the Central Arctic Ocean ranged from 11–174 pg/L. 13 PFASs (C6–C12, PFCAs; C6, 8, 10 PFSAs; MeFOSAA and EtFOSAA; and FOSA) were routinely detected. Average SumPFAS concentrations in snow and melt ponds on sea ice: 403 ± 405 pg/L.	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), pp.6735-6744.

Contaminant concentrations in sediment

Marine sediments from eight locations in the Arctic Ocean Basin showed **mercury (Hg)** concentrations varying from <5 ng/g up to 170 ng/g (Gleason et al. 2017) (Table 2.3). 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, although other sources, as well as influences of sea ice, atmospheric mercury depletion events, and anthropogenic Hg (in core top samples) on Hg isotopic signatures must also be considered (Gleason et al. 2017).

Atmospheric deposition is nowadays thought to be a major source of mercury (Hg) to the Arctic Ocean, resulting in approximately 100 metric tons of Hg to be added annually to the Arctic Ocean, 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 mercury dominating the total Hg pool for Arctic marine sediments (e.g. Soerensen et al. 2016).

PFAS concentrations in surface sediments were $1.3 \pm 0.5 \text{ ng/g} \Sigma 14 \text{PFAS}$, based on dry weight, at the border of the Amerasian basin in 2010 (Kahkashan et al. 2019) (Table 2.3). The main PFAS

components consisted of Perfluoro-butanoic acid (PFBS) and Perfluoro-octanoic 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 the low to moderate levels when compared with other coastal and marine sediments worldwide.

Compound	Sample type	Location	Sampling year	Reported concentrations	Reference
Mercury (Hg)	Surface sediment	CAO	2009	Lomonosov Ridge 120 ng/g	Gleason, J.D., Blum, J.D., Moore, T.C., Polyak, L., Jakobsson, M., Meyers, P.A.,
			2005 Lomonoso	Lomonosov Ridge 113 ng/g	Biswas, A. 2017. Sources and cycling of mercury in the paleo Arctic Ocean from He
			2005	Mendeleev Ridge 55 ng/g	stable isotope variations in Eocene and
			2005	Yearmak Plateau 55 ng/g	Cosmochimica Acta 197; 245–262.
			1996	Lomonosov Ridge 31 ng/g	
PFAS (also organochlorine pesticides)	Sediment	Bering Strait, Chuckchi Sea, border of CAO	2010 (4 th CHINARE expedition, July- September)	Total concentrations (dry weight) of S14PFAS in surface sediments in the Arctic Ocean were 1.27 ± 0.53 ng/g.	Kahkashan, S., Wang, X., Chen, J., Bai, Y., Ya, M., Wu, Y., Cai, Y., Wang, S., Saleem, M., Aftab, J. and Inam, A., 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, pp.959-968.

Table 2.3. Reported contaminant concentrations in sediment of the CAO.

Contaminant concentrations in biota

Contaminant data in biota in the CAO is severely lacking. Information on contaminant levels in biota of the CAO was found in one publication (Bidleman et al., 2013) (Table 2.4). **Hg**, **PCB** and **PBDE** levels in archived samples (1983-1998) of the scavenging amphipod, *Eurythenes gryllus*, from the deep sea were reported to be 55-1023 ng/g ww Σ Hg, 1020-74100 ng/g lw Σ 104PCBs, and 27-1140 ng/g lw Σ 7PBDEs.

Table 2.4	Reported	contaminant	concentrations	in	biota	of the	CAO.
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Compound	Sample type	Location	Sampling year	Reported concentrations	Reference
Mercury (Hg), PCBs, chlorobenzenes, organochlorine pesticides, and PBDEs	Biota	CAO – deep basin	1983 – 1998	Archived specimens of the scavenging amphipodEurythenes gryllus, collected from 2075 to4250 m below the surface on five expeditions to the western and central Arctic Ocean (1983 and 1998): Σ 104PCBs: 102074100 ng/g lw Σ 7PBDEs: 27-1140 ng/g lw Σ Hg: 55-1023 ng/g ww	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), pp.5553-5561.

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PCBs	Bacteria	CAO: northern Barents Sea, Makarov Basin east of the 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 were 0.5-5 ng/g OC (organic carbon).	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), pp.2586-2593.
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Concentrations in biota from surrounding areas

In shelf seas surrounding the CAO, some long-term marine **time-series** can be found for mussels, fish, birds and mammals (Figure 2.5) (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 ago or sex (Rigét et al. 2019). Lowest statistical power was found in fish liver and muscle, probably due to the low contaminant levels found in these samples. Therefore, some additional information on contaminant concentrations in marine mammals and birds from areas surrounding the CAO is compiled below.



Figure 2.5. Map of locations with long-term marine time-series of contaminants in areas surrounding the CAO. Symbols indicate animal group. Included also are freshwater fish and air monitoring stations. From: <u>AMAP</u> (2016) and Rigét et al. (2019).

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

In feathers of nine migratory seabird species, mercury (Hg) concentrations during the nonbreeding period were approximately three times higher than during the breeding period, and spatial differences existed within and between the Atlantic and Pacific regions (Figure 2.6) (Albert et al. 2021).



Figure 2.6. Mean mercury concentrations (μ g/g dry weight) in feathers of nine migratory seabird species, 2015-2017 (Albert et al. 2021).

Marine mammals in the Arctic live long and have thick blubber (lipid) layers. Those feeding on invertebrates, such as the bowhead whale and walrus, have lower contaminant concentrations in their tissue than marine mammals that feed on fish, such as seals, beluga and narwhals (O'Hara et al. 1999). Highest concentrations can be found 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 traditional diet (O'Hara et al. 1999). Indigenous people living on St Lawrence Island, situated in the Pacific Gateway to the Arctic Ocean, had much higher body burdens of PCBs in their blood than populations on the main land of the US and Canada, which was considered to be a results of long-range transport of PCBs to the Arctic (Miller et al. 2013).

A recent review of contaminants in polar bears from the circumpolar Arctic showed that contaminants such as Hg, PCBs, PBDEs, PFOS and other PFAS are the main contaminants to which polar bears are exposed (Routti et al. 2019). Circumpolar spatial trends varied largely between compounds (Figure 2.7).



Figure 2.7. Circumpolar trends of contaminants in polar bear: $ng/g \ lw \ \Sigma PCBs$ (upper left) and $ng/g \ lw \ \Sigma PBDEs$ (upper right) in fat tissue, $ng/g \ ww \ PFOS/\Sigma PFCA$ ($\Sigma PFAS$) in liver, and $\mu g/g \ Hg \ Hg$ in hair (Routti et al. 2019).

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 ww Hg 244-3389 ng/g ww Σ12PCB 2.10- 55.3 ng/g ww Σ5BDE 18.6- 118 ng/g ww Σ3PFAS (PFOA, PFNA, PFOS)	Lucia, M., Verboven, N., Strøm, H., Miljeteig, C., Gavrilo, M.V., Braune, B.M., Boertmann, D. and Gabrielsen, G.W., 2015. Circumpolar contamination in eggs of the high-Arctic ivory gull Pagophila 23burnean. Environmental toxicology and chemistry, 34(7), pp.1552-1561.

Table 2.5. /	Reported	contaminant	concentrations	in biota in	areas directly	y surrounding th	he CAO
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Mercury (Hg)	Feathers	Circumpolar breeding grounds of seabirds	2015-2017	During breeding:Overall mean Hg concentration: $1.20 \pm$ 0.83μ g/g dwHighest Hg concentration in the West Atlantic ($0.41-$ 6.97μ g/g)Lowest Hg concentration in crested auklets ($1.00 \pm 0.51 \mu$ g/g) and the highest in rhinoceros auklets ($3.47 \pm 1.63 \mu$ g/g)Non-breeding: 	Albert, C., Helgason, H.H., Brault-Favrou, M., Robertson, G.J., Descamps, S., Amélineau, F., Danielsen, J., Dietz, R., Elliott, K., Erikstad, K.E. and Eulaers, I., 2021. Seasonal variation of mercury contamination in Arctic seabirds: a pan-Arctic assessment. Science of the Total Environment, 750, p.142201.
PCBs	Bowhead blubber and liver	Barrow, Alaska	1992-1993	26 bowhead blubber samples: mean of 459 ng/g lw 11 bowhead liver samples: mean of 980 ng/g lw	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), pp.741-752.
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 mg:kg lipid) Ringed seal:	Muir, D.C. and Norstrom, R.J., 2000. Geographical differences and time trends of persistent organic pollutants in the Arctic. Toxicology Letters, 112, pp.93- 101.
Mercury (Hg), PCBs, PBDEs, PFAS and other compounds	Polar bear: Hair for Hg Adipose tissue (fat) for PCBs/PBDEs 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 Hg in hair 945-8187 ng/g lw ΣPCBs in fat 4.4-68 ng/g lw ΣPBDEs in fat	Routti, H., Atwood, T.C., Bechshoft, T., Boltunov, A., Ciesielski, T.M., Desforges, J.P., Dietz, R., Gabrielsen, G.W., Jenssen, B.M., Letcher, R.J. and McKinney, M.A., 2019. State of knowledge on current exposure, fate and potential health effects of contaminants in polar

				527-1070 ng/g ww ΣPFAS in liver	bears from the circumpolar Arctic. Science of the Total Environment, 664, pp.1063-1083.
PCBs	Human blood	St Lawrence Island, Bering Sea	2001-2003	bowhead oil – blubber samples: > 300 ng/g ww bearded and spotted seal, polar bear and bowhead whale mungtak samples (blubber and skin): > 100 ng/g ww	Miller, P.K., Waghiyi, V., Welfinger-Smith, G., Byrne, S.C., Kava, J., Gologergen, J., Eckstein, L., Scrudato, R., Chiarenzelli, J., Carpenter, D.O. and Seguinot-Medina, S., 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), p.21656.

Contaminant trends

Contaminant levels measured in air at the Zeppelin observatory at Svalbard show a general decrease in levels of most contaminants measured, although the levels of mercury have decreased only 14 % since 1994, while emission levels to air in Europe have decreased by 61 % over the same period (<u>https://miljostatus.miljodirektoratet.no/tema/hav-og-kyst/havindikatorer/barentshavet/forurensende-stoffer/lufttilforsler-av-miljogifter-til-barentshavet/</u>).

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 to 30 years, although it must be noted that the main decrease of PCBs occurred before 2000 (Figure 2.4) (Rigét et al. 2019). PFOS and PBDEs showed a common trend of a concentration increase until about the mid-2000s followed by decreasing concentrations (Figure 2.8).



Figure 2.8. PFOS concentrations (annual medians) in ringed seal from West Greenland (red) and ringed seal (blue) and polar bear (black) from East Greenland (Rigét et al. 2019).

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 is resting at 1673 m in the Norwegian Sea is leaking radioactive contamination to the marine environment (e.g. Gwynn et al., 2018; Heldal et al., 2019). 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 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 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/m3 and 10 Bq/kg, respectively (Skjerdal et al., 2020).

2.3.3 When does it occur in the CAO

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

2.4 Marine litter, incl. micro plastics

2.4.1 What is "Marine litter"

Marine litter is "garbage", particularly when made of plastic and microplastic is part of the definition of litter. Litter is one of the most pervasive stressors affecting marine ecosystems globally (UNEP, 2009; UNEP, 2016, UNEP, 2021). Without meaningful action, plastic waste into aquatic ecosystems is projected to nearly triple by 2040 (UNEP, 2021). Marine litter follows the definitions used in PAME (PAME, 2019). 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.

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 below) composed of plastic items greater than 5mm 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 macro - Plastic litter exists in various sizes and is often commonly defined as macro plastic (items larger than 5mm), micro plastic (items smaller than 5 mm in diameter), and nano plastic (particles with a size equal to, or smaller than 100 nm (1/10 000 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.

Initiatives on mitigation and guidelines for harmonisation and monitoring in the Arctic

Marine plastics, microplastics and their toxicity have been examined and identified (AMAP, 2017) 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 (SDWG, 2019), and the Kola Waste project (ACAP, 2021), which all contributes 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 involve responses to the distribution and effects of plastic pollution (PAME, 2021), including on Arctic seabirds and sea ducks (CAFF, 2021a, CAFF, 2021b, CAFF, 2021c), and plastics 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 (PAME, 2019, AMAP, 2021a). 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, 2021).

2.4.2 Where does it occur in the CAO

Litter is present in all parts of the ocean (Figures 2.9, 2.10), even where there is no or little population (PAME, 2019; AMAP, 2021, UNEP, 2021). The movement of marine 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 et al., 2012, Tekman et al., 2017, Evangeliou et al., 2020) and litter from distant regions is a significant source to the Arctic Ocean (Bergmann et al., 2022), brought in by the North Atlantic and the North Pacific Water. Buoyant marine plastic particles coming from the Eurasian riverine-coastal areas and may flow all the way from the greater North Sea area via the Barents, Kara and Laptev Seas into the Central Arctic Ocean (Huserbråten et al., 2022). The many rivers in the Arctic region carry about 11% of the globe's fresh water into the Arctic Ocean (Yakushev et al., 2021), which also includes litter and microplastics from the human settlements along the rivers (Figure 2.11 a, b). However, it is estimated that discharges from fishing and shipping contribute to far more discharges per year than the river discharges (10⁵ tonnes plastic/year from fishing and shipping compared with 10⁻¹ per year from river inflow (Dewey and Mackie, 2023)), and indicate where international agreements and mitigations can be most effective.



Arctic marine litter and microplastics distribution

Figure 2.9. Distribution of Arctic marine litter and microplastics (permission are granted from PAME and GirdArendal to use this figure).

Relatively fresh polyester fibers are found to be delivered to the eastern Arctic Ocean, via Atlantic Ocean inputs and/or atmospheric transport from the south, indicating the global input of textile fibers in domestic wastewater (from home laundry) reaching this remote region of the world (Ross et al., 2021). Kim et al. (2021) found that relatively large quantities of fibers are entering the Arctic from the North Atlantic, while fewer and older fibers in the western Arctic may result from smaller (and potentially older) inputs from the Pacific and Atlantic Oceans. They argue that the western Arctic Ocean ice zone may play a role both as a sink of global microplastics and 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 due to the fishery moratorium till 2035, abandoned, lost or otherwise discarded fishing gear may drift into the CAO by ocean currents from the adjacent areas where active fisheries take place (European Union, 2021, PAME, 2019).



Arctic marine litter entry and dispersion pathways

Figure 2.10. Arctic Marine Litter entry and dispersion pathways (permission granted by PAME and GridArendal)



The state of knowledge on marine litter, including microplastics, in the Arctic marine region primarily stems from information being more prevalent for 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 of plastic on the southeastern shores of Chukchi Sea coast up to 4,500 kg/km of plastic for the Kenai National Park in the Gulf of Alaska, which is sub-Arctic but can be a source for Arctic marine litter, including microplastics, via 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 2.8) 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 and suggest 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 and corroborates 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, 2019).

Microplastics is found in the Central Arctic Ocean, including the under-ice habitat, where polar cod was found to ingest it (Kühn et al., 2018) (Table 2.8). 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 recommendation 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 2.8.

Table 2.8. Plastic in different matrixes in the CAO and adjacent areas. Abbreviations: ww = wet weigh, MPs=Microplastics.

Region	Matrix	Concentration	Reference
Fram Strait and Svalbard	Snow	0-14.3 x 10 ³ L ⁻¹	Bergmann et al., 2019
	> 11 µm		
Hudson Bay to Baffin Bay	Snow	1 MP in one of 7 samples	Huntington et al., 2020
	> 10 µm		
Central Arctic Ocean	Water under ice flow	0-18 MPs m ⁻³	Kanhai et al., 2020
	> 100 µm		
Central Arctic Ocean	Sea ice	2-17 MPs L ⁻¹	Kanhai et al., 2020
	> 100 µm		
Fram Strait	Sea ice	4.2x10 ⁶ MPs m ⁻³	Peeken et al., 2018
	> 11 µm	-1.2x10 ⁷ MPs m ⁻³	
North of Svalbard	Sea ice	1.1-2.9x10 ⁶ MPs m ⁻³	Peeken et al., 2018
	> 11 µm		
Western Arctic Ocean	Sea ice	11.4±9.12x 10 ³ MPs m ⁻³	Kim et al., 2021
	> 100 µm		
Arctic Ocean	Surface water	21-65 MPs m ⁻³	Ross et al., 2021
	> 63 µm		
Central Arctic Ocean	Surface water	7.72 MPs m ⁻³	Huang et al., 2022
	> 300 µm		
Central Arctic Ocean	Surface water (8.5 m	0-375 MPs m ⁻³	Kanhai et al., 2019
	depth)	Median: 0.7 MPs m ⁻³	
	> 250 µm		
Central Arctic Ocean	Deep and bottom	0-104 MPs m ⁻³	Kanhai et al., 2019
	waters		
	> 250 µm		
Central Arctic Ocean	Atlantic water	0-95 MPs m ⁻³	Kanhai et al., 2019
	> 250 µm		
Barents Sea	Surface water	0.85 MPs m ⁻³	Pakhomova et al., 2022
	> 100 µm		
North Atlantic	Surface water	0.56 MPs m ⁻³	Pakhomova et al., 2022
	> 100 µm		
Siberian Arctic	Surface water	0.71 MPs m ⁻³	Pakhomova et al., 2022
	> 100 µm		
Hudson Bay to Baffin Bay	Surface water	0,22 ± 0.23 L ⁻¹	Huntington et al., 2020
	> 10 µm		
Northwest of Svalbard	Surface water	3819-9287 MPs km ⁻²	Hänninen et al., 2021

	> 300 µm		
Fram Strait	Surface water	11852 MPs km ⁻²	Hänninen et al., 2021
	> 300 µm		
Hudson Bay to Baffin Bay	Sediment	1.93 ± 4.12 g ⁻¹	Huntington et al., 2020
	Fragments > 0.28 μm		
	Fibres > 205 µm		
	Films > 0.25 μm		
Fram Strait	Sediment	42-6595 MPs kg ⁻¹	Bergmann et al., 2017
	> 11 µm		
Hudson Bay to Baffin Bay	Zooplankton	3.51 ± 4.00 g ⁻¹	Huntington et al., 2020
	> 100 µm		
Chukchi Sea and Bering Sea	Invertebrates	0.02-0.46 MPs g ⁻¹ ww	Fang et al., 2018
	> 100 µm		
Barents Sea	Polychaetes	0.2-2.4 MPs per	Knutsen et al., 2020
	> 45 μm	individual	
Chukchi Sea	Acticidae und.,	0-10 MPs per individual	Fang et al., 2021
	Chionoecetes opilio		
	and Ctenodiscus		
	crispatus		
	> 100 µm		
Svalbard	Bivalve (Hiatella	1-184 MPs per individual	Teichert et al., 2021
	arctica)		
	> 10 µm		
Arctic Ocean	Stomach of Polar cod	2 MPs in 72 fish	Kühn et al., 2018
	> 100 µm		
Svalbard	Northern fulmar	0.08 g per individual or	Trevail et al., 2015
	> 5 mm	15.3 pieces per individual	
Greenland Sea	Stomach of hooded	2 pieces	Pinzone et al., 2021
	seal pup		
	> 5 mm		

2.1.3 When does it occur in the CAO

Litter is continuously transported into and within the CAO and can be considered widespread.

3 Ship traffic in the CAO

Lis L. Jørgensen, Jackie Dawson, Ida-Maja Hassellöv, Paul Arthur Berkman, Jan Jakub Solski, Hjalti Hreinsson, Hauke Flores, Karen Edelvang, Kevin Hedges, Martine van den Heuvel-Greve, Bjørn Einar Grøsvik, Kathy Kuletz, Anders Mosbech, Matthew Bell T JR, Petter Helgevold Kvadsheim.

3.1 What is ship traffic about

North of the Arctic Circle the maritime ship traffic has increased with a Pacific to Atlantic East-West direction, with pronounced seasonality, and this increase is happening as sea ice is diminishing (Berkman et al 2022). The sailed distance (Infobox 2) within the Arctic LMEs (Infobox 1) 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-, Laptev- seas. The Northern Canadian Archipelagio had the lowest sailed distance.



Figure 3.1. The distribution of sailed distance (the mean across 2012-2020) per Large Marine Ecosystem (% nautical miles, nm) of all ships.

Compared to the Barents Sea, there are few ships in the Central Arctic Ocean (CAO) LME. Ship movements in the CAO indicates direct transit lines to the North Pole (e.g., to the 'Barneo Ice

Camp'), others are peripheral across extended or 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).

INFOBOX 1 – the Large Marine Ecosystems (LMEs):

The Central Arctic Ocean is surrounded by eight LMEs and the Barents Sea LME is the far 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 (nm) in the Barents Sea LME range from a minimum of 2.7 million nm in 2013 to a maximum of 8.8 million nm in 2020.



Read more on Large Marine Ecosystems and where this map comes from here: (LMEs, <u>https://www.pame.is/projects/ecosystem-approach/arctic-large-marine-ecosystems-lme-s</u>) of the Arctic.

International law requires that every ship be registered in a country, called 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 states jurisdiction. A ship owner can register their ship in other flag registries than their own nation. Up to 2019, the number of flag states operating in the CAO was increasing from 5 to 22 nations with Russian, USA 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 CAO LME.

Russian flagged vessels (RUS) which were present each year, had the most operation hours in the area, with a maximum of 4574 hours in 2020 (Table 3.1). German flagged vessels (GER) were present all years except 2013 and 2021 and with maximum operation hours in 2020. Vessels flagged in Canada (CAN), were present all years except 2012, had most activities in 2014 and 2015, while Swedish (SWD) and Chinese (CHR) vessels operated in some years, and were most active in 2018 and 2021, respectively. USA did not have any ship records before 2014, while Norway did not have any record before 2018. The USA were most active in 2015, Norway had the most activity in 2021 (Table 1).

Table 3.1. The annual number of operation hours (number of hours inside the CAO) per Flag
state in the period 2012-2022 within the Central Arctic Ocean LME (Data from the ASTD, see
Info-box 2)

Flagcode	Flag state	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
RUS	Russia	1047	1278	2738	1215	555	551	1524	2919	4574	911	2590
GER	Germany	1122		1648	848	779	104	645	2308	4592		89
CAN	Canada		152	1342	1696	968	193	164	191	146	193	58
SWD	Sweden	517	62	622		812		1110			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
	Republic of											
KOR	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			
	Norway International											
NIS	Ship Register	19									20	
VAN	Vanuatu	21										
MAI	Marshall Islands							12				
Unknown		19	239	64	1109		12	63	395	718	26	19

INFOBOX 2 – How ship-data was accessed and applied:

In this chapter we have used the ASTD System <u>https://www.astd.is</u>). This database uses data collected by receipt of Automatic Identification System (AIS) transmissions using satellites from Norway and USA. 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 EEZ's, Arctic LME's and the Polar Code area), and fuel consumption by ships. ASTD defines 15 different ship types and nine different measures including sailed distance, number of ships, operation hours, fuel consumption and a set of emissions (see appendix 1).

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

More information on limitation: <u>https://pame.is/images/03_Projects/ASTD/ASTD_Data_v5.pdf</u> Welch, H., Clavelle, T., White, T.D., Cimino, M.A., Van Osdel, J., Hochberg, T., Kroodsma, D. and Hazen, E.L., 2022. Hot spots of unseen fishing vessels. Science Advances, 8(44), p.eabq2109.

3.2 Spatial coverage of ship traffic in the CAO

The CAO is ice-covered with maximum sea-ice coverage (see light colour + dark blue in Figure 3.2) during the winter (March) and minimum sea-ice coverage (see only dark colour in Figure 3.2) during late summer (September). The sea-ice cover restricts the types of ships operating in the area and where they can operate. But the September Arctic Sea ice is now shrinking at a rate of 12.6% per decade, compared to its average extent during the period of 1981 to 2010 (https://climate.nasa.gov/vital-signs/arctic-sea-ice/).



Figure 3.2. The annual (2012-2021) maximum ice cover (light colour + dark blue colour) and minimum ice cover (blue dark colour) of the Central Arctic Ocean. 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. Years and numbers in bold are the years was lowest ice-cover.

Ten different ship-types were reported in the CAO for the period 2012-2022 (Table 3.2). But as the ASTD database does not include military vessels and is a voluntary registration system, we anticipate 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 year 2020. Unique vessels is defined as ship counts that are only made once annually when entering

the SAO, although these ships can enter the area multiple times in any given year. Cruise ships (both icebreakers and non-icebreakers) were present most years (1 - 4 ships), while other ship types were only recorded in a few years and with less than 2 ships during the entire year. Most ships were recorded in the years 2018-2020.

Table 3.2. Number of unique ships in the Central Arctic Ocean (CAO) for 10 different ship typ	es
during 2012-2022	

Shiptype in the CAO	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Icebreakers	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

The years 2014 and 2020 had the most shipping activity, while 2017 had the least sailing activity and operation hours (Figure 3.3). Icebreakers had the most operation hours and made up the most sailed distance inside the CAO (a maximum of 9735 operation hours in 2020, but a maximum of 26174 nm sailing distance in 2014). Cruise ships followed with a maximum of 4712 nm in 2014, with a maximum of operation hours in 2020 (1055 hours) inside the CAO.

Other ship types, mainly following the Northeast Passage, made a few short incursions into the CAO. But in 2020 "General cargo ships" (755 nm over 143 hours) and "Container ships" (441 nm over 142 hours) sailed more nautical miles and operated longer within the CAO than any other years. This was associated with the record low ice cover that year (see Figure 3.2).





Figure 3.3. The annual operation hours (upper panel) and nautical miles sailed (lower panel) by 10 different ship-types within the Central Arctic Ocean during 2012-2022.

The spatial distribution of ships within the CAO spread out from the Framstrait and from the Bering Strait and northward as illustrated by the most common ship type (icebreakers) in the most busy months (September, October) in year 2014 and 2020 (Figure 3.4).



Figure 3.4. The spatial distribution of icebreakers in the Central Arctic Ocean in August 2014 (left side) and in September 2020 (right side (MOSAIC cruise track missing for Sep. 2020) where maximum operation hours was recorded by the ASTD.

In early 2020, 36 new expedition cruise ships were deployed in the Arctic, and more ships are planned for the coming years (Anonymous 2021). An increasing proportion of these operations can be expected to also expand in the CAO, marketing to tourists looking for an authentic experience of nature. See also: <u>https://www.highnorthnews.com/en/forskningsskipet-kronprins-haakon-og-cruiseskipet-le-commandant-charcot-mottes-pa-nordpolen</u>



Figure 3.5. Cruise Ships in the central Arctic Ocean as the annual aggregated spatial distribution during 2012, 2014 and again in 2020 and 2022 (2022 only during Jan-Sep, upper two panels) and the sailed distance (nm, from ASTD) for Cruise Ships within the central Arctic Ocean LME during 2012-2022 (lower panel).

3.3 Temporal occurrence of ship traffic in the CAO

During most years, it is in July (shown in yellow in Figure 3.6), August (grey) and September (white) that usually have the most operational hours by ships in the CAO. But in 2015 and 2020 there was a continuous activity between Jan-May. From 2018-2022 there was more activity recorded in October (black), November (blue) and December (dark green), hence during the last part of the year (Figure 3.6).



Figure 3.6. The monthly operation hours by all ships within the Central Arctic Ocean during 2012-2022. Note the spread of operation hours across several more months in 2015 and 2020 compared to the other years.

When the annual September - ice cover is compared with the total operational hours by ships during same month in the CAO no clear pattern was observed (Figure 3.7). This may be explained by icebreakers, which do not depend on lower ice cover in order to operate in this area.



Figure 3.7. Scatterplot of ship operational hours in the CAO in September and the ice-cover in September of the Arctic during 2012-2021.

In the CAO icebreakers operations ranged from 4 months (2017) up to 11 months (2020) per year, while cruise ships that are present almost each year operate mostly during July-October. From 2018 to 2020, other ships (see Table 3.3) present with varied ship types having operational hours ranging from 3 (Oil product tankers in 2020) to 86 (Container ships in 2020) hours in the CAO.

Table 3.3. The number of monthly operational hours per ship-type during 2012-2022 in the Central Arctic
Ocean. Numbers written in bold are maximum values. Icebreakers includes both Research,
Towing/Pushing and "Unspecified".

Year	Shiptype	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012	Icebreakers						44	237	1271	1169	114		
	Cruise ships								83	172			
2013	Icebreakers						89	253	356	507	76		
	Cruise ships						428			62			
	Fishing vessels							16					
2014	Icebreakers						102	843	2702	2287	417		
	Cruise ships					18			802	214			
2015	Icebreakers	477	235	250	125		263	308	1833	2353	271		
	Cruise ships								145				
2016	Icebreakers						121	268	1566	1430	480		
2017	Icebreakers						134	353	614	216			1
	Container ships			2	9								
2018	Icebreakers						179	222	2004	1753	388		
	Passenger ships								16				
	Bulk carriers								12				
	Fishing vessels					10							
2019	Icebreakers		28				205	406	1570	1264	1480	720	743
	Cruise ships								27	30	8		378
	Chemical tankers	24											
	Service offshore vessels								14				
2020	Icebreakers	744	694	914	720	619	73	123	1344	2709	1599	196	
	Cruise ships		497	462						96			
	Container ships							26	86	31			
	General cargo ships							17	68	57			
	Oil product tankers								3				
2021	Icebreakers						3	351	1665	1600	544	11	0
	Cruise ships									250			
2022	Icebreakers	2						497	840		1156	721	748
	Cruise ships							335	324				

4 Tourism

Lis L. Jørgensen and Hauke Flores, Kevin Hedges, Paul Berkman, Jackey Grebmeier

4.1 What is tourism about

Tourism is about people visiting the Central Arctic Ocean. This can be done from cruise ships. This can also be done by transporting people by air onto the icecap for a day visit or for several days in established tent camps. Transport of groups of adventures skiing 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 summertime in the next 10-20 years, the Arctic has now become a destination of "last chance tourism" (Lemelin et al. 2010) and the drastically change its appearance. The further break-up of the Arctic sea-ice cover will promote this development by improving the accessibility of the CAO for less ice-capable vessels. Overall, touristic operations in the Arctic region are expected to continue their growth in the foreseeable future. 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). A market segment that has particularly grown is 'expedition cruising', i.e., cruises with relatively small boats (100-200 passengers) aiming at 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). Tourists (probably about 1,000) visit the North Pole every year, mainly hosted by Russian tour operators (Lukina et al. 2020).

Since 1991 the Quark tourist expeditions have brought about 500 people each year to visit the North Pole with the help of powerful nuclear icebreakers <u>https://explore.quarkexpeditions.com/north-pole</u>. In July 1999, the expedition company achieved the first circumnavigation of the Arctic Ocean. In 2008 they hosted the first maiden voyage to the North Pole of the nuclear ice-breaker <u>https://explore.quarkexpeditions.com/north-pole/north-pole-dreaming-journey-to-the-top-of-the-world</u>. In 2019 the Quark Expedition started its 60th expedition cruise to the North Pole before the Corona pandemic. The expeditions include sightseeing by helicopter, and possibly taking a tethered hot-air balloon ride at 90° N.

Most national tourism offices of Arctic countries have formed strategies to promote domestic Arctic tourism. Tourist services are characterised 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 meeting basic principles of sustainability in the development of tourist destinations in the Russian Arctic must be investigated (Timoshenko 2019). Timoshenko (2020) defines the most promising tourist attractions in the Russian Arctic as: experience travelling or cruising on the atomic icebreakers of Rosatomflot; transition through the Arctic Circle; visiting the North Pole, active and extreme

sports (ice diving, snowkiting, parachuting, helicopter flights, hot air ballooning, etc.), adventure tourism.

Tourist activities therefore includes both cruise ships, aircrafts, and automobiles on the ice. Tourism in the Arctic has rapidly increased in the past two decades and is believed to continue once people start travelling again after the Corona pandemic (Runge et al. 2020). 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 in the CAO

New ships are built or are modified to operate in the high Arctic. In early 2020, 36 new expedition cruise ships were deployed in the Arctic region, and more ships are planned for the coming years (Anonymous 2021). An increasing proportion of these operations can be expected to also expand in the CAO. See also: <u>https://www.highnorthnews.com/en/forskningsskipet-kronprinshaakon-og-cruiseskipet-le-commandant-charcot-mottes-pa-nordpolen</u>

Russia owns the largest territory of the Arctic, and at present, the most exclusive of Arctic tourism in Russia is a cruise to the North Pole - a growing industry still limited by the underdevelopment of transport and logistics channels of the Russian Arctic (Lukina et al. 2020). But the development of ecotourism, extreme, event, scientific, cognitive and ethnographic tourism is considered a promising direction of development of the Russian Arctic tourism¹.

Journeys to the North Pole by air (landing by helicopter or on a runway prepared on the ice) are or have been been available to small groups of tourists through <u>adventure holiday</u> companies.

Activity at the North pole	Transport	Year	Period
Russian camp of <u>Barneo</u> close to the north pole. for scientists and tourists	Aircrafts, helicopter, bulldozers, more?	Annually since 2000 to 2018; cancelled 2019-21 during Covid pandemic	March-April
The Adventure Consultants ski expedition	Aircraft	2022	April
The Quark Expedition to the north pole.	lcebreaker, helicopter, hot-air balloon	Since 1991	Ideally June and July
<u>Underwater</u> exploration of the North Pole	Submarines (not military)	1998 1999 2005	(April)
Manned descent to the ocean floor at the North Pole	Two <u>MIR submersibles</u> <u>to 4000 m</u>	2007	
Sport	Swimming	2007	

Table 4.1. Tourist activities in the CAO (excluding tourist cruise ships, but see chap. 2.1.4)

¹ National tourism Union, <u>https://rusunion.com/perspektivy-razvitija-arkticheskogoturizma/</u>

	Kayak	2008	
Russian Marine Live-Ice Automobile	Cars	2009	April
Expedition			
Skiing crossing the ice cap	1-2 explorer on skies	1990	March-May
		1994	March-April
		2006	Jan-March
		2007	May-June
		2019	Sep-Dec
		2001	?

The Barneo camp (<u>https://www.facebook.com/BarneoRu/) is</u> a unique tourism brand of the Russian Arctic is the temporary seasonal Russian camp of <u>Barneo</u> (arranged by SibwayTour), a camp deployed on drifting ice. The base allows to conduct scientific research and 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 has improvement of flight technologies and camps on Barneo made arctic tourism more accessible (Figure 4.1) (Timoshenko, 2021).



Figure 4.1. Transport to and from the Barneo camp. Pictures downloaded from: <u>https://www.facebook.com/BarneoRu/photos/a.121371817939925/1348604608549967/</u>.

In 2002 was the <u>Barneo</u> camp established in a short distance from the 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 to make a 1200 m long

(<u>https://thebarentsobserver.com/en/arctic/2018/04/north-pole-campers-pack-after-shortest-ice-drift-ever</u>) runway, aircraft flights for passengers and equipment into the ice-cap.



Picture 1. Bulldozers to make a 1200 m long runway of the Barneo camp. Picture downloaded from: https://www.facebook.com/BarneoRu/photos/ms.c.eJw9zskNAEEIA8GMVsYwgPNPbDXns9SAoKIdqWKiw I~;LBRfLs68NQwGPa~_6ez3M~;pY9KI6MQGT36ur3UJlxr93wucxvk8cCa77Pv3XO~_rJ5nx8C1ds~;n1eP848K 8720~;0kQwrg~-~-.bps.a.293176617426110/294830697260702.

After the camp is set up, the flights to the camp are made by a AN-74 airplane (<u>https://ru.wikipedia.org/wiki/%D0%90%D0%BD-74</u>). This is a "light" airplane to reduce the risk of breaking through the ice. Both the Longyearbyen, Svalbard or the Khatanga airport on the Tamyr Peninsula, Siberia and from Franz Josef Land are used as a starting point to reach the camp.

This type of aircraft may carry from10 to 52 people depending on modification and of cargo (equipment, instruments, scientific equipment etc.) and there may be several flights per day if the weather conditions are favourable. Up to 300 people stay on the camp annually https://tass.ru/arktika-segodnya/8472727 and can accommodate 100 guests and about 40 staff members per day

(https://www.jettravel.ru/about/photogallery/index.php?page=post&blog=another_planet&post_id=bar neo-a-journey-to-the-north-pole).

Some of the heavy equipment, such as the bulldozers, are landed by parachute and undocumented sources indicate that heavy equipment may stay on the ice when the camp is left. Barents observer (<u>https://thebarentsobserver.com/en/arctic/2020/02/about-20-bulldozers-have-sunk-arctic-seafloor-one-more-coming-soon</u>) writes that "given 20 years of operations"

some 20 to 40 bulldozers may have reached the Arctic seafloor down to 4,000 meters". Less heavy cargo landed by aircrafts are brought back from the ice (<u>https://kovlam.livejournal.com/3043915.html</u>), and some garbage may be burned. Sewage may be left because the bathroom facilities is a 0.5 m deep depression in the ice.



Picture 2. Parachuting equipment to the Barnoe camp. Picture downloaded from: https://www.facebook.com/BarneoRu/photos/1316374748439620.

INFOBOX – regulation of garbage in the arctic

The Arctic Ocean is international waters where the 1972 London Convention regulates dumping of waste and other matter. Moscow is a signature party to the convention. In 1996, the convention was modernized and replaced with the London Protocol. This protocol puts a ban on dumping of harmful materials at sea, but opens for dumping of unharmful materials in 'circumstances where such waste are generated at locations with no land-based alternatives.'

Noise, that can be considerable, comes from the camp due to aircrafts, snowmobiles, bulldozers.

Polar bears are visiting the area around the camp (<u>https://barneo-polus.livejournal.com/;</u> <u>https://barneo-polus.livejournal.com/47967.html</u>).

Other tourist activities

In 2019 the Quark Expedition (International Association of Antarctica tour operators *"IAATO"* and Association of Arctic Expedition Cruise Operators *"AECO"*) started its 60th expedition cruise to the North Pole with icebreaker vessels, before the Corona pandemic. This expedition included sightseeing by helicopter, and possibly 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 fatality. The next attempted dive at the North Pole was organized in April 1999 and ended in success.

In 2005 the United States Navy submarine <u>USS *Charlotte*</u> (SSN-766) surfaced through 155 cm (61 in) of ice at the North Pole and spent 18 hours there.

In July 2007 British endurance **swimmer** completed a 1 km swim at the North Pole. A later 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 his expedition found itself stuck in thick ice after only three days. The expedition was then abandoned.

August 2007 a Russian scientific expedition <u>Arktika 2007</u> 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 <u>MIR submersibles</u>.

In April 2009 the Russian <u>Marine Live-Ice</u> **Automobile** Expedition (MLAE-2009) with 7 participants reached the North Pole on two custom-built 6 x 6 low-pressure-tire ATVs. During March-May 2013 the Russian Marine Live-Ice Automobile Expedition (MLAE 2013) with 7 participants on two custom-built 6 x 6 low-pressure-tire ATVs. It started from Golomyanny Island (the <u>Severnaya Zemlya</u> Archipelago) to the North Pole across drifting ice and continued to the Canadian coast. It took 55 days across ~2300 km of drifting ice and about 4000 km in total. The expedition was totally self-dependent and used no external supplies.

Skiing across the Arctic ice cap has been done during 58 days in March-May 1990 (two explores) 800 km from Canada to the North pole, in March-April 1994 (one explorer) from Cape Arctic on the Severnaja Zemlja to the North pole, during Jan-March in 2006 (two explorer) following same distance, in May-June 2007 (two explorer) from the North pole to Frans Josef Land. In 2001 (one explore) spend 82 days from Siberia to Canada via the North pole. In Sep-Dec 2019, two explores set out on an 87-day ski traverse of the Arctic ice cap from Alaska via the north pole to Svalbard.

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

These above-described activities show that a continued and most likely growing interest for transporting tourists and explorer into the CAO icecap, and most likely all the way to the North pol. Assessing these human activities on the CAO nature need information on the impact, including pollution (emission, noise, light, garbage, sewage, graywater etc) and this is, as far as we know, a knowledge gap. A further expansion of the tourist footprint in the Arctic marketed as 'last chance tourism' may also set species at risk of disappearing (Lemelin et al 2010; Groulx et al 2016). Wildlife viewing of vulnerable species, such as polar bears, narwhals and beluga whales, is putting additional pressure on species threatened by climate change (Atwood et al 2016; Halliday et al 2018, 2020).

4.3 Temporal occurrences of tourism in the CAO

Many (most) guests stay in the camp up to 10 hours before returning. Many Arctic explorers use Barneo as 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 Pole itself may be arranged by helicopter. In April 2022 Adventure Consultants <u>https://www.adventureconsultants.com/expeditions/arctic/north-pole-ski-the-last-degree/</u> brought people to the camp by light aircraft from Longyearbyen/Svalbard to land on the ice at 89° North and the start of a trek.

The normal duration of the camp operation is about 4 weeks with guests visiting the camp up to 3 weeks. In 2017 and 2018 was the camp disassembled after 12 days and very few tourists visited it.

5 Military Activity

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

Confidence: 5 (Very low confidence for documenting *Military Pressures* in the CAO High Seas) **Studies from CAO**: no **Studies from other ice-covered marine areas**: no, only few references

5.1 What is military activity about

This chapter is without geopolitical orientation and is simply a matter of definitions regarding *military pressures* on the ecosystem in the Central Arctic Ocean (CAO) High Seas, specifically in view of Integrated Ecosystem Assessments (IEA) as framed by the International Council for the Exploration of the Sea (ICES 2023, WGICA 2023). The chapter 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. 2022a).

Military relates or belongs to "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" (Sun Tzu 5th Century BCE). Militaries involve nations individually as well as collectively with alliances, such as the North Atlantic Treaty Organization (NATO 2023a), which includes all Arctic states either as current or potential members, except the Russian Federation. With NATO (2023b), for example, there are five domains associated with the "armed forces" – "Air, Land, Maritime, Cyberspace and Space." NATO states have an active Arctic interest (Stoltenberg 2022, Stoltenberg and Trudeau 2022) as does the Russian Federation, which together encompass the military pressures along with those from non-Arctic states (Wilson Center 2023) being assessed by the ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean (WGICA 2023).

Militaries operate at security time scales to address immediate risks of instabilities, in contrast to sustainability time scales that operate with urgencies across generations (Berkman et al. 2022a). With NATO (2023c), 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

The practical consideration is "armed forces" seek to be stealthy, which limits details about "where does this activity occur" in general, recognizing also that data access is restricted especially regarding militaries. With respect to informed decisionmaking (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 as an Area Beyond National Jurisdictions (ABNJ) along with surrounding sea zones within national jurisdictions are 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 Exclusive Economic Zones under national jurisdictions (see Chapter 1). Consequently – to build common interests, rather than resolve conflicts (Berkman 2009) – this chapter is written only from the perspective of the CAO High Seas and common interests without consideration of *military pressures* in sea zones involved with national interests landward 200 nautical miles to the coastal baselines (UNCLOS 1982, Berkman and Young 2009).

The IEA method used in WGICA only considers existing and direct effects of human pressures on ecosystems. Limiting geographic context of this chapter also is 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 Russia has been creating Arctic laws since the early 19th century (Berkman et al. 2019) and dominates human presence in the Arctic Ocean today, mostly, as reflected by maritime ship traffic (Figure 5.1), mostly beyond the multi-year sea ice (NSIDC 2022).

TOP 5 NATIONS IN THE ARCTIC OCEAN

AIS derived vessel flag that most commonly occupied each pixel location 2009-2018

Russia United States United Kingdom Canada Norway Other



Data: Next Generation Arctic Marine Shipping Assessment Berkman et al. 2020 https://doi.org/10.18739/A2BV79W4V

Figure 5.1: GEOGRAPHIC DISTRIBUTION OF HUMAN PRESENCE IN THE WGICA STUDY AREA IN THE CENTRAL ARCTIC OCEAN (CAO), showing the CAO High Seas under law of the sea (solid line) and CAO large marine ecosystem area (dashed line) with flag states of maritime ship traffic, assessed with Satellite Automatic Identification System (S-AIS) data from 2009-2018, using space-time cube methods (ESRI 2017) with BigQuery (Google 2022) in the cloud. The map shows the most common flag state found in each 4km² 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. 2022c,d).

5.3 Temporal occurrences of military activity in the CAO

Military pressures are assumed to be continuous or anecdotal because activities of "armed forces", such as special national and international exercises, are classified information. When declassified data is available, there is low temporal and spatial resolution of *military pressures*, as illustrated by upward-looking sonar data from submarines since 1958 to interpret sea-ice thickness (Bourke and Garrett 1987). More specifically, access only to coarse sonar data across the Arctic Ocean obscured 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).

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

WHEN [#]	WHAT	WHERE			
1958-present every second year (1,2)	ICEX (United States 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)	<i>Nanook-Nunakput</i> (Canada with international partners)	Northwest Passage (outside CAO High Seas)			
2014 and 2016 (6)	Russian military <i>Flying Squad</i> – a combat group of Chechen special forces	Landed on Svalbard (outside CAO High Seas)			
2021-2022 (7,8)	Russian naval exercise interacting with fishing fleets	Barents Sea (outside CAO High Seas)			
2021 (9)	Russian missile test site on Novaya Zemlya	Barents Sea (but outside CAO High Seas)			
2021 (10)	Zapad 2021 (Russia and Belarus)	Barents Sea, Kara Sea and Laptev Sea (outside CAO High Seas)			
2022 (11)	Naval exercise led by Denmark with international partners	"500 km north of the Arctic Circle"			
2022 (12)	Cold Response (Norway with international partners)	Norwegian Sea (Barents Sea) (outside CAO High Seas)			
2022 (13)	Umka-2022 (Russia)	Chukchi Sea (outside the CAO High Seas)			
2023 (14)	Joint Viking Warrior 2023 (Norway with international partners)	Norwegian Sea (Barents Sea) (outside CAO High Seas)			
 # REFERENCES: (1) <u>https://en.wikipedia.org/wiki/ICEX: US_Navy_Mission_in_Arctic;</u> (2) <u>https://www.defense.gov/News/News-Stories/Article/Article/1461302/navys-arctic-ice-exercise-features-multinational-participation/;</u> (3) Berkman, P.A. 2010. <u>Environmental Security in the Arctic Ocean: Promoting Cooperation and Preventing Conflict</u>. (Foreword by Adm. James G. Stavridis, NATO Supreme Allied Commander for Europe). Routledge, London. 135p. (4) Ria Novosti. 2009. Russia Test Launches Second Sineva Ballistic Missile in two days. 18 July 2009. (Cited in Reference 3). (5) <u>https://www.canada.ca/en/department-national-defence/services/operations/military-operations/current-operations/operation-nanook.html;</u> 					

(6) https://thebarentsobserver.com/en/2016/04/chechen-special-forces-instructors-landed-svalbard

(7) <u>https://www.highnorthnews.com/en/norwegian-ocean-going-fishing-vessel-fleet-annoyed-new-russian-military-exercise-barents-sea;</u>

(8) https://thebarentsobserver.com/en/security/2021/09/fishermen-troubled-escalating-russian-war-games

- (9) https://thebarentsobserver.com/en/security/2021/08/russia-readies-burevestnik-testing-novaya-zemlya
- (10) https://thebarentsobserver.com/en/security/2021/09/how-ambush-arctic-seaport-russian-marines-stage-show; https://www.forsvaret.dk/en/news/2022/denmark-heads-naval-force-at-missile-live-fire-exercise/ (11)
- (12) https://www.nato.int/cps/en/natohg/news 192351.htm.
- (13)
- https://www.reuters.com/world/russia-conducts-military-drills-arctic-sea-opposite-alaska-2022-09-16/ SHAPE | Allied National Exercises and Activities (nato.int); Joint Viking 2023 Norwegian Armed Forces (forsvaret.no)

In addition to being difficult to detect where and when (above), it also is complicated to disambiguate 'military pressures' from pressures associated with other government assets. "Warships" are defined in Article 29 of UNCLOS (1982) 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 CAO High Seas from 1 September 2009 to 31 December 2018, involving 185 vessels identified with S-AIS data (Berkman et al. 2022c).

In context of "enforcement" vessels and icebreakers, the Arctic Coast Guard Forum (ACGF 2023) of the eight Arctic states involves ministries of defense that 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 Defense, noting the 2022 voyage of the 'Healy' to the North Pole was in support of "national security objectives" in a multipurpose context (Picture 5.1).

Picture 5.1: US Coast Guard Icebreaker 'Healy' at the North Pole with crew and science team on 2 October 2022 (Woody 2022).



6 Science activities

Grebmeier, Jacqueline¹, Barbara Niehoff², Bodil A. Bluhm³

The central Arctic Ocean (CAO) is an opening dimension 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. Coincidently, these changes are increasing opportunities for human use (e.g., transportation, potential fisheries). This emphasizes the critical time to determine drivers and impacts of an opening Arctic Ocean and the need to understand status and trends of the AO 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, due to our still limited understanding of 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 these gaps, several international projects have undertaken recent studies (here listed since 2019) to investigate the current CAO ecosystem and its environmental drivers, with future field activity in the planning stage. Below are brief descriptions of some of these recent programs, although not all inclusive.

6.1 What is science activity about

The following summaries provide overviews of the larger science activities that have occurred in the CAO in the past 4 years, both single year cruises as well as programs with long time-series foci.

• Synoptic Arctic Survey (SAS)

Multiple countries deployed ships from the shelf to the high Arctic as part of the International Synoptic Arctic Survey (SAS) during the 2020-2022 period 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 program and ongoing synthesis activities are a researcher-driven initiative that aims to enhance ongoing ocean monitoring through ship-based in situ measurements focused on the Arctic Ocean ecosystem, carbon cycle and associated hydrography. In the longer term, a main objective is to assess the rapid and the evolving Arctic Ocean system through decadal monitoring to enable detection and prediction of environmental and ecological changes. Unknowns, such as whether commercial fisheries could develop in the central Arctic Ocean beyond national economic zones (CAOFA 2021) or 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.

During the 2020-2022 period the SAS was organized around the overarching question "What is the present state, and what are the major ongoing transformations of the Arctic marine system?" Multiple ongoing national programs and country leads involved in the SAS include the

Nansen Legacy Project (Norway), 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 the USA, see Figure 1.1), field and networking observatory efforts through the Arctic PASSION program (Germany), annual ship activities associated with the HAUSGARTEN Observatory (Germany), the Nansen and Amundsen Basins Observational System (NABOS, USA) efforts, periodic cross-basin program under the CHINARE program (China), and the planned 2024 GO-SHIP program across the CAO. Further information at: https://synopticarcticsurvey.w.uib.po/

https://synopticarcticsurvey.w.uib.no/

MOSAiC field program: 2019-2020

The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition was a major one-year-long expedition into the Central Arctic supported through multi-national efforts led by Germany. The MOSAiC Expedition (2019-2020) studied Fram Strait and the northern Eurasian Basin using the RV Polarstern that was frozen into the Arctic sea ice for studies of 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 MOSAiC success, a new multi-disciplinary, multi-nation project led by Germany was initiated in 2023 called EcoOmics that will evaluate biodiversity change in the Arctic Ocean through identifying unique species and assessing their extinction risk to guide future conservation efforts. Further information about MOSAiC at <u>https://mosaic-expedition.org/</u>.

Nansen Legacy 2021 SAS cruise

The Nansen Legacy project is a large, Norwegian led program to make climate and ecosystem field studies from 2018 and 2022 using the Norwegian research icebreaker 'Kronprins Haakon' as a main research platform. Besides ship-based sampling, the program used underwater robotics, year-round moored observing platforms and satellite-based observations, and state of the art modeling tools to investigate the dynamics of the physical and biological components of the northern Barents Sea into the Arctic Basin to understand present and future dynamics of the Polar North. In 2021 the Nansen Legacy extended their study into the CAO (Fransson et al. 2022). An overview of the Nansen Legacy research activities and future plans are summarized in the -Annual Reports (Nansen Legacy 2019-2023). Further information at: https://arvenetternansen.com/about-us/

Arctic PASSION.

As part of the Arctic PASSION project's goal to coordinate observing systems across disciplines, sectors and communities, several cruises from different countries during late summer/early autumn in 2021 and 2022 occurred across the Arctic Ocean. New multi-disciplinary moorings were also deployed in the interior Arctic Ocean. The moorings cover the Atlantic Water-influenced western Nansen Basin and the Transpolar Drift-dominated western Amundsen Basin. Through the Arctic PASSION program, 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 July 2022 under the Arctic PASSION program. Further information at: <u>https://arcticpassion.eu/</u>

HAUSGARTEN time series

Since 1999, the Alfred-Wegener-Institut (AWI; Bremerhaven, Germany) has operated the LTER observatory HAUSGARTEN in the Fram Strait (Soltwedel et al. 2005, 2016). The 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 during summer, also in 2019, and in 2021-2024 using the research vessel Polarstern (Germany). The stations are located along a bathymetric east-west transect between ~250 m and ~5500 m water depth at about 79° N from the 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 sea floor. 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 at: <u>https://www.awi.de/en/science/biosciences/deep-sea-ecology-and-</u> technology/observatories/lter-observatory-hausgarten.html.

• SUDARCO

Under the Sustainable Development of the Arctic Ocean (SUDARCO) 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 will return in 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 at: <u>SUDARCO: Forskning for god forvaltning av Polhavet - Framsenteret</u>.

• Expeditions to special habitats

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

 $_{\odot}$ 2019 and 2021 HACON – exploration of the Aurora vent field in two international field expeditions (Ramirez-Llodra et al. 2023)

2021 and 2022 ALOIS (Arctic Lithosphere-Ocean Interaction Study) along the
 Gakkel Ridge, including the Aurora vent field and the Lena Trough (Schlindwein 2022)

2022 and 2023 GoNorth expeditions studying hydrothermal vents and various geological structures and their related ecosystems, Daglige rapporter fra toktet 2023 (sintef.no). Further information: <u>GoNorth (sintef.no)</u>

 Russian autonomous drift-boat "Severny Polyus", launched in 2022, is drifting for up to two years towards the Greenland Sea. The *Severny Polyus* is a research vessel -operated by the Russian Meteorology Service Roshydromet and can undertake geological, acoustic, geophysical, and marine research (see https://thebarentsobserver.com/en/arctic/2022/10/russias-north-pole-platformstarts-ice-drift-towards-greenland-sea). •

Upcoming field and planned monitoring activities in CAO

• **Framtidens Polhav. Famtidens Polhav (the Future CAO)** is a 10-yr Norwegian program currently in its preparation phase and targeted to start in 2025. Seventeen universities and research institutes across Norway are in the consortium, covering multiple disciplines in natural sciences but also including law and geopolitics. Further information (mostly in Norwegian): Bakgrunn og beskrivelse av prosjektet | UiT

• **GO-SHIP.** *GO-SHIP* is part of the Global Climate Observing System, Global Ocean Observing System (GCOS/GOOS) program. In 2024 GO-SHIP will have a two month (August-October 2024) oceanographic cruise across the CAO for physical oceanographic, carbon cycling, marine geochemistry and ecosystem components via hydrographic measurements using standard techniques. These data will provide valuable results for comparison with previous CAO ship sampling, including the recent SAS activities in the Eurasian and Amerasian Basins. Further information at: <u>https://www.go-ship.org/</u>

Central Arctic Ocean Fisheries Agreement (CAOFA)

The International Agreement to Prevent Unregulated Fishing in the High Seas of the Central Arctic Ocean (CAOFA) and Joint Program of Scientific Research and Monitoring (JPSRM) under the Scientific Coordinating Group has developed a monitoring program. The draft monitoring plan will be evaluated at a June 2024 meeting of the Conference of Parties (COP) and once approved, will be made public for coordination with ongoing CAO research activities. Specific to developing fisheries, the monitoring program 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 programs by international partners. For further information see: https://vlab.noaa.gov/web/caofa

In summary, all the ongoing and planned CAO science programs 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 health of the planet.

6.2 Spatial coverage of science activity in the CAO

The primary season for science activities in the CAO is in the fall (September-October) when the sea ice coverage is at the minimum. The exception was during 2020-2021 when the RV Polarstern was locked in the drifting sea ice as part of the MOSAiC program (see statements above). Figure 6.1 provides a schematic of many of the science activities and associated countries as leads for the programs outlined in section 2.5.1 above.



Figure 6.1. Schematic of ship occupations to the CAO, including from the surrounding marginal shelf seas, as part of the Synoptic Arctic Survey 2020-2022. (Figure updated from Ashjian et al. 2019; see <u>https://synopticarcticsurvey.w.uib.no/</u> for further details).

6.3 Temporal occurrences of science activity in the CAO

Scientific activity can occur year-round with icebreakers being frozen in the ice and scientific activities performed during the entire year. But usually are scientific activities at the most active during late summer (August – September).

Box: Future perspectives

As the Central Arctic Ocean 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 ecosystem, 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 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 its 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, Lis Jørgensen

7.1 What is fishery activity about

Commercial vessel-based fisheries use a variety of fishing gears to catch individuals within a certain size range from one or more target species. Bottom trawls, longlines, gillnets and traps can all be used to catch demersal fish living near the sea floor. Pelagic trawls, longlines and gillnets can be used to catch fish throughout the water column, from a few meters above the seafloor to at the sea surface. Active fishing gear such as trawls are pulled by a vessel through the water, and in the case of bottom trawls across the seafloor, catching animals that a herded and swept into the net. The size of the trawl, size of the mesh in the trawl, and the speed at which it is towed affect how well the trawl fishes and traps, are set and left in place to fish. Animals can be attracted to the gear by bait when fishing longlines and traps, or snared as they swim through the areas, as with gillnets. The hook size in longlines, type of bait used, and mesh size in pots and gillnets all affect the composition of the catch with passive gears.

7.2 Spatial coverage of fishery activities

Commercial fisheries in the High Sea in the Central Arctic Ocean (Figure 7.1, 7.2) are presently forbidden 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 October 3, 2018. On June 25, 2021, the last of the Parties ratified the agreement, bringing the agreement into force. According to CAOFA no fishing shall take place unless a joint program 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, R., 2019).

While CAOFA presently prohibits commercial fishing, it does permit scientific surveys and exploratory fisheries. 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 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 CAOFA, the conservation and management measures for exploratory fishing are to be established by June 2024, within 3 years of CAOFA coming into force. Given that timeframe, exploratory fishing could begin in the high seas of the Central Arctic Ocean (Figure 7.1) in 2024.



Figure 7.1. The Central Arctic Ocean (CAO) Large Marine Ecosystem (LME) (red) and National Exclusive Economic Zones (green) delimiting the Central Arctic Ocean High Sea (green).

Parts of the Central Arctic Ocean LME surrounding the CAO High Seas, consisting of shelf and slope areas, and 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 CAO LME were mainly found in the northern Barents Sea and the Chukchi Sea, and much less in the Kara Sea, the East Siberian Sea, the Laptev Sea and the Beaufort Sea. No fishing activities were recorded in the Central Arctic Ocean basin and 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, that is the Northern Barents Sea, the eastern parts of Fram Strait, and 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, when ice melts in the summer. However, overall, fishing activity in the northern Barents Sea is low compared to further south in the Barents Sea (Silber and Adams 2019). Since all ongoing fishing in these areas is connected to the continental shelf and upper slope, targeting mainly shelf associated species, fishing effort by bottom trawls is not expected to expand northwards from the Atlantic gateway into the CAO basin even when more northern areas become accessible due to increased ice melt (Haug et al, 2017). It is, however, likely that

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fishing effort will increase in intensity in established fishing areas, if fish and shellfish concentrations increase in response to increased temperatures.

In Canada, Greenland Halibut are found in the Beaufort Sea, which is directly adjacent to the CAO, 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; remoteness from ports and markets in the context of potential harvest levels and prices drive interest in fishery development.

Overall, fisheries within the Central Arctic Ocean LME represent a minor human impact due to long distance to ports, which increases costs incurred to catch fish and bring them to market, restrictions in accessibility due to ice, and overall low biomass of fish (Snoeijs-Leijonmalm et al 2020). According to Table 3.2 in chapter 3 of the present report only 4 out of 154 unique ships that were registered in the Central Arctic Ocean (CAO) between 2012-2022 were fishing vessels. These were registered in 2013, 2018, and 2020, respectively.





Figure 7.2. Sailing routes (green lines) of fishing vessels in 2017, 2018 (upper panel) and in 2022 and 2023 (lower panel) around CAO. The figures may indicate that fishery 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, polar cod, herring, blue whiting, and redfish. 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.

To conclude, fishery in the Central Arctic Ocean LME is limited and is expected to continue to be so also in the foreseeable future. It should be noted, however, that this expectation of low interest of the fishing industry in future expansion in the CAO is founded on the assumption that sufficient harvestable resources remain available in better accessible areas, and that the agreement to prevent unregulated fisheries remains in force also 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. 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. Non-target species that are encountered as bycatch suffer increased mortality, often without the benefit of direct population assessments and management regimes target at 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

Lis L. Jørgensen, Jackie Dawson, Ida-Maja Hassellöv, Paul Arthur Berkman, Jan Jakub Solski, Hjalti Hreinsson, Hauke Flores, Karen Edelvang, Kevin Hedges, Martine van den Heuvel-Greve, Bjørn Einar Grøsvik, Kathy Kuletz, Anders Mosbech, Matthew Bell T JR, Petter Helgevold Kvadsheim, Grebmeier, Jacqueline, Barbara Niehoff, Bodil A. Bluhm.

Human activities in the Arctic are regulated at different levels of governance. Instruments of global application, such as the comprehensive United Nations Convention on the Law of the Sea (UNCLOS),² sector-specific Fish Stocks Agreement (FSA),³ or MARPOL,⁴ apply in 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 Central Arctic Ocean Fisheries Agreement (CAOFA)⁵ is anchored in the context of UNCLOS and the FSA; the International Code for Ships Operating in Polar Waters (Polar Code)⁶ has been made effective by amending globally applicable IMO instruments: primarily MARPOL and SOLAS,⁷ 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 Exclusive Economic Zones (EEZs), in accordance with the jurisdiction, rights and obligations, as allocated by the 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, Article 234 of the UNCLOS 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 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 Agreement) is expected to strengthen this framework.

² United Nations Convention on the Law of the Sea 1833 UNTS 331 (signed 10 December 1982, entered into force 16 November 1994).

³ 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, 1995.

⁴ International Convention for the Prevention of Pollution from Ships as modified by the Protocol of 1978 (signed 17 February 1978, entered into force 2 October 1983), 1340 UNTS 61 and 1341 UNTS 3.

⁵ The Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean (CAO)

⁶ IMO, MSC 385(94) - MEPC 68/21/Add.1, Annex 10, "International Code for Ships Operating in Polar Waters" (Polar Code).

⁷ International Convention for the Safety of Lives at Sea, (signed 1 November 1974, entered into force 25 May 1980), 1184 UNTS 278.

Below we will describe, define (ODEMM and our definitions) and, if possible, identify management in place for the 11 pressures relevant for the CAO we anticipate coming from the ship traffic (science activities, tourist activities and military activities), humans on the ice (Figure 8.1).



Figure 8.1. Ships' onboard systems and ship operations give rise to different environmental pressures. The arrows are not proportional in size and 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 (permission from and modified after Jalkanen et al 2021.)

8.1 Contaminants

Definition (ODEMM): 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 regional specific challenges, such as to prohibit discharges into the sea of oil or oily mixtures; noxious liquid substances or mixtures containing noxious liquid substances, cargo residuals, 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 International Maritime Organization (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 Ships⁸ prohibits the use of harmful organotin compounds in anti-fouling paints used on ships and have established a mechanism to prevent the potential future use of other harmful substances in anti-fouling systems.

Confidence: 3 (Very high confidence that ship-induced pollution is happening in the CAO because data from the ASTD supports this insight)
Studies on ship-induced pollution in the CAO: ASTD emission data from the CAO Studies from other ice-covered marine areas: Baltic Sea

Beside the pressures from global sources described in chapter 2, one of the largest contributions of contaminating compounds originate from atmospheric deposition from the ships in CAO. In the case where a ship is equipped with an exhaust cleaning systems, emissions can be contributed through scrubber discharge water; 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 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.

⁸ International Convention on the Control of Harmful Anti-fouling Systems on Ships (signed 5 October 2001, entered into force 17 September 2008), 3356 UNTS.

Science activities in the High Arctic are limited due to sea ice conditions, although they have increased in recent years due to climate warming and sea ice reduction. Research vessels have internationally agreed controls on the release of contaminants. As outlined in Chapter 2.2, science research vessel activities, primarily icebreakers, are the dominant vessel type used in science activities in the CAO, although their relative impact via introducing contaminants is limited in comparison to increasing commercial ship traffic (see Ch 2.2, section 3.2).

Metals

Antifouling paints have been identified as the main source of both copper and zinc from shipping, but 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 that increases the overall toxicity and to control the leaching process (Amara et al., 2018). The use of antifouling paints has shown to cause elevated concentrations in marinas and natural harbours in the Baltic Sea (Egardt et al., 2017; Kylin and Haglund, 2010; 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 μ g/cm²/day 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 lowfouling areas such as the Baltic Sea. Recent studies suggest that a release rate between 2.2 $\mu g/cm^2/day$ and 5 $\mu g/cm^2/day$ could be sufficient to prevent macrofouling (e.g. barnacles and macroalgae) in the Baltic 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 low growth rates of Arctic organisms in even lower temperatures than in the Baltic Sea, the same can be assumed for the CAO. Beside copper and zinc, scrubber discharge water is also recognized to contribute to the load of vanadium and nickel to the marine environment (Ytreberg et al. 2022).

Oil

Oil leakage from machinery can reach 6 litre per day and it can increase with ice and distance (<u>https://www.sintef.no/siste-nytt/2022/stort-og-usynlig-oljesol-vokser-mottrekk-haster/</u>). On average, 2.6 litres of oil per day leaks out from the stern tube of ships with risk of entering the marine environment (Lundberg, J., 2021). The causes that could influence the leakage rate were design related, such as vibrations, the rotational speed of the propeller shaft, radial and axial movements of the propeller shaft, as well as external causes such as the quality of water and foreign materials.

Chemicals

Absent 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 Cooperation (AMEC) program that began in 1996 (Sawhill 2000, Ortman 2009). 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. We anticipate that pollution from military

activities (vehicles in air, on the ice, in the water and walking on the icecap) activity within the CAO High Seas or in the surrounding areas may enter the CAO ecosystem.

Scrubbers

An increasing number of ships use exhaust gas cleaning systems, or "scrubbers", to remove SO_x from their exhausts to in order to meet stricter global regulations, which 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 emission of SO_x into the air. However, the scrubber wash water that is most often discharged back into the sea, is heavily acidified (typically 500-1000 m³/h, pH 3) leading to the 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 2021).

Emissions to air and atmospheric deposition

The main environmental impacts of marine transportation (Walker et al, 2019) include air pollution generated by engine fuel combustion (Cullinane & Cullinane, 2013; Eyring et al., 2010). Ships contribute to emission of carbon dioxide (CO₂), methane (CH₄), 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 (SO₂) and nitrogen dioxide (NO₂) are important air pollutants and 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 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 of the albedo of ice and snow surfaces and introduce pollutants from the atmosphere into the ocean (Mayer 2014). 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, comprising CO₂, methane (CH₄), and nitrous oxide (N_2O) , from marine transportation are a significant contributor to global anthropogenic air pollution, and increased CO₂ 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 don't deliberately leave unnecessary traces of their presence, including pollution. Despite this, use of ammunition and expendable sensor and weapon countermeasures such as sonar buoys, XBT's and flares leads to contaminant pollution, including copper, 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 and the fuel consumption reached a record value in the CAO in 2020 for icebreakers (mainly research ships). Cruise ships reach a maximum fuel consumption volume in 2022 of 899 km³. The fuel consumption within the CAO LME in the maximum year 2020 was 5122 km³, compared to volumes in the Barents Sea of 596648 km³ during 2020.


Figure 8.2. The fuel consumption (km³) per ship-type per year during 2012-2022 for the CAO LME.

On 01 January 2020, a new global cap was implemented by the IMO on sulphur content in marine fuels to reduce the air pollution created in the shipping industry (IMO 2020). The "IMO 2020" rule limits the sulphur in the 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), sulfur dioxide, SO2 (Figure 8.3 right), carbon dioxide (CO2, Figure 8.4 left) and aerosols (i.e., particulate matter, PM, Figure 8.4 right) in metric tons.



Figure 8.3. The nitrogen oxides (NOX, left) and sulphur oxide (SO2, right) emission in metric ton per ship-type per year during 2012-2022 in the CAO LME.



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

It is not only ships that add to atmospheric emissions in the CAO but also aircrafts. During landing, takeoff, and taxiing, aircraft generate pollutant plumes including particulate matter (PM), especially ultrafine particles (UFPs) from jet engines; volatile organic compounds; oxides of sulfur; 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 (<u>https://unece.org/air-pollution-ecosystems-and-biodiversity</u>).

8.2 Nonindigenous species

Definition (ODEMM): Introduction of non-indigenous species 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)⁹ is the main international instrument addressing introduction of non-indigenous species. 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

⁹ International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM) (signed 13 February 2004, entered into force 8 September 2017), 3282 UNTS.

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.

Confidence: 4 (Low confidence if NIS are introduced by local ships in the CAO and capable to survive and produce offspring in the 4000m deep area) **Studies showing NIS in the CAO**: **Studies from other ice-covered marine areas**: Baltic Sea, Barents Sea

Beside the spreading of non-indigenous species via global sources as described in chapter 2, the primarily spread is through ballast water discharge (are not expected to be happening in the CAO), biofouling on hulls and hitchhiking among trade goods (<u>Drake et al.</u>, <u>2007</u>; <u>Boltovskoy et al.</u>, 2011) but also through black- and grey water, and food waste.

The risk of introduction is related to the volume of ships and the risk of establishment is tied to climate similarities between the source location and the location to which it is introduced (Nong et al 2019).

Ballast water release during science missions is most likely to occur when approaching ports for refueling activities in the marginal seas, with minimal input in the CAO. For antifouling needs, a self-polishing paint is used and the potential contaminant from this source is possible due to the regular contact of ships with sea ice. Additional ccorrosion protection and antifouling paint are also used inside tubes and cooling systems on the ship. See Ch 2.2 for further information.

Presently the number of non-indigenous species (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 & 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 system.

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 due to 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 stabilise 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 to fish of 30 cm or longer (Carlton, 2001; HELCOM, 2018). Shipping may introduce non-indigenous species that have high dispersion capacity and the ability to survive in ballast tanks (Riccardi, 2006).

Increase of non-indigenous species 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 will be fully implemented by 2024 (IMO, 2017).

8.3 Marine litter, incl. micro plastics

Definition (ODEMM): 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.

Confidence: 2 (High confidence that ships produce litter and that all/some are dumped in the sea with or without intention. But as different ships, depending on ship-age and size, have different approach to litter handling, it is not possible to have highest confidence as to specific sources)

Studies on litter from CAO: yes, Peeken et al. 2018 on microplastics in sea ice, Kühn et al. on microplastics in polar cod

Studies from other ice-covered marine areas: yes (Barents Sea, Hausgarten, Bering Sea)

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)

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

Investigations have shown a correlation between increasing shipping activity and increasing densities of macroplastics and microplastics found in Arctic waters (Martínez et al 2020)

The 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 inwater cleaning operations to remove biofouling (Tamburri et al 2022).

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

The Bering Strait region of Alaska experienced a marine debris event that brought litter ashore that was different from the types and amounts typically observed, most associated with foreign ship traffic through the region (DOI: 10.25923/jwag-eg41).

Shipping (thermal insulation, varnish for ship protection) and wastewater can be a local source of microplastics (e.g., Grøsvik et al. 2018; Herzke et al. 2021; Tekman et al. 2017).

The Central Atlantic and Barents Sea appeared to have more microplastics in terms of weight concentration (7–7.5 μ g/m³) than the North Atlantic and Siberian Arctic (0.6 μ g/m³) which mostly originate from terrestrial input (Pakhomova et al 2022).

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

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

Science activities primarily retain their equipment and supplies onboard, 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 programs 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 Ch 2.2 for further information.

8.4 Artificial noise pollution

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

Confidence: 1 (Very high confidence that ships in the CAO are producing significantly higher noise) **Studies from CAO**: **Studies from other ice-covered marine areas**: yes

Noise pollution is related to quiet natural areas decline and biodiversity loss (Laiolo, 2010; Iglesias-Merchan et al 2015). Energy-related pollution, including noise, are 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 (e.g. engines, propellers, ice crushing, use of scientific equipment as e.g., trawling, echosounders, and military operations) is the biggest contributor to underwater anthropogenic noise (PAME 2021) and substantially higher than those occurring in the natural acoustic environment in the polar regions where ice melting, pressure cracking, and iceberg calving dominate the soundscapes (Dziak et al 2015, PAME 2019). Noise from earthquakes, undersea volcanoes, and hydrothermal vent activity, and other are geophonic components produces 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, and 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. But naval ships typically use long range, low frequency active sonar systems to detect submarines this intense noise pollution have been associated with whale strandings and are 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 fueled icebreakers and research conducted from submarines) collect multiple types of data including: <u>seismic data</u>, sub-bottom profiler data, geological sampling with the use of special equipment, borehole drilling, gravity

and <u>magnetic anomalies</u>, offshore <u>geodetic data</u>, multi-beam <u>bathymetry</u> surveys, fish eco 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 $30 \text{ dB}/\mu\text{Pa}^2$ (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 2021).

In the eastern Canadian Arctic, icebreaker and tankers (during July to October) had the highest sound levels, followed by general cargo and bulk carriers (Jones 2021). In July and Oct, the sea surface temperature is colder and water column more mixed, which increases propagation of radiated sound from ships (Jensen et al., 1993).

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).

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

Table 8.1. Examples of natural and anthropogenic noise relevant for the CAO (from PAME 2020 and Duarte 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 the depths between 100 and 200 m. This water layer acts as a strong acoustic duct, channelling sound across distances of 80 to 100 km (Poulsen and Schmidt, 2016).

But because the Arctic environment is poorly sampled, (including seafloor topology, sediment characteristics, and the oceanography) there is uncertainty for acoustic propagation. Sea ice morphology parametrisation needs to be addressed, soundscape modelling needs to be validated with observations, and needs exist to include ice, wind, biological, and anthropogenic sources (PAME 2021).

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 due to 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 2021).

Sound speed is a function of 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 which allows sound generated near the surface, such as noise from ships, to propagate great distances, and 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 2021).

Ocean **soundscapes** are rapidly changing because of changing abundances of soundproducing 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 and/or amplitude modulated and can be emitted as single pulses or occur in regular sequences or temporal patterns, such as pulse trains of fish calls and melodic phrases of whale songs (Duarte et al 2021).

We anticipate 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 of the Central Arctic Ocean. Movements of surface ships, submarines and aircraft with personnel as well autonomously could create noise disturbances. Supersonic military jets, for example, may influence the behavior of marine mammals (Laney and Cavanagh 2000) that could interact with the CAO High Seas ecosystem. With surface ships, in the context of the vast majority of ships that are non-military, including icebreakers that are designed for Open Science research, it would be difficult to distinguish noise from "warships" or "enforcement" vessels specifically. 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 times 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 due to a

combination 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).

From science activity we anticipate this is a minor component in relation to noise from seismic activities, primarily though geological resource exploration activities.

8.5 Nutrient and organic enrichment

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

We anticipate that nutrients and organic material from military activity within the CAO or in the surrounding areas may enter the ecosystem of the Central Arctic Ocean. 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, do release gray water periodically during their voyage, 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 (ODEMM): Targeted extraction of species.

Regulations: Extraction of living resources is regulated based on the provisions of the 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),¹⁰ 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. Hunting of polar bears is strictly regulated due to the 1976 agreement on the Conservation of Polar Bears that prohibits 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 (NAMMCO) contributes to conservation, management and study of marine mammals in the North Atlantic

¹⁰ 1980 Convention on Future Multilateral Co-operation in North-East Atlantic Fisheries (NEAFC), entered into force in 1982.

Confidence: Very high confidence that scientific investigations take samples from the sea and sea floor in the CAO

Studies on seabed disturbance in the CAO: yes, see scientific literature. Studies from other ice-covered marine areas: Yes, all the surrounding seas

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* that prohibit on the killing of polar bears, subject to specific exceptions, including killing for scientific or conservation purposes and by local people using traditional methods in the exercise of their traditional rights, and the *1992 Agreement on Cooperation in Research, Conservation and Management of Marine Mammals in the North Atlantic (NAMMCO)* that contribute to conservation, management and study of marine mammals in the North Atlantic (read more in chap 5).

But research and scientific operation has sampled in the CAO for decades (see science literature) using grabs, cores, nets and in the ice-free areas, trawls on the slopes. Such equipment samples vertebrates and invertebrates for scientific purposes.

Resource extraction for living resources, such as scientific exploratory fishing planned under the CAOFA agreement (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 bottom-trawling is undertaken it will disturb deep sea benthic communities due to damage to organisms living on the bottom as part of test trawling activities. During commercial trawling, the size of its nets (10-100s of meter length) to cover very large spatial areas (10s of meter openings and of kms length) that can contact the seafloor have a much greater impact spatially compared to the limited seabed disturbance from science pelagic or epibenthic trawling that normally uses much smaller nets (3-m openings and up to 10 m length nets). See Ch 2.2 for further information. Current extraction of microbes and marine invertebrates and fishes in research expeditions is limited to sampling areas mostly <1 m2 in area.

8.7 Physical seabed or sea-ice disturbance

Definition (ODEMM): Physical interaction of human activities with the seafloor and with seabed fauna/flora causing physical damage and/or mortality (e.g. from trawling or anchoring), excluding 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.

Confidence: 1 (Very high confidence that scientific investigations take samples from the seafloor with equipment that smother the sediment) **Studies on seabed disturbance in the CAO**: No

Studies from other ice-covered marine areas: Yes, trawl tracks in the Barents Sea and North Sea

Deep sea mining can have a negative impact on long-lived species attached to hard substrates of interest or in surrounding soft sediments during the extraction process. Damage to hydrothermal vent chimneys, and other sea-bed 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. Currently Norway has approved exploratory mining in an area south of Fram Strait and will be the test case on impacts of this activity on the biodiversity of deep-sea organisms. This impact should be tracked on appropriate time scales of years to decades, and evaluated to determine the impacts before a large opening of deep-sea mining should occur. Scientific expeditions do 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; (https://www.npd.no/globalassets/2force/2019/documents/archive-2010-2018/joining-forces-2018/gonorth---forwick.pdf). This equipment impact the seabed by abrasion, smothering and substrate loss.

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

There is consideration by Indigenous populations that both habit change and noise impacts via icebreakers have negative impacts on subsistence hunting.

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 developed for the southern hemisphere. It is likely that artificial light pollution will qualify as 'pollution' under UNCLOS, Art. 1 and thus become part of the general obligations on all states to prevent, reduce and control such pollution.

Confidence: Very high confidence that ships use light when in the CAO, particularly during period with full or partly darkness.

Studies on light pollution in the CAO: no Studies from other ice-covered marine areas: YES, Berge et al. (Arctic Ocean, but not CAO)

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 night-time artificial light (Davies and Smyth 2017; Marangoni et al 2022). Many species use natural light cues (sun, moon, stars, 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 2017; 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 lights, which will increase local impacts to marine taxa.

Artificial light from fishing vessels and stationary platforms are known to influence invertebrates and fishes (McConnell et al. 2010, Berge et al. 2020) and marine birds (Merkel and Johansen 2011), but less is known about its impact on marine mammals and birds. Large vessels, such as cargo ships and tankers, with concurrently greater radiance, increase artificial light emissions in the CAO and adjacent shelves, particularly in gateway areas. Due to the high sensitivity of marine animals for changes in light intensity, increased artificial light can locally affect the vertical distribution of zooplankton and fish, leading to locally 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 on ecosystem surveys (Berge et al. 2020). Artificial lights attract and cause injury and death to marine birds, which are disoriented by lights and then fly into coastal buildings, vessels (including those anchored), and offshore platforms, with numbers ranging from individual birds to hundreds in one incident. 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 (Gjerdrum et al. 2021; Merkel and Johansen 2011; Rodriguez et al. 2014). The species affected by light pollution depend on the region, 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 due to 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 during months of nighttime darkness, potentially resulting in higher risk of vessel-bird collisions. 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 avoiding 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 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 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 due to increasing potential for ship strikes of migrated seabird and marine mammal species. Since natural light is limited or non-existent above the Arctic Circle in marginal seas in winter, science vessels have strict limits for reducing or eliminating light use during transit in marginal seas in the Arctic, except during actual science operations. However, there is uncertainty for the protection of upper trophic level species in the CAO from commercial ship traffic. A limited numbers of scientific ships freeze into the Arctic Sea ice, such as RV Polarstern did for the MOSAiC program, or build ice camps, such as international field camps by Russian and other

countries. Those expeditions that do, however, have the potential for near-field light pollution on the ecosystem.

We anticipate that light pollution from military activity (in the air, on the icecap, submerged in water) within the CAO High Seas or in the surrounding areas only have a local impact on the CAO ecosystem, e.g. local attraction of fish and zooplankton (Berge et al. 2020). However, light pollution and incidental ship strikes of migrating seabirds (which are attracted by lights) 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 the fall (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. But there are 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.

Confidence: 4 (Low confidence that there are ship strikes of megafauna happening in the CAO)

Studies of unintended injury and mortalities in the CAO: no

Studies from other ice-covered marine areas: photo documentation from ?

Transport roads may directly impact wildlife via physical contact or by creating barriers to animal movement, and indirectly by causing wildlife to modify their behaviour to avoid transport roads (Alamgir *et al.* 2017). 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 of torpedoes hitting whales exists (e.g.

https://www.news.com.au/world/british-navy-mistakes-whales-for-submarines-and-torpedoesthem-killing-three-during-falklands-war/news-story/92e895efd40db654fa41a62a3312f4c0). Military exercises can also lead to accidents such as ship or aircraft collisions, with

subsequent contamination of the marine environment (Rossland 2019).

Marine habitats and megafauna can be threatened by new and existing trade routes (Yang *et al.* 2018) due to ship strikes with marine megafauna (Van Waerebeek *et al.* 2007) in the CAO.

A major consideration for all marine transportation is the possibility of impacts with marine animals, and recorded ship-strikes are likely underestimated, or go unreported, and often are not recognized until reaching ports, with the whale draped over the bulbous bow bulb (Félix & Van Waerebeek, 2005). At present the probability of vessels colliding with marine mammals in the CAO is low (Stevenson et al 2019). In the Bering-Chukchi-Beaufort area, scars from ship strikes are infrequent and occur on ~2% of all harvested bowheads, but bowhead habitat is changing rapidly resulting in e.g., sea ice reduction (George et al 2017). 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).

We anticipate that the use of military weapons within the CAO High Seas may have an impact on the CAO 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 to 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

Regulations: 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.

When coming to ship-traffic we do not consider the "ship" itself as "a human presence" but only "Tourist" and people on the ice. We anticipate 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 CAO ecosystem.

https://doi.org/10.1016/j.atmosenv.2006.04.062https://thebarentsobserver.com/en/profil/thomasnilsenhttps://thebarentsobserver.com/en/arctic/2020/02/about-20-bulldozers-have-sunk-arcticseafloor-one-more-comingsoonhttps://doi.org/10.1016/j.atmosres.2015.07.023https://doi.org/10.1002/ecs2.1370https://doi. org/10.1371/journal.pone.0227189https://doi.org/10.1016/j.annals.2021.103205

8.11 Table: Human Activities – Pressures relevant for CAO

The CAO LME	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/sea-ice disturbance	Artificial light pollution	Unintended injury and mortality in open water	Human presence on ice
Science icebreakers and research activity ¹	1	2	2	1	5	1	1	1	1	5	3
Tourist vessels and activity on the ice/camps ¹	1	2	2	1	5			1	1	5	3
Military ships and activity ²		4	4	3	5			1	3	3	5
Global sources drifting into the CAO	3	4	2								

1: Reviewed by Ida-Maja Hassellöv.

2: confirmed by Petter Helgevold Kvadsheim,

Pressure relevance:

YES
Maybe
NO
Not relevant

Confidence score for evidence:

- 1. Very high
- 2. High
- 3. Medium
- 4. Low
- 5. Very low.

9 Existing international management frameworks in the CAO

Alf Håkon Hoel, David Fluharty, Lis Lindal Jørgensen, Lisa Speer, Alain Dupuis, Anne Kristine Frie

9.1 Background

The central Arctic Ocean (CAO) is under the jurisdiction of the five coastal states to the Arctic Ocean - Russia, USA, Canada, Denmark/Greenland, and Norway. There is also a 2,5 million km2 high seas area in the middle of the CAO. The WGICA area (Figure 1.1) is in the high seas area beyond national jurisdiction, as well as in northernmost parts of the maritime zones of Canada, Greenland, Norway and Russia. This chapter addresses international governance mechanisms for the WGICA area, with an emphasis on legally binding instruments.

The international governance framework consists of global agreements, the cornerstone of which is the 1982 Law of the Sea Convention (UNCLOS), and regional agreements. As regards the global framework, it applies in 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 domestic legislation and in cooperation with other states, as appropriate.

This chapter is organized as follows: an introductory description of the Law of the Sea Convention 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. A concluding part briefly describes 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 1973-1982 and entered into force in 1994. Currently the Convention has 168 parties. It is ratified by four of the CAO coastal states. The 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 International Maritime Organization (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 and in the *territorial sea*, the seaward limit of which may extend to 12 nautical miles (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 the 200 nmi (370 km) *Exclusive Economic Zones* (EEZ) coastal states have extensive powers, including jurisdiction over the natural resources. Other States have to comply with the coastal state's regulations regarding exploring and exploiting the resources, but also enjoy rights, notably freedom of navigation. Where the distance between opposing coasts of coastal states is less than 400 nautical miles 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 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 its land territory (Figure 9.1). 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 limits of EEZs, coastal states are to submit information on their claims to the Continental Shelf Commission (CLCS) which provides recommendations on the final extended limits that the coastal state are 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.



Maritime Zones and the International Law of the Seal?

Figure 9.1: Maritime zones.

9.2.3 The implementing agreements of 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 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.³

Also, 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 2001.⁴ The objective of the 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 in the UNGA. Negotiations on a treaty was 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.

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)⁵ 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.⁶ To date two such assessments have been produced.

9.3 Living marine resources

9.3.1 UNCLOS and UNFSA

At the global level, the Law of the Sea Convention and the UN Fish Stocks Agreement (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 EEZ, the Convention codifies the coastal State's sovereign rights for the purpose of exploring and exploiting, conserving and managing the fish stocks. These rights are subject to certain duties, among them taking into account the best scientific evidence available, to ensure that the maintenance of the living resources is not endangered by over-exploitation, 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 the precautionary approach and an ecosystem approach. The Agreement strengthens regional and sub-regional 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)⁷ (in force 2003). The objective is to promote compliance with international conservation measures on the high seas, by flag states ensuring that fishing vessels entitled to fly its flag 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). The objective of the agreement is to prevent, deter and eliminate IUU-fishing through the implementation of effective port State measures.

The FAO Code of Conduct for Responsible Fisheries⁸ was concluded in 1995 as a voluntary instrument (soft law). It contains principles 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 establishes 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*⁹ (in force 1983). The objective of the CMS 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), (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.¹⁰

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 coastal states and managed by them. 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 1980 Convention on Future Multilateral Co-operation in North-East Atlantic Fisheries¹¹ (NEAFC), (in force 1982) aims to ensure the long-term conservation and optimum utilisation of the fishery resources in the Convention Area. NEAFCs regulations apply to the high seas in its Regulatory Area which includes the high seas areas of a part of the Central Arctic Ocean (the Atlantic wedge). NEAFC has adopted a significant number of regulations, including to prevent adverse impacts from bottom fishing on vulnerable marine ecosystems.

*The 1992 Agreement on Cooperation in Research, Conservation and Management of Marine Mammals in the North Atlantic (NAMMCO)*¹² (in force 1992). The objective is 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 provides management advice for walrus and toothed whales.

In 2015 the five coastal states to the central Arctic Ocean agreed to a declaration¹³ where they undertook to not let their vessels start fishing in the high seas of the central Arctic Ocean 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*¹⁴ was signed in 2018 (in force 2021). It establishes that the parties will not let their vessels start commercial fishing in the high seas of the CAO until 2037 the earliest, should commercially viable resources be discovered there. The moratorium will be continued in 5-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*¹⁵ (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 multilateral as well as bilateral agreements, renewed annually. There is also an annual North Atlantic Fisheries Ministers' Conference and a Nordic cooperation at 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 on 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 International Maritime Organisation (IMO). Regulations of navigation, safety at sea, and vessel source pollution are primarily developed through the IMO.¹⁶

The Law of the sea Convention requires flag states to adopt laws and regulations for the prevention, reduction and control of pollution of the marine environment from vessels flying their flag. Coastal States have a wide jurisdiction to adopt regulations on shipping within their Territorial Sea to protect the marine environment. In the 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 the 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.¹⁷ The most important are:

The 1974 International Convention for the Safety of Life at Sea (SOLAS) (in force 1980). 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).¹⁸ 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).¹⁹ The BWMC is aimed at preventing the transfer of harmful aquatic organisms and pathogens through ships' ballast water and sediments.

IMO also has a number of non-binding instruments, including *General Provisions on Ships' Routeing* (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 the risks that are specific to operations in polar waters.²⁰ 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, in force 2013.²¹ 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, establish rules for the conduct of search and rescue operations, and details the content of cooperation.

9.5 The environment

9.5.1 UNCLOS

The *Law of the Sea Convention* provides the international legal framework for 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)²² (in force in 1993) addresses the conservation of biological diversity, the sustainable use of its 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).²³ Its objective is to protect human health and the environment from persistent organic pollutants (POPs). It requires

parties to prohibit production and use, and restrict trade, of certain listed POPs. Substances defined as POPs (persistence, bio-accumulation, long-range transport, and adverse effects) 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)²⁴ addresses the transboundary movement of hazardous wastes though the establishment of a prior informed consent procedure in respect of the import of such wastes.

*The 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, London ((The London Convention)*²⁵ (in force in 1975) and the *1996 Protocol*²⁶ (in force 2006) is the primary international agreement controlling the deliberate dumping of non-ship generated wastes 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 Convention Framework Convention on Climate Change (UNFCCC)²⁷ (in force 1994).²⁸ The objective is 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 Agreement²⁹ seeks to enhance the implementation of the UNFCCC inter alia by holding the increase in global average temperatures well below 2°C above preindustrial 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).³⁰ It aims to protect human health and the environment against adverse effects from human activities which 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, such as the 1995 Global *Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA)*³¹ which seeks to prevent the degradation of the marine environment from land-based activities. Also, the 1992 *United Nations Conference on the Environment and Development* (UNCED) produced a global action plan for the environment, *Agenda 21* promoting 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.³² And the 2012 *UN Conference on Sustainable Development, Rio+20* produced a political outcome document, *The Future We Want* renewed past commitments and addressed a number of thematic issues, including oceans and seas.³³ Also non-binding, but of considerable political importance, are the 17 *Sustainable Development Goals (SDG)*³⁴ including SDG 14 "Life below water" adopted by UNGA in 2015.

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)³⁵ 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).³⁶ The objective of OSPAR is to prevent and to eliminate marine pollution and to achieve sustainable management and to 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 address the rights and obligations of 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. States have a duty to promote and facilitate the development and conduct of marine scientific research.

Coastal States have the exclusive right to regulate, authorize and conduct marine scientific research in their Territorial Sea. They also have jurisdiction with regard to marine scientific 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, and 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 programs in marine research, services, observation systems, hazard mitigation and capacity development. While not having a regulatory mandate, the IOC plans, coordinates, and supports global and regional programs.

The *Decade of Ocean Science for Sustainable Development* ³⁷ runs from 2021 to 2030. 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 pointed out, the Law of the Sea Convention contains general provisions regarding marine scientific research. In addition, there are also regional binding and nonlegally binding instruments and institutions that play an important role.

The 1992 Convention for a 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 northward from 30 degrees North Latitude in the Pacific Ocean.

The 1964 Convention for the International Council for the Exploration of the Sea (ICES)³⁸ builds on the ICES organization established in 1902. It 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, in particular fisheries effects in the Northeast Atlantic. In support of this, ICES facilitates data and information exchange is a marine data centre for oceanographic, environmental, and fisheries data.

The 2017 Agreement on Enhancing International Arctic Scientific Cooperation (in force 2018)³⁹ seeks to enhance cooperation in scientific activities in order 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)⁴⁰ and the International Arctic Social Sciences Association (IASSA) 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 (IASSA)⁴¹ aims to promote international cooperation and to increase the participation of social scientists in Arctic research.

The *Polar Years* (most recently 2007-2009)⁴² 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 nautical miles, for the purpose of exploring it and exploiting its natural resources, which includes 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. Also, the Convention contains an obligation to prevent pollution from seabed activities. Coastal states are required to adopt laws and regulation 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 (see above) 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 co-operation with other states. The Convention covers oil pollution incidents involving ships, offshore units, seaport and oil handling facilities.

UNEP has developed nonbinding guidelines for state practice with regard to offshore mining and drilling. $^{\rm 43}$

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.⁴⁴ 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, includes obligations to protect and conserve ecosystems and the biological diversity of the maritime area.

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*⁴⁵ (in force 2016) aims to strengthen cooperation, coordination and mutual assistance among the parties on oil pollution preparedness and response, in order 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 addressed above. Environmental impact assessments are addressed both by the UN Economic Commission for Europe (ECE) (and is therefore open to all Arctic countries) as well as by Arctic Council guidelines.

The 1991 *ESPOO Convention on Environmental Impact Assessments*⁴⁶ (in force 1997) sets out an obligation to assess the environmental impacts at an early stage of planning and before decisions are made.⁴⁷ Parties to the Convention must have a system for EIAs and have to carry out an EIA before the decision is taken to authorize or undertake proposed activities t.

9.9 The Arctic Council

The mandate and activities of the Arctic Council spans environmental protection and sustainable use. The non-binding Ottawa Declaration of 1996⁴⁸ established the Arctic Council as a high-level intergovernmental forum to promote cooperation, coordination and interaction among the Arctic States, in particular 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 the United States of America. 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), Sustainable Development Working Group (SDWG). Each Working Group has a specific mandate, and a Chair and Management Board or Steering Committee, and is supported by a Secretariat. The Working Groups execute the programs and projects mandated by the Arctic Council Ministers stated in the Ministerial Declarations that result from bi-annual 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 programs 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 (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, as for example the Arctic Marine Strategic plan, or project reports on issues of concern, as for example ecosystem-based oceans management.

9.10 Conclusions

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

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

10 The vulnerability of the CAO ecosystem components toward pressures

This part of the report describes the relevant ecosystem components for the Central Arctic Ocean (CAO), where they are distributed in the CAO, and when they occur in the CAO.

Finaly, are each of the ecosystem components described for their vulnerability toward the set of relevant pressures (see chapters 1-7) from relevant local human activities evaluated to happen in the CAO. This also includes Global Sources which are not a local activity but are a global source of additional Contaminants and Litter also relevant for the identified human activities local in the CAO.

Table 10.1. The 11 Pressures identified from the human activities: research activity, tourism and military activity, and global sources (see chapters 1-7).

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/sea-ice disturbance
Artificial light pollution
Unintended injury and mortality in open water
Human presence on ice

NB: The impact of climate change originated from human activity (the pressure "heating") on the ecosystem components are described in chapter 10, but not included in the assessment work because Climate change is not a local activity that can be managed locally, and neither does the pressure" "heating" come from any of the human activities in the CAO.

10.1 Climate-related effects on the ecosystem of the CAO

Lisa Speer, Pauline Snoeijs Leijonmalm, Cecilie H. von Quillfeldt, Hauke Flores, Bodil Bluhm, Amanda Ziegler, Jacqueline Grebmeier, Lis Jørgensen, Kevin Hedges, Harald Gjøsæter, Anders Mosbech, Kathy Kuletz, Maria Gavrilo, Anne Kirstine Frie, Mario Acquarone, Lisa Speer

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 CAO, including climate change and the introduction of contaminants, plastics, invasive species, and noise pollution into the region from sources outside it.

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

10.1 Climate-related effects on the physical and chemical characteristics of the CAO

The 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 to three times as fast in the Arctic as in the mid-latitudes, but 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 two-fold over the last 24 years (Oziel et al. 2020).

Decline of Arctic Sea ice: Annual ice and multi-year ice in the Arctic Ocean, including the Central Arctic Ocean, 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 Central Arctic Ocean could be largely ice-free in summer by the 2030s (AMAP 2017(b)), 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 sea 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 the spring) from 1967 through 2012 (Derksen and Brown 2021). Snow cover duration has continued to decline in the Arctic, with its annual duration decreasing by 2–4 days per decade (AMAP 2017(b)). However, the general increase in precipitation may result in more snow on sea ice in some regions and times of the year (von Quillfelt, pers. Com. 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 Chapter x (CAFF, 2017(a)). In addition, sea ice reduces light penetration into the underlying water by up to 99%. Theloss 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 the susceptibility to light pollution is at its extreme in the high Arctic (Ludvigsen et al., 2018).

Changes in salinity: increased river runoff and melting sea ice are resulting in significantly elevated freshwater inputs into the ocean. This freshwater is changing salinity levels, particularly in the top 45m of the ocean (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 cubic kilometres, or more than 11%. This volume equals the combined annual discharge of the Amazon and Ganges rivers (AMAP 2017(b)).

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, Q. 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 carbon dioxide in the atmosphere are taken up in part by the oceans, which leads to ocean acidification, a phenomenon that is amplified in the Arctic as colder water absorbs more carbon dioxide than warmer water. Simulation models show the Arctic Ocean may experience the greatest acidification within the global ocean, with the largest simulated pH changes worldwide occurring in Arctic surface waters (Wassman et al. 2011, Steinhacher et al. 2009). Model simulations for the Central Arctic Ocean indicate that acidification will increase with decreasing sea-ice cover, which will permit greater CO₂ uptake and accelerate freshwater input (AMAP 2018). Freshening of surface seawater lowers the concentration of calcium ions (AMAP 2018), 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 due to 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 atmosphereocean 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 of the CAO

10.2.1 Microbial processes

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

10.2.2 Primary producers

A suite of environmental variables (e.g. sea ice, nutrients, light, water stratification, salinity, temperature) determine abundance, biomass, primary production and taxonomic composition of primariy 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. 2023).

For example, sea ice drives the taxonomic structure of protist communities in the under-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 of sea ice extent, and particularly of MYI, may reduce species diversity in all habitats of the Central Arctic Ocean. 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 sea ice (and the shift from multiyear ice to first-year ice) and therefore enhanced light availability, bottom communities may develop earlier in the season (Van Leeuwe et al. 2018, Lim et al. 2022, Stroeve et al. 2024) and reach higher biomass, though more condensed in time (Leu et al. 2015). Also, a declining snow cover is likely to have an increasing importance for the primary production (Selz et al. 2018). Also, a declining snow cover is likely to have an increase in meld pond formation (Hancke et al. 2022). However, it has been suggested that nutritional content of key ice algae taxa will vary in response to shifts in under-ice light conditions which may result in a net loss of nutritional output (Duncan et al. 2024). Thinner ice and more open water leads increase light transmission may 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 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), for example 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 coldwater 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 favor a regenerating community and small species, e.g. flagellates over diatoms (Lie 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, for instance, a change in the spring bloom phytoplankton community structure due to 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 worldwide. 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. 2021). So far, 36 potentially harmful/ 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 and lowered fitness in marine mammals and potential public health threats attributable to these taxa is uncertain. However, there have been reported algal toxins presence in marine mammals in the Arctic (Lefebvre et al. 2016).

If strong algal blooms become increasingly common in Arctic waters, this could lead to impacts on seabirds and fish, due to 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 on-going rapid decline in overall areal extent and thickness of sea ice, as well as lengthening ice-free periods, the demise of multi-year 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 abundances of protists and sympagic crustaceans related to the loss of multi-year ice (Melnikov 2018; Hop et al. 2021). In pelagic zooplankton, the changing phenology of ice algal blooms has increased the risk of recruitment failure due to a mismatch of life cycles and bloom phenology, as described for the ecologically important copepod *Calanus glacialis* (Soreide et al. 2010).

The already observed changes in the magnitude, timing and phenology of ice algae and phytoplankton production described above 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 of ice algae production therefore likely has impacted standing stocks and reproductive success of ice-algae dependent species, such as the widely distributed ice amphipod *Apherusa glacialis* (Barber et al. 2015).

In the CAO, the seasonal change of light intensity controls the seasonal vertical migration of zooplankton, as well as diel vertical migration during spring and autumn. Notably, light levels as weak as the moonlight or the illumination of ships affect the vertical distribution of zooplankton (Last et al. 2016; Berge et al. 2020). Model projecections indicate that the on-going 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 on winter survival (Flores et al. 2023). While it is certain that sea-ice decline during the past decades has impacted on the light regime and hence the seasonal and diel/lunar change of the vertical distribution of zooplankton, it is not known how strongly this has impacted on the standing stock biomass and the community structure.

Recent studies of the effects of ocean acidification imply both neutral and negative impacts 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 food webs, progressing from the marginal shelf seas towards the slopes of the Arctic Basin. This borealisation reflects the northward expansion of abundant zooplankton species, such as the Atlantic copepod *Calanus finmarchicus* (e.g. Dalpadado et al. 2020), but also predators, such as the jellyfish *Cynaea capillata* (Crawford 2016). Borealisation increases competitive pressure on Arctic communities, often leading to a northward retreat of endemic Arctic fauna.

10.2.4 Benthos

Changes in primary production described above resulting from sea-ice decline, surface warming, salinity decline and increased stratification (in the Amerasian Basin, Polyakov et al.

2020) or decreasing stratification (in the Eurasian Basin, Lind et al. 2018) are expected to affect benthic communities, as they relate to vertical flux of food particles to the seafloor. There is evidence consistent with weakened pelagic-benthic coupling with potentially reduced food supply to the benthos in the Chukchi Borderland/Canada Basin region (Zhulay et al.2023). In the much less stratified Atlantic inflow through Fram Strait, in contrast, abnormally warm surface waters during 2005-2008 resulted in reduced sea-ice cover and increases in phytodetrital food availability to benthic invertebrates (Taylor et al. 2017 and references therein). Response to such increase in food availability has been observed in other deep-sea habitats such as mass occurrence events of mobile epifauna in the northern North Atlantic (e.g. Billet et al. 2001, 2010).

Ocean acidification elicits varied responses in experiments involving benthic biota, ranging from a certain level of resilience in Chukchi Sea clams (Goethel et al. 2017) to reduced growth and metabolic rates and/or decreased calcification in other bivalves (outside the Arctic, Gazeau et al. 2007) and in sub-Arctic red king and tanner crab juveniles (Long et al. 2013), as well as the opposite effect of increased metabolic rate and calcification at the expense of other body functions (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 (pers. obs.), perhaps rendering them vulnerable to acidification.

10.2.5 Fish

Being generally ectothermic, changes in ambient temperature have a direct effect on a fish's body temperature and metabolic rate. When fishes 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 and when the temperature approaches the upper tolerance level further increases may have negative effects and individuals will increasingly demonstrate behavioral 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 and may result in increased use of habitats that have lower food availability or higher predation pressure as a tradeoff to stressful ambient temperatures.

Sea-ice decline may also directly affect fish. Ice-associated production will vanish, directly affecting fish that prey on ice associated species, as for instance young polar cod (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 favor active visual predators and increase 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 CAO, 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 CAO 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 at the Atlantic side (Aschan et al. 2013, Hollowed et al. 2013, Fossheim et al. 2015, Kortsch et al. 2015, Johannesen et al. 2016, Frainer et al. 2017, Johannesen et al. 2017, Haug et al. 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 CAO indicate that nektonic predators have been under-estimated 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 to 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 CO₂ concentrations during the first 25 days post hatching in Atlantic cod. Frommel et al. (2011) found that exposure to CO₂ resulted in severe to lethal tissue damage in many internal organs in Atlantic cod larvae in a mesocosm experiment, with the degree of damage increasing with CO₂ concentration. Kuntz et al. (2016, 2018) reported that swimming performance and metabolism were affected by increased temperatures and CO₂-levels both in 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) argue that even though laboratory studies show sensitivity to elevated CO₂ 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 is 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 *Gadus morhua*, 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 codfish 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 birds have been recorded in the CAO, eight of them regularly. Ivory gulls have been documented to forage around the peripheral pack ice within the CAO in summer, and the CAO is particularly important during theirtheir late summer/fall post-breeding staging and migration (Fredriksen et al., 2018; Gilg et al., 2010, 2016). Similarly, the Ross' gull uses the Arctic Basin extensively for replenishment during its post-breeding migrations (Andreev, 2006, Gilg et al., 2016). In addition, portions of one Atlantic population of black-legged kittiwakes regularly migrate across the CAO (Ezhov et al., 2021). Other seabirds encountered in the CAO 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 break up 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., 2016b), but one of the most important feeding grounds are where the MIZ coincides with the shelf slope (Bluhm et al., 2021, M.Gavrilo, unpublished 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 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 (ACIA 2007, Gilg et al., 2016). 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 e al., 2015). Levels of contaminants in eggs, blood, and feathers of the ivory gull are among the highest ever reported in arctic seabirds and may have sub-lethal 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. Removing 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 high-arctic year-round residency. There are also indications that Pacific seabirds may migrate into the Atlantic via the North Pole (Mckeon et al., 2015).

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, Jetz 2010), while some Arctic seabirds shift pole-wards (see chapter 9 in WGICA Report 1, 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 and walruses (Hamilton et al. 2015a, Hauser et al. 2018, Hamilton et al. 2021). Generally, these species are believed to occur in the CAO only seasonally and for some species like walrus only a few individuals have been observed (Hamilton et al. 2015). The highly ice affiliated bowhead whales have been tracked in the CAO (Kovacs et al 2020), while not the highly ice affiliated harp seals, but in areas immediately to the south of the CAO border are important feeding and residence areas for these species (Vacquie-Garcia et al. 2017, Hamilton et al. 2021). Ice associated bearded seals, spotted seals and ribbon seals have sporadically been close to CAO, but their reliance on this area so far appears to be very limited (Boveng et al. 2013, McIntyre et al. 2013, Citta et al. 2018).

In adjacent ice-free areas, cosmopolitan species like minke, fin, blue and humpback 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 are increasingly observed in summer on the ice-free shelves of the Pacific-gateway area (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 (Elwen and Gridley 2013, Scheinin et al. 2015, France24 2021) most likely via increasingly ice-free passages in the Arctic Ocean as also supported by a recent 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 2021); 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) 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 and Atlantic 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).

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 indicate 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 (Vacquie-Garcia et al. 2017b, 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. 2017). 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, Woodgate et al. 2015, Tremblay et al. 2014). 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, Vacquie-Garcia et al 2017b) have prompted a downlisting from critically endangered to endangered in the 2021 revision of the Norwegian redlist (Artsdatabanken 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 (Kovacs et al. 2020, Chambault et al. 2018).

Increasing killer whale presence in the Atlantic gateway (Storrie et al. 2018, De Boer et al. 2019) and the Pacific gateway area (Stafford 2018) 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 (Vacquie-Garcia et al. 2017b). 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 behavior 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 degrees although warmer waters were close by (Chambault et al. 2018). This very narrow temperature niche Within the historic distribution area of narwhals, the warmest areas 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 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 are closely related to narwhals but are less consistently ice afiliated. 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 45000 belugas summer in these areas and some of them explore the deeper waters within the CAO (Lowry et al 2017b, Hauser et al. 2018). In contrast to the Pacific gateway area, beluga whales around Svalbard exhibit a strictly coastal distribution pattern (Vacquie-Garcia et al. 2018).

10.3 Conclusion for climate impact on ecosystem

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 long very 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, 2019).

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.

10.2 The spatial – temporal distribution of ecosystem components and vulnerability

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



Illustration of an example of interactions of Arctic biota with marine litter and microplastics. Used with the permission from GRID-Arendal graphics.

11 Microbial communities, including viruses

Pauline Snoeijs-Leijonmalm, Stockholm University

11.1 The groups

Microbes (single-celled organisms) form the backbone of all ecological systems by controlling the cycling of elements essential for life – for themselves and other organisms. This prominent ecological role of microbes is not only based on their ubiquitous mass occurrences and fast turn-over rates (generation times), but also on their high diversity of metabolic pathways and symbioses with viruses and multi-celled 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.

Microbial communities consist of prokaryotes (bacteria, archaea), single-celled eukaryotes (protists: fungi, algae, protozoa), and viruses that can infect cells. Millions of microbial cells and viruses and thousands of species are present in every litre of water, sea ice and sediment in the marine environment (Gasol & Kirchman 2018). Some members of microbial communities (algae, cyanobacteria, and other autotrophic bacteria) use light energy for photosynthesis and are called "primary producers" (see Chapter 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).

The versatile microbial matter cycles driven by microbes allow other organisms to fulfil their life functions, often in symbiosis. However, microbes can also hamper other organisms as parasites and cause diseases. Microbial community composition strongly depends on habitat and responds instantly to environmental change due to high species diversity and short generation times (the time it takes for a population to double in number), which is, e.g., within in the range of hours for bacteria in the wild. However, since the CAO is a cold, ultraoligotrophic ocean, productivity is extremely low at all levels (Figure 4.1.1), and microbial generation times may be slightly longer than elsewhere. In the CAO ecosystem the three dominant microbial habitats are: sea ice, water column, and deep-sea sediments, and each of these habitats have their 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 varies from hypersaline in winter (salinities up to 3-4 times 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 in the CAO) 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 bottom ice (lower 5-10 cm) where the sea ice is soft and porous, and in contact with seawater, since seawater usually contains more nutrients than ice and snow. Here not only primary producers thrive, but also other microbes and viruses involved in microbial metabolisms in association with the primary producers (including decomposition), reach highest biomass in the Arctic summer. In winter the ice habitat in the CAO 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 is highly diverse because the two groups meet here (Fernández-Gómez et al., 2019). Oceanic species prevail further down and the purely water-column communities are less diverse (Ghiglione et al., 2012; Bano and Hollibaugh, 2002; Galand et al., 2010; Li et al., 2016). Most of the deeper-occurring oceanic microbial species in the CAO are the same species as those in the global ocean elsewhere since this is an interconnected environment with relatively uniform levels of structuring factors such as salinity and temperature.

11.1.3 Benthic microbial communities

Similar to the deep water column, the sea-floor microbes and viruses are mainly the same species as found in the global ocean. At the seafloor their main roles 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 seas that are more nutrient-rich. Therefore, patches of higher inorganic and organic nutrient availability can cause patchiness in the distribution of microbes and viruses (but they are never absent). A small patch of

decaying algae captured inside the sea ice can create patchiness on a micro-scale, a piece of a tree transported with the transpolar drift from Siberia to the CAO 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 abundance of microbes and viruses varies also with ice depth: at the ice-seawater interface (the lower ca. 5 cm of the 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 highest abundances at the chlorophyll maximum (in the CAO usually at 10-40 m of depth) 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, a 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 seafloor. The most pronounced differences are between the half-year polar night and the half-year polar day when phototrophic processes occur in addition to all other metabolic pathways.

11.4 Vulnerability toward pressures from human activities

It is assumed with low confidence (i.e., the assessment is based on expert opinion only because no literature is available for the CAO), that the ten pressures: "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 <u>negative</u> effects on microbes and viruses in the CAO at the population/community level although they might have a very small local effect on a very short time scale. For example, disturbances of microbial communities from vessels breaking the ice are local and short-term. Moreover, this human pressure is neglidgible in comparison with storms that create similar disturbances at a much larger scale and much more frequently than ice-breaking ships in the CAO.

Some of these ten pressures might have <u>positive</u> effects, e.g., marine litter, including microplastics could provide physical substrate to sessile bacteria and viruses, which directly could increase abundance and biodiversity, marine litter and microplastics could also be degraded (used as nutrient substrate) by some bacteria, while also nutrients and organic enrichment could directly stimulate growth of microbes and viruses. Artificial light pollution from ships in winter can wake up hibernating photoautotrophic cells and exhibit photosynthesis in winter, which is unnatural but not harmful.

It is assumed with low confidence (score 1 = assessment based on expert opinion only, no literature available for the CAO) that the two pressures "Contaminating compounds" and

"Introduction of non-indigenous species", might have <u>negative</u> effects on the microbes and viruses in the microbial communities of the CAO (see the following tables and explanations).

11.4.1 Contaminants

Contaminating compounds may have negative effects on microbial communities. It cannot be excluded that contaminating compounds from <u>global sources</u> arriving in the CAO by air, ice-drift or water transport have direct negative effects on sea-ice and water-column microbes and viruses (Table 4.1.1). This could, e.g., be strongly toxic compounds such as mercury. The negative effect would be <u>widespread (W) and occur persistently (P)</u> because contaminants that arrive by air, ice-drift or water transport can be spread over the entire CAO and this happens continuously. No direct negative effect of such compounds is expected on sea-floor microbes and viruses; because of the great depth of the CAO contaminants are not expected to reach the seafloor without becoming extremely diluted. The here presented assumptions are made with low confidence, i.e., the assessment based on expert opinion only because no literature available for the CAO.

It also cannot be excluded that contaminating compounds from <u>ships</u> (research, tourism/recreation, military) in the CAO can have a direct negative effect on sea-ice and water-column microbes and viruses. This could, e.g., be pharmaceuticals. If so, the effect occurs only <u>near the (ship) site (S)</u>, i.e., only when a ship that is discharging such compounds would pass by, and would be <u>rare (R)</u> for tourism/recreation and military ships (less than 1 month per year) and <u>occasionally (O)</u> for research vessels (1-4 months per year).

In all these cases the degree of impact on microbial communities (including viruses), is expected to be <u>low (L)</u>, 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 <u>high (H)</u> 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 <u>low (L)</u>, 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.

Table 4.1.1. Vulnerability analysis of <u>contaminating compounds</u> on microbial communities (including viruses) in the CAO.

Sector	Ecological characteristic	Extent	Frequency	Degree of impact	Resilience	Persistence	Confidence
Global sources	Sea-ice microbes and viruses	w	Р	L	н	L	1
Research	Sea-ice microbes and viruses	S	0	L	н	L	1

Tourism/recreation	Sea-ice microbes and viruses	S	R	L	н	L	1
Military	Sea-ice microbes and viruses	S	R	L	н	L	1
Global sources	Sea-floor microbes and viruses	NO					
Research	Sea-floor microbes and viruses	NO					
Tourism/recreation	Sea-floor microbes and viruses	NO					
Military	Sea-floor microbes and viruses	NO					
Global sources	Water-column microbes and viruses	w	Р	L	н	L	1
Research	Water-column microbes and viruses	S	0	L	н	L	1
Tourism/recreation	Water-column microbes and viruses	S	R	L	н	L	1
Military	Water-column microbes and viruses	S	R	L	н	L	1

11.4.2 Non-indigenous species

It cannot be excluded that non-indigenous species that are pathogenic or competing for resources with native species of microbes or viruses (free or embedded in other non-indigenous species) that are transported to the CAO by <u>ships</u> (research, tourism/recreation, military) have direct negative effects on sea-ice and water-column microbes and viruses. If so, the effect occurs only <u>near the (ship) site (S)</u>, i.e., only when a ship leaking non-indigenous species would pass by, and would be <u>rare (R)</u> for tourism/recreation and military ships (less than 1 month per year) and occasionally (O) for research vessels (1-4 months per year) (Figure 4.1.2). The here presented assumptions are made with low confidence, i.e., the assessment based on expert opinion only because no literature available for the CAO.

Pathogenic species of microbes and viruses are not expected to arrive in the CAO from <u>global sources</u> by air, ice-drift or water transport because they would probably die during the 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 CAO with species of, e.g., zooplankton, squid, fish, birds and mammals that expand their distributions northward as a response to climate change.

In all these cases the degree of impact on microbial communities (including viruses), is expected to be <u>low (L)</u>, 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 <u>high (H)</u> 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 <u>low (L)</u>, 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.

Table 4.1.2. Vulnerability analysis of <u>non-indigenous species</u> on microbial communities(including viruses) in the CAO.

Sector	Ecological characteristic	Extent	Frequency	Degree of impact	Resilience	Persistence	Confidence
Global sources	Sea-ice microbes and viruses	NO					
Research	Sea-ice microbes and viruses	S	0	L	н	L	1
Tourism/recreation	Sea-ice microbes and viruses	S	R	L	н	L	1
Military	Sea-ice microbes and viruses	S	R	L	н	L	1
Global sources	Sea-floor microbes and viruses	NO					
Research	Sea-floor microbes and viruses	NO					
Tourism/recreation	Sea-floor microbes and viruses	NO					
Military	Sea-floor microbes and viruses	NO					
Global sources	Water-column microbes and viruses	NO					
Research	Water-column microbes and viruses	S	0	L	н	L	1
Tourism/recreation	Water-column microbes and viruses	S	R	L	н	L	1
Military	Water-column microbes and viruses	S	R	L	н	L	1

12 Primary Producers

12.1 The groups

12.1.1. Sea ice algae and phytoplankton

In this context 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 1276 sympagic algae and other protists have been recorded (Bluhm et al. 2017) from sea ice and 2241 phytoplankton taxa (Lovejoy et al. 2017) 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

Microscopic primary producers are patchy, but widely distributed across the Central Arctic Ocean due to transport by ocean currents and drifting ice (Abelmann 1992, von Quillfeldt 2000, Poulin et al 2011, Hop et al. 2020, Hegseth and von Quillfeldt 2022), but differences 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 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 is likely to be more common and widespread with more frequent lead formation (Assmy et al. 2017). There are, however, indications that different mechanism (light conditions, nutrient availability, advection etc.) 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 (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 central Arctic Ocean are coupled to sea ice coverage and nutrient supply

(Ulfsbo et al 2014), but typically there is an increased primary production at the ice edge (Sakshaug 2004).

12.3 Temporal occurrence in the CAO

If there is sea ice, protist will usually be present in the ice, 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 (Niemi et al. 2011, Leeuwe et al. 2018). Biodiversity may also increase over time as the community develop but is also dependent on type and origin of the ice (Hop et al. 2020, Hegseth and von Quillfeldt 2022). Furthermore, different ice communities reach their maximum at different times, and melt pond algal mats communities are assumed to reach their maximum last and may play an important role as a concentrated food source late in the season (Hancke et al. 2021). The abundance of protists in winter assemblages is often greatly reduced (Niemi et al. 2011) compared to spring and typical bloom situations where there is sufficient light and nutrients, but is also depend on location (Leu et al. 2015). Photosynthesis in sea ice is mainly controlled by environmental factors on a small scale and not type of ice (Leeuwe et al. 2018).

A few cells will be present in the water column all year round, but higher biomasses (e.g. blooms) occur during spring and summer. Dominant polar phytoplankton keep their photosynthetic apparatus functionable 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 is 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 of phenology and the 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 serios pressure of today, is dealt with in chapter 10 of this report. Of the remaining identified pressures, only contaminating compounds, microplastic and non-native 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

The increasing environmental pollution is an anthropogenic stress factor which may affects 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 of the knowledge is obtained from experiments and observed at higher concentrations than those measured in the open ocean (Gioia et al. 2011). Species sensitiveness to the same chemicals may also differ notably (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 or crude oil than those grown when UV is excluded (Echeveste et al. 2011). Thus, synergistic interactions between several impact factors may be important, especially in the light of the ongoing climate change induced effects in the Central Arctic Ocean. In addition, potential effects will depend on season, since biomass, species composition and production of primary producers as well as the distribution and faith 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 the 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 an increased biomass and production in aquatic ecosystems, due to excess discharge of nutrients, causes a chain event that results in 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. 2016). However, altered primary production and food web lipid dynamics, which may influence pathways of for example lipophilic POPs have been suggested, but not tested in Arctic marine ecosystems (Dietz et al. 2018).

12.4.2 Marine litter, including microplastic

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, e.g., 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, interaction between ice algae and microplastic may influence the uptake of microplastic 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 microplastic (Tekman et al. 2020, Bermann et al. 2023) and may affect the 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), since most studies have tested high concentrations of plastic particles, thus not accurately reproducing the current environmental concentrations reported in studies investigating the occurrence of plastic in marine and freshwater systems (Nava and Leoni 2021). Most studies are also from areas/environments or conducted on species not necessarily occurring in the Arctic.

12.4.3 Non-indigenous species

There are several factors which needs 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 Hilden, 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 to be an invasive species (Fernandez et al. 2014). The species has also been observed in Islandic waters and Fernandez et al. (2014) recommend that *M. helysia*, should be paid attention to 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 favorable conditions for harmful dinoflagellate species that may arrive in the region, for example by ships (Goldsmit et al. 2020), and thereby change the species composition of the phytoplankton community in certain areas (in addition to pose a potential threat to species at higher trophic levels). However, non-indigenous species is not considered as a threat to the phytoplankton community of today's Central Arctic Ocean.

13 Sea-ice invertebrates and zooplankton

Hauke Flores, Haakon Hop, Barbara Niehoff, Pauline Snoeijs-Leijonmalm, Martine van den Heuvel-Greve

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, most taxa not exceeding 1 mm in size. The dominant sea-ice meiofauna taxa are ciliates, dinoflagellates, harpacticoid copepods, and rotifers (Figure 13.1 A, 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 *O. 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 *Beroe cucumis* and *Mertensia ovum*, the copepod *Calanus glacialis*, the pelagic amphipod *Themisto libellula*, and the chaetognath *Eukrohnia hamata* (Figure 13.1 C, D; Runge and Ingram 1988, 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, the light-driven vertical migration of pelagic animals 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 the 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 B) and *C. hyperboreus*, however, migrate to several hundred meters 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).

Zooplankton range in size from small, single-celled protists to large siphonophores of several meters length. Typically, they are divided according to their approximate size into the three categories microzooplankton (< 0.01 mm), mesozooplankton (0.02 mm – 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. 2011; 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 under-sampled in the CAO, in spite of their high ecological relevance at the base of the food web (microzooplankton) and for higher predators, including fish, squid and mammals. Among the most abundant microzooplankton taxa are radiolarians (Figure 13.2 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 C, 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).



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).

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



Figure 13.3. Taxonomic composition of sea-ice meiofauna in different regions of the Arctic Ocean. From: Bluhm et al. (2018). Figure under Creative Commons (CC BY) license.

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 abundances of rotifers in the Transpolar Drift domain versus lower relative rotifer and higher nematode abundances 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 13.4. Occurrence of ice amphipods in different regions of the Arctic Ocean. From: CAFF (2017).

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 (multi-year or first-year sea ice; e.g. Hop et al. 2000; Gradinger et al. 2010; Hop et al. 2021a). Hence, community composition is likely to be different between areas in the Greenland/Canadian sector of the CAO that are still covered by multi-year 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 (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.

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 1,000 m, and deep water below, results in vertically distinct communities which are to some extent connected through vertical migration (Kosobokova et al. 1998, 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 Calanus 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 (Figure 13.5). 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).



Figure 13.5. Distribution of vertically integrated mesozooplankton biomass in the CAO, based on historical records. From: Bluhm et al. (2015). (Under copyright by Elsevier. $44 \in$ - Hauke Flores asked Bodil if she has a modified version)

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 (Hop et al. 2019, 2021b; Bluhm et al. 2020). 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 on-going 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 borealisation 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 has 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 13.6; 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.

The inter-annual 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 of 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). However, 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). Other taxa, such as *Calanus* spp., *Themisto* spp., chaetognaths and jellyfish, may only be attracted to the under-ice habitat during the summer months, when blooms of ice algae and phytoplankton nourish the food web under the sea ice (Ehrlich et al. 2020).



Figure 13.6. Seasonal variability in the abundance of key sympagic meiofauna taxa in sea ice. From: Bluhm et al. (2018). Figure under Creative Commons (CC BY) license.

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 13.7). A similar pattern during the winter-spring transition as described from the SHEBA drift study was found in the Eurasian Basin during the N-ICE expedition (Hop et al. 2021b). The inter-annual variability of 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 borealisation of the Arctic zooplankton community which progresses from the peripheral shelf seas into the CAO (Polyakov et al. 2021). Strong borealisation of the zooplankton 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). Also, the distribution and abundance of endemic Arctic zooplankton is 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 Calanus 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, to which extent the zooplankton community has already changed in the CAO is difficult to assess due to a lack of (quasi-) time series data from the CAO.



Figure 13.7. Seasonal changes in the abundance of abundant copepods in the Beaufort Gyre during the SHEBA drift (modified after Ashjian et al. (2003); figure provided by C. Ashijan).

13.4 Vulnerability toward pressures from human activities

Contaminating compounds (pollution)

Exposure to contaminants may lead to uptake and bioaccumulation in zooplankton and sea ice fauna, as was observed from crude oil in the Arctic copepod *Calanus hyperboreus* (Agersted et al. 2018), and organochlorine contaminants in zooplankton from areas surrounding the CAO (Hoekstra et al. 2002). A widespread distribution of mobile contaminants from global sources, such as Hg, PCBs, PBDEs, and PFASs, may result in a chronic, long-term exposure 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 life spans 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 copepod *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 to get 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 food web through bioaccumulation, as has been demonstrated for example 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.

13.4.1 Non-indigenous species

The on-going borealisation of the Arctic Ocean promotes the introduction of Atlantic species, such as *Calanus finmarchicus*, euphausiids and *Themisto abyssorum* and to a lesser extent Pacific species, such as *Metridia pacifica* into the CAO by increasing influx of Atlantic and Pacific waters. The introduction of non-indigenous species (NIS) from human activities acts on top of this large-scale borealisation 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 which are transported into shallow seas bordering the CAO. While these species are unlikely to find habitat in large parts of the CAO due to its great depth, there is a significant potential of 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). In a warming CAO with less sea ice allowing more light to enter the water, the 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 2015), 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, their impact on the zooplankton community will likely be permanent for as long as the conditions prevail which facilitated their arrival in the Arctic Ocean. The effects of NIS on the ecosystem of the CAO, however, are barely understood. Due to the unique environmental conditions in the CAO, our ability to gauge the ecological impact of NIS based on experiences in other ecosystems is limited.

13.4.2 Marine litter, including microplastics

Large-sized marine litter (> 5 mm) is unlikely to affect sea-ice invertebrates and 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 size), however, are in the size range of zooplankton prey and are therefore prone to ingestion (Figure 13.8). Due to its abundance in the ocean and sea ice, MP constitutes a widespread risk to zooplankton and sea-ice fauna which is 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 MP 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. Surfacedwelling 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 sea ice may therefore increase exposure of sympagic fauna and surface-dwelling zooplankton to MP. The MP 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).

In the future, 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.



Figure 13.8. Polymer types within different size ranges found in zooplankton samples (PE: polyethylene; <u>PS:</u> polystyrene; PU: polyurethane; <u>PVDC</u>: polyvinylidene chloride). From: Botterell et al. 2022). Figure under Creative Commons (CC BY) license.

13.4.3 Artificial light pollution

Light levels as weak as the 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 on-going 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 the vertical migration of Arctic zooplankton. Research vessels, tourist vessels and other ships emit light intensities far above these thresholds (Figure 13.9; 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 km²), 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 behavioral responses at the wrong moment in their life cycle, as other marine invertebrates show similar behavioral 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 defenses (Krapp et al. 2009). Several Antarctic taxa of under-ice fauna show a distinct light-dependent diel vertical migration behavior (Flores et al. 2011), suggesting that also taxa in Arctic under-ice fauna may be susceptible to disturbance by artificial light.

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, behavior and predator-prey interactions. Such large-scale effects on marine communities have been observed in various ecosystems at lower latitudes (Marangoni et al. 2022). A major effect is the reduction of sea ice, which will increase light levels in the water column during spring and make zooplankton more susceptible for predation by visual predators (Varpe et al. 2015).



Figure 13.9. Research vessel emitting light during the polar night. From: Berge et al. (2020b). Source picture under Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/).

14 Benthos



Picture: the deep-sea holothurian (sea cucumber) Elpida sp. Picture from MAREANO.HI

14.1 The groups

Benthos from the Arctic deep-sea bed (Ramirez-Llodra et al accepted) (1100 benthic invertebrate species, Figure 14.1, Zhulay et al. 2019, Sirenko 2001, Sirenko et al. 2010, Bluhm et al. 2011) has until now been affected only weakly by anthropogenic activities, but the predicted ice-free summer in the Arctic in the near future may change that situation (Grebmeier and Jørgensen 2022). We differentiate "soft-bottom" fauna that covers the vast abyssal seafloor and parts of other geomorphological features of the CAO (Bluhm et al. 2011, 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 (Zhulay et al. 2019, Ramirez-Llodra et al. 2023).



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) (Open access source: Ramirez-Llodra et al. 2024 Elementa)

14.1.1 Soft-bottom benthos

Soft-bottom benthos are represented in the thin benthic boundary layer by hyperbenthic and abysso-pelagic taxa (Raskoff et al. 2010, Zhulay et al. 2019) with distinct 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, Renaud et al. 2006, Kröncke et al. 2000, Bluhm et al. 2011, 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. 2011) 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 inhabit soft-bottom areas of the CAO including brittle stars, sea cucumbers, sea anemones and other cnidarians, and sponges among others (McDonald et al. 2010, Taylor et al. 2018, Rybakova et al. 2019, 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).



Picture: The deep-sea sea-pen Umbellula sp. Picture from MAREANO.NO

These faunal taxa include a variety of feeding types but as is common in the deep-sea, many are detritivores, and the benthic food web is detritus-based, and relies on the flux of organic matter from the surface (e.g., Degen et al. 2015, Zhulay et al. 2023), though all other common feeding groups are also represented (Zhulay et al. 2021, Oleszczuk et al. 2023). As the CAO is comprised of predominantly fine-grained sediments, namely clay, silt, and sand (Stein et al. 1994). The softbottom benthos occupies a large area of the CAO seabed, and although present in low densities and representing overall low biomass compared to shallow regions, the soft-bottom benthos plays a key role in carbon and nutrient cycling (Klages et al. 2004) and houses partly endemic biodiversity (Bluhm et al. 2011).

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, sponge stalks, etc. is present. Available studies show that hardbottom benthos is dominated by sponges and anemones, but barnacles, crinoids, bryozoans, hydroids, and polychaetes also colonize hard substrates in the deep Arctic Ocean (Zhulay et al. 2019, Schulz et al. 2010, Meyer-Kaiser et al. 2022). Because many hard-bottom benthos are suspension feeders (e.g., sponges, barnacles, bryozoans, crinoids, etc.), they contribute to the functional diversity of the CAO beyond enhancing taxonomic diversity. Due to the patchy nature of hard substrate in the CAO, comprehensive study of the hard-bottom benthos remains limited and a complete understanding of spatial patterns in abundance, biomass, or 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. 2023), 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 hydrothermal vent systems, chemosynthesis can play a large role in providing nutrients to deepsea benthic communities (Sweetman et al., 2013). Submarine 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 1100-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. 2023). It is likely that even more new species of Arctic 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. 2023). 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, 2022), and 2023 have begun to close this gap.

14.2 Spatial coverage in the CAO

<u>Soft-bottom benthos</u> is **Widespread – patchy: > 50%** because soft sediment covers the seafloor of the basins making up the major area of the CAO.

<u>Hard-bottom benthos</u> is **Localized: 5–50%** 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) yet no clear mid-depth peak that is often found around 1000-1500 m in other word oceans (Bluhm et al., 2011, 2020). The lower slope and basin benthic community structure is distinct from the upper slopes based on taxonomic identity (Vedenin et al. 2019, 2022, Bluhm et al. 2020). 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).

In soft-bottom benthos, faunal abundance and biomass decrease significantly with increasing depth as in the global ocean, with abundances in the CAO at the lower end of those in the global deep sea (Wei et al. 2010, Bluhm et al. 2011). 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), Benthic communities of the deep Arctic Ocean reflect a distinct food web typical of oligotrophic systems, namely one where deposit feeders represent a high trophic level when assessed via stable isotope trophic markers because available food is highly reworked material (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. For example, meiobenthic biomass in the soft sediment areas of the Lomonosov ridge was found to be enhanced relative to the nearby deep Makarov basin (Schewe, 2001). Suspension feeding macrofauna increased both in abundance and species richness towards the Lomonosov Ridge, likely from increased organic matter transport in currents affected by the ridge topography (Kröncke, 1994). 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 much higher in very localized areas (e.g. at the Aurora vent site on the Gakkel Ridge, Ramirez-Llodra et al. 2023).

Spatial coverage in the CAO

	Spatial coverage in the CAO				
Group	Site: Local: Widespread Widespread				
	> 0–5%	5–50%	– patchy:	– even:	
			> 50%	> 50%	
Softbottom benthos				Х	
Hardbottom benthos		Х			

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 timescales based on lifespans, but time series data from single locations are sparse to evaluate 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 occur commonpersistent timescales.

	Temporal occurrence in the CAO					
Group	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		
Softbottom benthos				Х		
Hardbottom benthos				Х		

14.4 Vulnerability toward pressures from human activities

14.4.1 Contaminants

Temporal trends and thresholds of pollutants effects 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 2018 and references therein). Some of these pollutants can have extremely long half-lives; for example, most polychlorinated biphenyls (PCBs) 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 Greenland 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 (e.g. 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 from the Barents Sea marginal ice zone than in sympagic and pelagic invertebrates. As is the case with mercury, 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 vessels and sea ice), and the potential for such spills could increase as shipping traffic increases in intensity or shipping corridors shift (Berkman et al. 2022). 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 CAO unless far-field transport were to occur. Substantial acute, chronic and interactive effects of oil compounds on benthic biota have been documented from other cold-water areas such as the Gulf of Alaska (Petersen et al. 2003).

Mercury enters the CAO via atmospheric deposition, from 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/hunting activities. Again, our 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 mercury 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 mercury concentrations decreasing from west to east (Riget et al. 2011). On the Atlantic Arctic side, Hg concentrations in surface sediments are in fact higher in the Nansen and Amundsen basins (to 116 ng/g) than on the Barents Sea shelf, attributed to transport of fine-grained sediment into the basin (Kohler et al. 2022). For mercury in biota, however, no clear trend has been observed, but data from Canada and Greenland have shown increasing trends compared to the Atlantic Arctic (Riget et al. 2011). In both referenced publications, the authors stress that only solid time series providing several decades of coverage could show statistically significant trends. The anthropogenic contribution of mercury within Arctic organisms has increased over the past 150 years (Dietz et al. 2013). Although the biological transfer of mercury is most likely to occur in surface waters, most Arctic Ocean mercury 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 mercury in benthic fauna of the shallow Chukchi Sea has been documented (Fox et al. 2014), but it differed among benthic invertebrate feeding types and the the overall biomagnification power was lower than elsewhere. Without deep-diving and benthic-foraging mammals in the CAO, trophic transfer of mercury from benthos is likely minimal. Bidleman et al. (2013) determined concentrations of several contaminants (total mercury (TotalHg), methyl mercury (MeHg), PCBs, PBDEs and organochlorine pesticides) in archived samples of the large scavenging amphipod *Eurythenes gryllus*. Concentrations consisted of 55-1023 ng/g ww Total Hg and 1.85-49.6 ng/g ww of MeHg (1.7-20.1% (median 3.7% of the TotalHg).

14.4.2 Non-indigenous species

The introduction of marine invasive species (MIS) is one of the most important ecological threats to global biodiversity (Bax et al. 2003); however, knowledge about the potential spread and impact of invasive species in the CAO is limited. The most common vectors for introduction of MIS globally are via ship ballast water and biofouling. To date, 34 non-indigenous species in the Arctic have been introduced via ships (Chan et al. 2019). Global shipping traffic is expected to increase by >200 % by 2050 (Sardain et al. 2019) and Northern Sea Route traffic has been increasing by nearly 20 % per year since the mid-2000s (Miller and Ruiz, 2014). Future shipping routes in the Arctic are likely to take advantage of reduced sea ice thickness and extent by crossing more of the CAO in less time than present routes (Stevenson et al. 2019). Thus, the potential for MIS introductions in the Arctic is increasing. While the risk of invasion into shallow, coastal Arctic ecosystems remains high there are several factors that limit the introduction and establishment of benthic MIS in the CAO.

Reduced sea-ice within the CAO will reduce ice-scour on ships that usually removes hullfouling organisms along sailing routes as seen in the Antarctic where hull-fouling organisms survived during transit along ice-free routes (Hughes and Ashton, 2017; Lee and Chown, 2009; Lewis et al. 2004). 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. Also ballast water exchange is limited to the deepest portions of the CAO where establishment of benthic taxa released thousands of meters above the seafloor is unlikely. For example, transoceanic vessels entering Canadian ports are required to exchange ballast water at depths greater than 2000 m and at more than 200 nautical miles from the Canadian coast when possible (Holbech and Pedersen, 2019). 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 2016; Holbech and Pedersen, 2019). However, future shipping routes across the CAO are likely to take less time than at present due to 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 population levels around the Arctic Ocean, this area is not less polluted from plastics than areas further south (Collard and Ask 2021). Microplastics are widespread

at the gate way to the CAO in Fram Straight at HAUSGARTEN (42–6595 microplastics kg⁻¹ sediment) with highest quantities at the northernmost stations (Bergmann et al. 2017). Microplastics have also been identified from sediments far inside the CAO, reaching up to 200 pieces kg⁻¹ sediment (Kanhai et al. 2019). The only available time series in the HAUSGARTEN observatory in the Fram Strait (2500 m depth) suggests that litter densities have increased over time from <4000 between 2002-2011 (Bergman et al. 2012) to >7500 items km² by 2014 (Tekman et al. 2017). These plastics constituted about half of the litter, followed by black fabric (11%) and cardboard/paper (7%) (Bergmann et al. 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 surficial sediments of the deep CAO suggests processes that facilitate the vertical transport of fragments and the alteration of otherwise low-density materials (Kanhai et al. 2019). Microplastic abundance in sediments from the Chukchi Sea was positively correlated with the reduction of Arctic sea-ice, suggesting that the melting sea ice contributes to the increase in microplastic levels in the sediment (Fang, 2021). Berkman et al. (2017) postulate that a positive correlation between microplastic abundance and algal biomass suggests vertical export via incorporation onto sinking sympagic algal aggregates. These authors point out that microplastic quantities are among the highest recorded from any benthic sediments, confirming earlier findings of the deep sea serving as a major sink for microplastics, and further discuss that the presence of accumulation areas in Fram Strait, suggests that the area may be fed by plastics transported via North Atlantic thermohaline circulation. Yet links between increased Arctic shipping traffic (as opposed to outside sources) and plastic/ litter have also been shown (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 in HAUSGARTEN were entangled in or colonized by invertebrates such as sponges and sea anemones (Parga Martinez et al. 2020), documents an interaction between the living organisms and litter components.

14.4.4 Artificial noise pollution

Not considered relevant for benthos in the CAO but possible future seabed mining may induce underwater noise associated with seismic exploration activities that may in turn influence the condition of benthic species (Oak et al., 2020).

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. Canadian Science Advisory Secretariat (CSAS).

14.4.5 Selective extraction of species

Not considered relevant for benthos in the CAO, since scientific collections are currently done in minute areas of the seafloor (typically <1 m² per sample). Sampling covering
hundreds of square meters 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., $< 1m^2$ or individual organisms) or non-destructively observe the seabed over 100s of meters. Great water depth and sea-ice cover prevent widespread sampling across the CAO (see Figure 1.1), thus, the total seabed footprint of biological scientific research activities is likely small relative to the area of the CAO.

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 which can increase the suspended matter concentrations in the sea as a consequence of the extraction process (Oak et al., 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 locally destroy habitat by breaking up or covering organisms present within or on top of the sediment, similar to installations the oil and gas industry (Cordes et al. 2016). Generally, seabed disturbance from mining activities is expected to reduce species abundances and species richness within tracks made by mining vehicles (reviewed in Jones et al. 2017) while sediment plumes may carry fine-grained sediments several hundred meters 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- 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 et al., 2020). 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 (Stratmann et al. 2018, Simon-Lledo et al. 2019) 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 with 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

15.1 The groups

15.1.1 Sympagic fishes

Sympagic fishes are associated with sea ice for at least part of their lifetime. They use the sea ice as a shelter from predators (e.g., seals) and as a source of ice-associated prey (e.g., 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 ice-associated (Bouchard and Fortier 2011). A summary of the role of sympagic fish in the CAO was provided by Flores & Volckaert (2020). Based on the paucity of quantitative information on sympagic 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 ca. 200-500 m of depth 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 3170 km long DSL with zooplankton and small fishes in the Atlantic water layer at 100-500 m of depth 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 (*G. 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 fish community associated with the seafloor habitat in the CAO is more species-rich than in sympagic and pelagic habitats as far as we know today. These include non-commercial species such as eelpouts (Zoarcidae), sculpins (Cottidae), and snailfishes (Liparidae). However, a single record exists of a juvenile Greenland halibut (*Reinhardtius hippoglossoides*) also existing inthe CAO, but only 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 reported for the Arctic region, distribution maps and records (Mecklenburg 2018) for 19 overlap with Central Arctic Ocean 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, 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 CAO, but data are scattered in space and time, and there is almost no quantitative information (Melnikov & Chernova 2013). The first large-scale under-ice sampling indicated that the Transpolar Drift transports young polar cod from hatching areas on the Siberian shelf across the CAO (David et al. 2016).

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. Probably they are widespread but the number of individuals is low because of the low productivity of the CAO ecosystem.

	Spatial coverage in the CAO							
Group	Site: > 0–5%	Local: 5–50%	Widespread - patchy: > 50%	Widespread – even: > 50%				
Sympagic fish			х					
Mesopelagic fish			х					
Benthic and benthopelagic fish			х					

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. Melnikov & Chernova 2013, and references from Russian drift stations in Flores and Volckaert 2022). The DSL also occurs year-round as observed during the MOSAiC expedition. Diel vertical migration (DVM) of this central Arctic DSL was lacking 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 one 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).

		Temporal occuri	rence in the CAC)
Group	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
Sympagic fish				х
Mesopelagic fish				х
Benthic and benthopelagic fish				x

15.4 Vulnerability toward pressures from human activities

15.4.1 Contaminating compounds (pollution)

Acute chemical pollution, even at a sub-lethal 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 fishes unfit as food for humans (Vieweg et al. 2021). An oil spill following a shipwreck or a blow-out from an oil rig would affect the behavior of adult fishes (scaring them away) and could negatively affect their reproductive development and survival of eggs and larvae (Bender et al. 2021).

15.4.2 Non-indigenous species

Non-indigenous species could act as novel competitors and predators of native species, which would have negative impacts on 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 non-indigenous species may not represent equally valuable prey resources as native forage (e.g. capellin vs. polar cod).

15.4.3 Marine litter, incl. microplastics

Microplastics may be eaten by fish (Kühn et al. 2018) and possibly affect their ability to grow and survive. Microplastics and larger plastics, which are likely wide-spread in the CAO (Huserbråten et al. 2022, Tekman et al. 2022), can directly affect the buoyancy of animals and result in gut fullness and reduced food intake, as well as having longer term physiological impacts (add reference).

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 by human activities to surface waters will have little direct impact on any fishes other than sympagic species, who may be able to directly consume deposited material. Pelagic, bentho-pelagic and benthic fishes would be affected only indirectly through changes in overall ecosystem productivity starting with algae, microbes and zooplankton that are directly 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, the European Union, Iceland, Japan, Norway, Russia, South Korea, the United States of America and came into 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 survey and exploratory fishing are both allowed under agreement as long as activities adhere to conservation and management measures that are to be established by the Parties by June 2024.

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 wide spread effects on populations.

The use of trawls or equipment on the seafloor 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). Bottom trawling would only be relevant along the shelves surrounding the CAO (Jørgensen et al. 2020).

15.4.9 Artificial light pollution

A changed light regime may change the behavior of fish living in the euphotic zone, the feeding conditions for visual feeders, and also 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 behavior of fish species more permanently (either by attracting them or repelling them) (Berge et al. 2020 reference).

15.4.10 Unintended injury and mortalities

Unintended injuries from human activities other than fishing and seabed disturbances would 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 sea floor.

16 Seabirds

Extra references NB: that may already be in the ref list:

Day, R. H., J. R. Rose, A. K. Prichard, and B. Streever. 2015. Effects of gas flaring on the behavior of night-migrating birds at an artificial oil-production island, Arctic Alaska. *Arctic* 68:367-379. <u>https://doi.org/10.14430/arctic4507</u>

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.

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.

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. <u>https://doi.org/10.1007/s00300-016-1933-y</u>

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

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*(1), pp.168-172.

16.1 The groups

More than 30 species of marine birds have been recorded in the CAO basin and slopes, but only eight of these occur regularly in the CAO. 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 CAO. The following seabird groups have been defined for this report:

16.1.1 Transient seabirds

The transient seabird species have been recorded in the CAO, but do not occur on a regular basis and the CAO is not important for their populations. There are currently about 22 species in this category, comprised of Alcids (9 spp), gulls (5 spp), skuas/jaegers (4 spp), and shearwater (1 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 grylle* are regularly observed in the CAO, but in very low densities, and the CAO appears to have low importance for their populations.

16.1.3 Ice obligate seabirds: Ivory gull, Ross's gull

Two seabird species are ice obligates: The 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.



Picture: An ivory gull, an ice obligate seabird species, scavenging on polar bear leftovers on the sea ice. Picture used with permission from <u>Otto.plantema@planet.nl</u>.

16.2 Spatial coverage in the CAO

Seabird numbers are extremely low in the CAO basin and slopes, and likely include primarily nonbreeding birds migrating over circumpolar regions. Breeding colonies on coastal islands or the mainland are in most areas too distant for foraging trips to the CAO (Figure 16.1, 16.2). However, in the Wandel Sea corner of the CAO, 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 document foraging areas in ice habitats north of Svalbard and Franz Joseph land up to 85 N. (Strøm et al 2019, Gilg et al 2016 a)

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	Nonbreeding and postbreeding habitat, migration
Ross's gull	Rhodostethia rosea	Common	All	Nonbreeding and postbreeding 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
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 Iannonicus	Occasional transit vagrant	Pacific	Negligible



Figure 16.1. Left: Ivory gull distribution during the annual cycle, showing breeding areas, postbreeding foraging areas, migration patterns, and wintering areas in the marginal ice zone in the Atlantic and Pacific sectors. (Reprinted with permission from Gavrilo et al. 2022 (report 1). Right: Foraging trips into the CAO (Wandel Sea) by ivory gulls breeding in Northeast Greenland (Dumas et al. 2022, Reprinted with permission from Frederiksen et al. 2019).



Figure 16.2. Left: Ross's gull general distribution (Reprinted with permission from Gavrilo et al. 2022 (report 1). Right: post-breeding movements of two Ross's Gulls monitored between 24 June and 03 November 2013 (Reprinted with permission from Gilg et al. 2016 b); 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.

		Spatial coverage in the CAO						
Group	Site: > 0–5%	Local: 5–50%	Widesprea d – patchy: > 50%	Widespread – even: > 50%				
Transients seabirds			Х					
Seasonal seabird residents		Х						
Ice obligate seabirds: Ivory gull, Ross's gull		х						

16.2.1 Longevity and resilience of seabirds

All seabirds are long-lived with a life expectancy above 10y, meaning that recovery from a mass mortality like a large oil spill will 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. Report 1), although ivory gulls forage in the CAO during summer as well.

	Temporal occurrence in the CAO								
Group	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					
Transients seabirds		Х							
Seasonal seabird residents		Х							
Ice obligate seabirds: Ivory gull, Ross's gull			Х						

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 CAO. 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 of ship traffic in the CAO will undoubtedly lead to an increase in marine pollutants, in addition to the long-distance transported contaminants, such as persistent organic pollutants (POPs), or mercury (see below), 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 (PCBs, mercury, etc.).

Mercury

AMAP has monitored and reviewed the knowledge on mercury in the Arctic and this section is mainly based on the new AMAP Mercury assessment (AMAP 2021; Albert et al. 2021; Chastel et al 2022) and the AMAP assessment of Biological Effects of Contaminants (AMAP 2018, Dietz et al. 2019). Mercury 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). Mercury is also (to a lesser extent) atmospheric, sea-current, and riverine long-range transport, but mercury is also (to a lesser extent) mobilized within the Arctic from melting glacier ice and permafrost (AMAP Assessment 2021). Methylmercury biomagnifies to high levels in Arctic marine food webs, due to long food chains and long-lived species. However, feather molt represents a major excretion pathway in birds during which 60-90% of accumulated Hg is excreted yearly, thus lowering the body burden. In the AMAP Assessment (Chastel et al. 2022) it is concluded that seabird Hg concentrations are above toxicity benchmarks in several Arctic seabird populations, based on the following threshold levels for estimated risk to total mercury (Ackerman et al. 2016):

		No risk	Lowrisk	Moderate risk	High risk	Sewre risk
Species	Matrix	NRC	LRC	MRC	HRC	SRC
Marine bird	Egg (µg/g WW)	<0.11	0.11-0.47	0.47-1.30	1.30-1.70	≥1.70
	Liver (µg/g WW)	<1.40	1.40-7.30	7.30-22.7	22.7-30.5	≥30.5
	Blood equivalent (µg/g WW)	<0.20	0.20-1.00	1.00-3.00	3.00-4.00	≥4.00
	Body feather (µg/g DW)	<1.58	1.58-7.92	7.92-23.75	23.79-31.67	≥31.67

Based on these toxicity benchmarks, the AMAP Assessment (2021) 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 μ g/g ww), and that 1% of the analyzed birds were either at high or severe risk (See AMAP Assessment 2021). However, most (95%) Arctic birds were generally at lower risk (i.e., were in one of the three lowest risk categories) of toxicity from Hg exposure (see Figure 16.3)

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



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).

Because the feather concentrations of mercury reflect the mercury concentration in the 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 mercury concentrations during the breeding season in the Arctic than during the winter season when they migrate farther south (Figure 16.1, 16.2). Thus, mercury 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 (2021) 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 number of monitored populations. A close monitoring and further studies into combined effects of pollutants and climate change is needed.

Persistent Organic Pollutants (POPs)

The effect of persistent organic pollutants on seabirds have recently been assessed and reviewed by AMAP (AMAP 2016, 2017 and 2018, Dietz et al. 2019). AMAP calculated Risk Quotients (RQ = BR/CBR = Body Residue/Critical Body Residue) for a number of species in the Arctic region where sufficient published data were available. Because PCB concentrations are the dominant effect contributor among POPs, AMAP used a conservative PCB critical body residue (CBR) of 10 μ g/g lw for the RQ calculations. For the majority of 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 the immune or hormone system. 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) did a meta-analysis of more than 1000 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 to 30 years, likely as a result 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 mercury, more complete knowledge will require monitoring and studies into combined effects of pollutant mixtures and climate change.

Oil spills

The Arctic basin acts in some ways as a closed system, with currents that transport water in or out 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 at a distance of many hundreds of miles, which makes it virtually impossible for adequate response in the case of an oil spill in the central Arctic.

A potential serious effect on seabirds would be an accidental spill of oil from a ship inside the CAO or oil drifting into the CAO. If the oil is not a light evaporating oil, the oil 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*). 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 an oil spill would most likely be low in the CAO 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 revealed global and increasing distribution of plastic, both macro- and micro-plastics, including most remote areas of the Arctic Ocean (Walther and Bergmann, 2022). Marine litter, including macro- and microplastics is currently coming almost exclusively from outside the CAO and from a variety of sources. The primary maritime activities around the CAO are fishing and shipping, including cruise tourism (which also occurs in the CAO 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 as 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, pathways and the precise distribution of marine litter originating from each source (PAME, Regional Action Plan on Marine Litter in the Arctic, May 2021).

Globally, the majority of 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 plastic pollution, both macro- and micro-plastics, 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 our understanding 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, Franeker et al. 2021).

The northern fulmar is the most studied seabird species for plastic ingestion. It is a suitable biomonitor of plastic pollution due to 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 EcoQ 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) analyzed 145 preen gland oil samples from 32 seabird species belonging to 8 families, with different foraging habits and life history strategies from around the world, for plastic additives and legacy persistent organic pollutants. This study found patterns that can be explained if the additives in gland oil are mainly from ingested plastics rather than diet, and demonstrated 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 studied are needed on this issue.

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 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).



Figure 16.4. Plastic ingested by Northen Fulmar in the Arctic. Permission to use this figure grated by PAME and GridArendal.

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 murret *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.

Potential hazardous underwater noise may be associated with seismic exploration in the CAO which could affect physiology and cause physical injury, behavioral 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 CAO, 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, such as by removal of prey, or indirectly via bycatch 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, 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 *Boreogadus saida*, 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 should be low on breeding populations, as seabirds do not forage in the CAO while raising young. However, non-breeding or post-breeding birds that cross the CAO for migration and wintering risk conflicts, including disruption of foraging (e.g., Krüger et al. 2017) and bycatch or vessel strikes during fishing operations.

As the seabed in the CAO 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 night-time artificial light (Marangoni et al. 2022). Many species use natural light cues (sun, moon, stars, 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 increase local impacts to marine taxa.

Artificial lights attract and cause injury and death to marine birds, which are disoriented by lights and then fly into coastal buildings, vessels (including those anchored), and offshore platforms (Day et al. 2015), with numbers ranging from individual birds to hundreds in one incident. Secondary mortality occurs when birds have trouble taking off from the vessel and hide in deck spaces where they are exposed to oil contaminants, which soils feathers and thereby cause 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 (Day et al. 2015, Gjerdrum et al. 2021; Merkel and Johansen 2011; Rodriguez et al. 2022, Ryan et al. 2021). 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 due to loss of 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 avoiding 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 highrisk locations or time periods.

16.4.6 Cumulative effects

Recent studies on globally threatened ivory gull, one of the species which regularly uses the CAO, is also 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 e al. 2015). It is of major concern that the effects of contaminants may become more severe when the 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 eggs, blood, and feathers of the ivory gull are among the highest ever reported in arctic seabirds and may have sub-lethal effects in combination with other stressors, such as climate warming (Strøm et al. 2019).

17 Marine Mammals

17.1 The groups.

Based on their partial dependence on the CAO as a habitat, WGICA has selected polar bears, ringed seals, beluga whales, narwhals and bowhead whales as focal species for 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 2021, Skjoldal 2022). Since walruses are primarily benthic feeders, it was, however, concluded that their use of the CAO will likely always be limited to a small number of straggling animals relying on an atypical foraging pattern centered on seal predation. In the absence of further details, walruses are therefore not included among the WGICA 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).

17.2 Spatiotemporal coverage in the CAO

17.2.1 Polar bear

Of 19 recognized polar bear populations (Figure 17.1), 8-11 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 the 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 life style currently appears to be energetically superior to a 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 fr 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 by the Polar Bear specialist Group (2023).



Picture. Polar bear on the icecap. Picture: Lis Lindal Jørgensen. Institute of Marine Research, Norway

17.2.2 Ringed seals

Throughout their circumpolar range (Figure 17.2), ringed seals have an affinity for icecovered waters all year round. This species feeds mainly on pelagic and ice associated fish and crustaceans like krill and amphipods (Bengtsson et al. 2020, Crawford e al. 2014). There are several anecdotal reports of widespread occurrence of ringed seals within the Arctic Basin, but so far 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 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 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 postbreeding 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, due to lower environmental productivity (Bengtsson et al. 2005).

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. 2015), 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 life-time reproductive output (Hamilton et al. 2015). 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.



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

17.2.3 Bowhead whales

Bowhead whales are large baleen whales feeding mainly on copepods and other crustaceans, both pelagically and along the sea floor (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 animals cross into the WGICA area during both summer and winter (Vacquie-Garcia et al. 2017, Kovacs et al. 2020). This population likely numbered around 50000 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 et al. 2018). In contrast, the Bering-Chukchi-Beaufort Sea bowhead whale population numbers around 17000 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).

It has been hypothesized that the particularly strong affinity to ice observed for the Spitzbergen bowhead population is partly due to a behavioural selection pressure exerted by the historical hunt, 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 waters 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 et al. 2020). 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.



Figure 17.3. Current and historical ranges of bowhead whale stocks. Pink—current range; Dark pink—areas of high summer density; Dotted—historical distribution. Source: Map by John Citta in George and Thewissen (2021).

17.2.4 Narwhals

Narwhals are deep-diving toothed whales feeding 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. 2019). The largest global population of Narwhals (numbering ~140000) is found in the Baffin Bay area (Doniol-Vacroze et al. 2013, but see also NAMMCO 2023), which is still practically isolated from the Central Arctic Ocean 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. 2020). Surveys have also identified a summer occurrence of at least 800 narwhals within the Nansen basin area (Vacquie-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 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, both 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.



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. (Hobbs et al. 2019, with permission from NAMMCO)

17.2.5 Belugas

The Pacific gateway region is the summering habitat for the Chukchi Sea and Beaufort Sea beluga populations (Figure 17.5) numbering a total of around 50000 beluga whales (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. 2015, Hauser et al. 2018, Muto et

al. 2021). Calving and moulting seems to occur in coastal habitats although juveniles may also be observed offshore (Clarke et al. 2023, Frost et al. 1993, Mayette et al. 2023).

Telemetry based analyses of habitat use of Chukchi and Beaufort Sea belugas suggested a certain overlap with the WGICA study area CAO during July-October (Hauser et al. 2014). Later extensions of this and other data series 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, we find it reasonable to assume that belugas may be present in the WGICA area up to eight months of the year, satisfying the classification as "common".

The Atlantic gateway region is home to the small Svalbard population of belugas estimated at about 549 (95% CI: 436–723) whales (Vacquie-Gracia et al. 2020) and further Eastto 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 (Vacquie-Garcia et al. 2018). Reports from the Russian Arctic are also mainly from nearshore areas (e.g. Belikov and Boltunov 2002, Shpak et al. 2023), but some observations have also been made far into the CAO during the period from June to October (Belikov and Boltunov 2002).

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 three different populations: The Svalbard population, the Kara Sea-Laptev Sea population and the Beaufort Sea population (NAMMCO 2023). The latter finding in particular, emphasizes the potential importance of the Arctic ocean as a habitat and migration corridor for belugas. Beluga 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 anti-predation strategy towards killer whales (Karlsen et al. 2002). Their white skin color 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 (Vacquie-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).



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), and 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. (Hobbs et al 2021 Global Review of the Conservation Status of Monodontid Stocks. Marine Fisheries Review doi: <u>https://doi.org/10.7755/MFR.81.3–4.1</u>, with permission from NAMMCO)

	Spatial coverage in the CAO								
Group	Site: > 0–5%	Local: 5–50%	Widespread – even:						
			> 50%	> 50%					
Polar bear			х	х					
Ringed seal			х	х					
Bowhead		х							
Narwhals		х							
Beluga	x								

Table 17.1. Focal marine mammal spatial coverage in the CAO

	Temporal occurrence in the CAO								
Group	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					
Polar bear				х					
Ringed seal				х					
Bowhead			х						
Narwhals			х						
Beluga			х						

Table 17.2. Focal marine mammal temporal occurrence in the CAO

17.3 Vulnerability toward pressures from human activities

17.3.1 Contaminants

Of the five focal marine mammal species, narwhals, belugas and polar bears are inherently most vulnerable to anthropogenic contaminants due to their high trophic levels. Odontocetes furthermore have low ability to metabolise 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 mentioned three high trophic level arctic marine mammal species (summarized in Dietz et al. 2019). Despite bans and stricter regulations of use, legacy chemicals like PCBs and mercury 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 arctic marine mammals as seen for East Greenland polar bears (McKinney et al. 2013). In the Svalbard subpopulation, polar bears summering in the CAO are found to have higher levels of some PFAS compounds ("forever chemicals") than resident bears and levels also appear to increase towards the Northeast, where little monitoring occurs (Tarttu 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. 2019). Climate change

induced changes in habitats and diets are also thought to affect contaminant levels in Beaufort Sea belugas (Smythe et al. 2018). Although contaminant 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). Earlier studies by Wolkers et al. (2006) have found that narwhals in the Svalbard area have higher levels of PCB and other OHCs than belugas (Wolkers et al. 2006), but lower levels than Northwest Atlantic narwhals (Dietz et al. 2019, Wolkers et al. 2006, Pedersen et al. 2024). This is consistent with larger reliance on lower trophic level prey in East Atlantic narwhals found by Watts et al. (2013). In contrast to narwhals from Western 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 Eastern Greenland (Garde et al. 2021). 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 mammal populations occurring in the CAO can be attributed directly to 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 presence in the CAO does not necessarily imply exposure if the main feeding activity occurs in other places. This is at present uncertain for the Nansen Basin narwhals. 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 are long range atmospheric deposits, both directly and indirectly via release of accumulated deposits from melting multi-year ice (AMAP 2021a). Ongoing human activity such as ship and submarine traffic may furthermore cause local exposure to acidic water from scrubbers (Hermansen 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 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. 2015, 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 (Werth et al. 2019, but see also Rubjerg et al. 2021). This may on the other hand enhance the ingestion of harmful oil residues. Polar bears are particularly vulnerable to oil fouling because it may reduce the

isolating capacity of their fur. Attempts to clean it may lead to ingestion of dangerous amounts of oil. No dose response levels exist for oil ingestion in any marine mammal species although early experiments do suggest tolerance to low levels of intake (Helm et al. 2015).

17.3.2 Non-indigenous species

The clearest example of introduced harmful non-indigeneous species to Arctic waters is the occurrence of the tropical parasite Toxoplasma gondii in arctic marine mammals (Reiling and Dixon 2019) and barnacle geese (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).

Among marine mammal populations occurring 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 (Dubey et al. 2020, Conrad et al. 2005). Latent infections with T. gondii have also been correlated with reduced immunological status (Kirk et al. 2010) and behavioural changes (Contopoulos-Ioannidis et al. 2022, Johnson and Koshy 2020), 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 Toxoplasma 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 (Burgess et al. 2018, Conrad et al. 2005). Oocysts may furthermore be accumulated in cold-blooded filterfeeders 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 (Jensen et al. 2010, Prestrud et al. 2007, 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 payed 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 T. gondii, as also suggested by Jensen et al. (2010). The ecological significance would, however, depend on the volumes, origins and treatment procedures of this water.

17.3.3 Marine litter, incl. microplastics

Large 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. Gall and Thompson 2015; Unger et al. 2017; Baulch and Perry 2014; IWC 2019). Marine mammal interactions with macroplastic is known to have caused mortality due to entanglement and subsequent asphyxiation, physical injuries and/or starvation. These phenomena have so far rarely been reported from the high Arctic (Zantis et al. 2021; Lusher et al. 2022) but could increase with increasing fishing effort and cargo traffic closer to the CAO. Recent investigations of gastrointestinal tracts of harp and hooded seals in the Greenland Sea have, however, revealed one case of macroplastic ingestion (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 due to inexperience and curiosity (Unger et al. 2017).

Larger data sets 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 the Arctic marine mammal species, harmful interactions with macroplastic and debris are so far 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 (Lohman 2017; Lee et al. 2023). In whales, microplastic fragments have been found to translocate from the gastrointestinal tracts to the lung, blubber, melon and acoustic fat pad (Merill et al. 2023) increasing the scope for potential effects. Microplastic 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 (Bourdage et al. 2020, Jardine et al. 2023a and 2023b). Low levels of microplastic have also been found in polar bears in the Canadian Arctic (Iyare et al. 2024) and in the Fram Strait area (Routti 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 beluga 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 potential clogging of the bowhead baleens by both microplastic and marine debris (Werth et al. 2024).

17.3.4 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, 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 longrange vessel avoidance (Martin et al. 2022). Increased swim speeds were observed up to 79 km from vessels and likely lateral avoidance behaviour were observed at 12.6- ~43.6 km distance (Martin et al. 2022). For satellite tagged narwhals in East Greenland Tervo et al. (2022) 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 behaviors 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 (Koski et al.2009, Wartzok et al. 1989). More recent studies specifically on vessel noise in the Beaufort and Chukchi Sea have shown very little bowhead avoidance behaviour to vessels well within their detection range (Martin et al. 2023). Not much systematic data is 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 from passing vessels. This puts bowhead whales at significant risk for ship strikes and post-mortems of subsistence killed whales 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 (Blackwell et al. 2015, McDonald

et al. 2012) and force the whales to increase sound levels or give up communicating. Modelling the aggregated exposure and responses of bowhead whales Balaena mysticetus 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 masking of biologically relevant sounds, including sounds made by a prey species like arctic 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 have been found to increase in response to vessel detection, particularly for 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 hear 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 in 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 impcacts 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 aircrafts, but some marine mammal responses have been reported (e.g. Smith et al. 2016).

17.3.5 Selective extraction of species

All five focal Arctic marine mammals addressed in this report have been subject to significant hunting in the near-shore areas of the Arctic, but not within the borders of the WGICA area. Several marine mammal populations occurring in the CAO are subject to subsistence hunting at lower latitudes. This is known to be true for 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 apart from some few individuals which apparently have come from the Beaufort Sea either via the CAO, Arctic Ocean shelf waters or inner waters of the Canadian Arctic archipelago.

17.3.6 Artificial light pollution

Artificial light may interfere with the synthesis of melatonin among a wide specter of vertebrates with potential consequences for circadian rhythms and overall fitness (Cowart et al. 2014, Grubisic et al. 2019). However, no specific studies on marine mammals appear to be available (Stanton and Cowart 2024).

17.3.7 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, for whales, also on the feasibility of breaking up ice (George et al.1989). Both narwhals, belugas and bowhead whales have demonstrated impressing abilities to detect approaching dangers (Breed et al. 2020, Martin et al. 2023, Matthews et al. 2020), 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, which may enable effective escapes, 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 up to 15 km from a ship (Richardsson and Malme 1993), but at other times do not seem to respond (Martin et al. 2023). Not much systematic data is 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 from passing vessels. This puts bowhead whales at significant risk for ship strikes and post-mortems of subsistence killed whales in Alaska in fact suggest a significant increase in signs of ship strikes (Stimmelmayr et al. 2021). Due to their rather slow movements they may be particularly at risk for collisions with fast-going 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 Artic 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 (Helal et al. 2024; Aniceto et al. 2020) including monitoring of marine mammals (Aniceto et al. 2020).

17.3.8 Human presence

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 behavior, but likely has little effect on nearby whales.

Loss of habitat

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 (Table)

Group/species	Contaminants	Non-indigenous species	Litter, incl. micro plastics	Artificial noise pollution	Nutrient and organic enrichment	Extraction of species	Extraction of non-living resources	Physical Seabed Disturbance	Artificial light pollution	Unintended injury and mortality	Human presence	Climate change
Ice prokaryotes and viruses	1	2	2	1	1	1	1	1	2	1	2	1
Water column prokaryotes and viruses	1	2	2	1	1	1	1	1	2	1	2	1
Seafloor prokaryotes and			2			4	4			4		
viruses	1	2	2	1	1	1	1	1	2	1	2	1
Ice algae	5 ¹	-6	5 ²		33				54			13
Phytoplankton	5⁺	4°	5 ²		33				5 ⁴			4°
Ice invertebrates	4	3	info	1		3	4	4	NO info	2	2	1
Zooplankton	3	1	4	1		3	3	3	1	2	2	1
Pelagic squid	no info	No info	4	2		2	4	4	2	3	no info	3
Softbottom invertebrate species	4 ⁷	no info	4 ⁷			3	3	4 ⁷				no info
Hardbottom invertebrate species	4 ⁷	no info	4 ⁷			3	3	4 ⁷				no info
Sympagic fish	2	2	2	2	4	3	4	4	2	1	3	1
Mesopelagic fish	2	3	2	2	4	2	3	3	2	1	3	2
Demersal & bentho-pelagic fish	2	3	2	2	4	2	3	3	3	1	3	2
Polar Bear	2		2	2				2 ⁸			2 ⁹	1
Ringed seal	2		4	3				2 ⁸		3	2	1
Bowhead	2		1 ¹⁰	1				2 ⁸		3		2
Narwhals/Beluga	2		3	1				2 ⁸		3		1
Transients birds	3	3	3	4	2	3	4	4	2	3	4	3
Seasonal Residents birds	3	3	3	3	2	3	4	4	2	3	4	2
Ice obligates: Ivory gull, Ross's gull	3	4	2	3	2	3	4	4	3	3	3	1

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 have an effect (positive or negative), especially since this is only an issue when in it is dark, i.e. when there is 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 i 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.

Colours vulnerability (Degree of vulnerability):

Very vulnerable

Moderately vulnerable

Low vulnerablity

Not vulnerable

No information

Not relevant for the ecosystem component

Potential positive effect

|--|

1. Very high

2. High

3. Medium

4. Low

5. Very low.

Keep in mind while scoring:

Direct link between pressure and component

Imagine it does take place in the CAO

Potential impact on (most sensitive part of a) component (that potentially affect population/communities)

Try to use information from CAO itself, if it's not there, get as close as possible

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Appendix 1: Global Sources - additional papers on contaminants

Some additional information was found for other contaminant types, such as organochlorine pesticides (see table 6).

Compound	Sample type	Location	Sampling year	Reported concentrations	Reference
Organochlorine pesticides (DDT)	Sea Water	CAO	2001-2005	0.10-66 pg L-1	Carrizo, D., Sobek, A., Salvadó, J.A. and Gustafsson, O., 2017. Spatial distributions of DDTs in the water masses of the Arctic Ocean. Environmental science & technology, 51(14), pp.7913-7919.
Organochlorine pesticides (DDTs, HCHs and CHLs)	Sediment	Bering Strait, Chuckchi Sea, border CAO	2008	Sum DDTs: 0.64-3.17 ng/g DW Sum HCHs: 0.19-0.65 ng/g DW SumCHLs: 0.03-0.16 ng/g DW	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, pp.109-117.

Table 6. Reported concentrations of other contaminants in several compartments of the CAO.

Additionally, information on contaminant studies in the adjacent areas was compiled (table 7).

Table 7. Contaminant concentrations in compartments surrounding the CAO.

Compound	Sample type	Location	Sampling year	Reference	
Hg	Sea water, sediment, biota (amphipods, clams, snow crabs, arctic cod and whelks)	northeastern Chukchi Sea	2009, 2010	Fox A. L., Hughes E. A., Trocine R. P., Trefry J. H., Schonberg S.V., McTigue N. D., Lasorsa B. K., Konar B. and Cooper L. W. 2013. Mercury in the northeastern Chukchi Sea: distribution patterns in seawater and sediments and biomagnification in the benthic food web. Deep Sea Res. II 102, 56–67	
PCBs, pesticides	Sea water	Fram Strait		Ma, Y., Adelman, D.A., Bauerfeind, E., Cabrerizo, A., McDonough, C.A., Muir, D., Soltwedel, T., Sun, C., Wagner, C.C., Sunderland, E.M. and Lohmann, R., 2018. Concentrations and water mass transport of legacy POPs in the Arctic Ocean. Geophysical Research Letters, 45(23), pp.12- 972.	
PCBs	Air, sea water	North Atlantic, Fram Strait, border of Eurasian shelf	2004	Gioia, R., Lohmann, R., Dachs, J., Temme, C., Lakaschus, S., Schulz-Bull, D., Hand, I. and Jones, K.C., 2008. Polychlorinated biphenyls in air and water of the North Atlantic and Arctic Ocean. Journal of Geophysical Research: Atmospheres, 113(D19).	
PFAS	Sea water	North Atlantic to Fram Strait	2018	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), pp.9958-9967.	
PFAS	Seawater	western Arctic Ocean – on border of Amerasian	2013	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.	

		shelf (R/V Mirai) – Bering Strait		
PCBs, pesticides	Sea water	Fram Strait		Ma, Y., Adelman, D.A., Bauerfeind, E., Cabrerizo, A., McDonough, C.A., Muir, D., Soltwedel, T., Sun, C., Wagner, C.C., Sunderland, E.M. and Lohmann, R., 2018. Concentrations and water mass transport of legacy POPs in the Arctic Ocean. Geophysical Research Letters, 45(23), pp.12- 972.
PCBs, PBDEs and pesticides	River water	Arctic rivers: Ob and Yenisey	2003, 2005	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), pp.69-74.
PCBs	River water	Pan-Arctic		Carrizo, D. and Gustafsson, O., 2011. Pan-Arctic river fluxes of polychlorinated biphenyls. Environmental science & technology, 45(19), pp.8377-8384.
PCBs, PBDEs and pesticides	River water	Arctic rivers: Ob and Yenisey	2003, 2005	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), pp.69-74.
PCBs	Air	Monitoring stations around the CAO	Long-term	Carlsson, P., Breivik, K., Brorström-Lundén, E., Cousins, I., Christensen, J., Grimalt, J.O., Halsall, C., Kallenborn, R., Abass, K., Lammel, G. and Munthe, J., 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), pp.22499-22528.
PCBs	Air	North Pacific to Arctic Ocean	2012	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.
PCBs	Air	Monitoring stations around the CAO		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, pp.391-399.