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ICES/PICES/PAME WORKING GROUP ON INTEGRATED ECOSYSTEM ASSESSMENT (IEA) FOR THE CENTRAL ARCTIC OCEAN (WGICA)

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International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

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ICES Scientific Reports

ICES/PICES/PAME WORKING GROUP ON INTEGRATED ECOSYSTEM AS-SESSMENT (IEA) FOR THE CENTRAL ARCTIC OCEAN (WGICA)

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Contents

i Executive summary

The Working Group on the Integrated Assessment of the Central Arctic Ocean (WGICA) aims to provide a holistic analysis of the present and future status of the ecosystem and human activities therein. Data collection in the Central Arctic Ocean (CAO) has been inconsistent both spatially and temporally, which can limit the ability to conduct comprehensive analyses of trends and warning signals. However, coverage of data collection has been improving over the past few years. WGICA collates and analyses this regional information, which will be used to help guide the production of an Ecosystem Overview (EO) that relates the main regional pressures in the CAO with the human activities and the ecosystem components that are most impacted by these pressures.

Climate change reduces sea ice, increases light penetration, causes regionally variable trends in stratification and mixing of the water column, increases inflow in both the Atlantic and Pacific sectors, and heating of waters at the surface and extending deeper and deeper. These changes in turn affect primary production and cascade through the food web to ice-associated fauna, zoo-plankton, fish, benthos, and sea mammals.

These changes may be exacerbated by increasing human activities in and around the CAO, including increasing pollution from ship traffic and from the transport of contaminants to the ecoregion by rivers and ocean currents. The number of ships and distances traveled are increasing and it is anticipated that both commercial and tourist traffic by sea and air will continue to rise. The CAO has become an important sink for many pollutants such as microplastics, which have been found in sea ice and wildlife. Current and future threats to the ecoregion from these activities also include increased risk of oil spills and biodiversity loss if ocean mining expands into the Arctic.

While an agreement has been made to ban commercial fishing in the high seas of the Central Arctic Ocean; fish populations continue to be impacted by the effects of a warming ocean, re-treating ice-cover and acidification. These threats have important ecological and policy implications for the entire food web and the Arctic community. For example, negative impacts on the polar cod population will negatively impact ringed seals and beluga whales and therefore will also affect subsistence harvests in the future.

In upcoming years, WGICA plans to further define and describe human activities and resulting pressures and related management organizations, and develop a climate and vulnerability assessment of the CAO.

ii Expert group information

Expert group name	ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean (WGICA)
Expert group cycle	Multiannual fixed-term
Year cycle started	2019
Reporting year in cycle	2/3
Chair(s)	Lis Lindal Jørgensen, Norway
	Sei-ichi Saitoh, Japan
Meeting venue(s) and dates	9-10 May 2019, Sapporo, Japan(26 participants)
	27-19 April, 2020, online meeting (36 participants + 5 ICES Secretariat and observers)

iii Summary of the main conclusions

Oceanography:

Summer sea ice extent in the past decade or so has remained fairly stable at -22 ± 8 per cent relative to the mean climatic norm for the available range of satellite observations (1979-2019). Ice thickness declined across the central Arctic by 65%, from 3.59 to 1.25 m, between 1975 and 2012.

The Atlantic gateways to the Arctic Ocean are currently is experiencing greater inflows, manifested in a warmer ocean and atmosphere, northward and eastwards spread of Atlantic Water in the Barents Sea and the Nansen Basin, and reduced stratification and increased mixing in the upper ocean in the Eurasian Basin.

The Bering Sea recorded unprecedented high sea surface temperatures in 2014 and the warm condition has persisted into 2019. The Canadian Basin showed strong freshening and a deepening of the nutricline and deep chlorophyll maximum.

A more energetic state of the intermediate water layer in the CAO is projected in future years. This new state will be presumably supported by stronger currents and shear, leading to increased turbulent mixing and larger upward oceanic heat fluxes.

Human activities:

The CAO and adjoining waters remain relatively unpolluted, but the Arctic is a sink for pollutants transported from lower latitudes, and pollution from local sources is increasing. Emissions of chemical compounds (e.g. mercury, POPs) from outside the CAO are currently the main source of air pollution. Other pollutants, including flame retardants, pesticides, and phthalates, are an emerging concern. Macro-, micro- and nanoplastics, transported by rivers and ocean currents, have been found in sea ice and wildlife. Sea ice is an important sink for microplastics. The number of ships and the distances traveled are increasing in the Arctic; currently up to 45% of traffic is associated with fishing vessels, but larger vessel traffic is increasing. We also consider future activities that may impact the CAO as sea-ice cover decreases. For example, oil spills from activities on the continental shelves may affect the CAO ecosystem. Ocean mining may expand into the Arctic, resulting in biodiversity loss even as most species in the CAO remain undiscovered or unidentified. An agreement has been made to ban commercial fishing in the high seas of the Central Arctic Ocean; still, the problem of Abandoned, Lost or otherwise Discarded Fishing Gear (ALDFG) is a factor to consider in the CAO area even if commercial fishing is not allowed. Tourism is generally associated with ships or, in smaller volumes, as flights to the North Pole.

Ecosystem components:

Microalgae, Sea Ice Biota and Zooplankton: Changes in the amount, type, timing and location of sea ice in the Arctic, along with related changes in light availability, temperature, salinity and nutrient concentrations in surface layers, are affecting the timing and abundance of primary production and the biomass and species composition of ice biota and the major zooplankton species, with likely important consequences for food web functioning.

Benthos: Diverse deep-sea habitats, including undersea mountains, ridges, glacial deposits and other features support increased benthic biodiversity, but little is known about changes to these and other deep-sea communities. On the shelves, there is evidence of declining benthic biomass in the northern Bering Sea and the southern Chukchi Sea along with a northward shift in dominant macrofaunal biomass, which has also been observed in the European Arctic. The long lifetimes, slow growth rates and low fecundity of deep-sea organisms make them more vulnerable to human activities such as mining, oil exploitation, bottom fisheries, climate change as well as light, noise, plastic and chemical pollution.

Fish: Diminishing sea ice, earlier melt, higher ocean temperatures and resulting changes in salinity, nutrient availability and prey availability are affecting the biomass, abundance and distribution of different fish populations, including that of polar cod (*Boreogadus saida)*, a keystone Arctic species. Increased human presence in and near the CAO is exposing fish populations to plastic and other pollutants and increasing ocean noise, which has been shown to affect polar cod (*B. saida*) behavior. Should commercial fishing, mining or oil development commence in the CAO, a variety of impacts on fish can be expected.

Marine mammals: Based on current knowledge, the CAO appears to be relatively scarcely populated by marine mammals; with continued ice retreat, however the importance of the CAO may increase over time, especially for ice dependent pelagic-feeding or generalist species like ringed, ribbon, harp and hooded seals, belugas,(walrus, polar bear,) narwhals and bowhead whales, some of which are already experiencing population declines. Some polar bears currently also use sea ice in the CAO as a summer hunting habitat but increasing distance to denning habitats on land may compromise this strategy in the future. Many marine mammals rely on acoustics for key life functions; increasing human presence in the region will bring increasing noise from seismic airguns, ship engines, military operations, fisheries, research sonars and possible mining, which can interfere with vital behaviors.

Seabirds: Large numbers of breeding, non-breeding, and migratory seabird individuals use open water habitats in marginal shelf waters of the Central Artic region during summer and fall, foraging on zooplankton, invertebrates and forage fish. However, few seabirds occupy the mostly ice-covered CAO region itself. Predicted ice-free summers in the CAO are likely to impact seabird populations, in part through impacts on prey species (e.g. *B. saida*). Other impacts of diminished sea ice range from smaller scales, e.g. reduction in very ice-dependent species like ivory gulls and Ross's gulls, to possible extremely large-scale changes in longstanding migration and distribution patterns of northern hemisphere marine birds. Also, post-breeding and migrating marine birds in newly ice-free CAO waters would overlap with increased vessel traffic (bird-ship collisions), and pollution or plastic debris can also be detrimental to marine birds.

Review and report on new studies on fish in the CAO ecosystem:

Research on marine fishes in the CAO and adjacent waters published during 2017-2020 is summarized, building on earlier summaries by other groups (e.g. related to the Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean). Polar cod (*Boreogadus saida*), a keystone species in Arctic food webs, continues to be research focus, with publications detailing more about the species ecology, distribution, genetics, links to other species and impacts from climate change. Other research has examined fish community structure and anticipated impacts of climate change (e.g. potential for species to expand northward into the CAO). Policy papers have also developed recommendations regarding commercial fishery development.

Priority research needs and monitoring:

Dato collection of physics, contaminants, primary and secondary producers and sea ice biota must be standardized and also obtained i.e. during winter. Mapping and baseline studies were identified as priorities for benthos, sea mammals and fishes including the development/use of new technology. Marine mammals need studies on life history, health and ecology.

Regarding possible future fisheries development of new management tools can safeguard sustainable development of ecosystems and human stakeholders in the face of a rapidly changing environment. Studies of arctic mammal sensitivity to low frequency anthropogenic noise, were identified as priority research.

For monitoring are a coordinated array of regional transect lines recommended with key parameters to evaluate the regional to pan-Arctic scales. Such international, coordinated observation can help identify focal areas for monitoring on an interannual and decadal basis. This involves also CAFF and its Circumpolar Seabird Expert Group (Cbird), the IUCN Polar Bear Specialist Group, and other relevant working groups.

Ecosystem overviews:

Development of an Ecosystem Overview commenced in 2020 with the identification and prioritization of ecosystem pressures. Links between the five main pressures (sea-ice loss, non-indigenous species, contaminants, marine litter and noise), human activities and ecosystem components were initially discussed; these links will be further examined by WGICA during 2020-2021.

1   Introduction

The international governance framework for the Central Arctic Ocean

The central Arctic Ocean (CAO) – as every ocean in the world – is governed by Law of the Sea Convention (UNCLOS). UNCLOS (in force 1994) is the "Constitution of the oceans", providing the rules for how countries are to establish maritime zones, principles for the management of natural resources, conduct marine science and protection of the marine environment.

Coastal states are entitled to establish 200 nautical mile exclusive economic zones (EEZs) where they have sovereign rights to the natural resources. In the high seas beyond national jurisdiction, flag states are responsible for the vessels flying their flag, ensuring that they comply with international obligations in UNCLOS and other international treaties. Also, coastal states can submit claims to the continental shelf extending beyond the 200 nautical miles limit. UNCLOS therefore has implications for managing all human activities in the oceans such as shipping, tourism, seabed mining, oil and gas activities, marine scientific research, and fisheries.

UNCLOS has 169 parties and is ratified by four of the five CAO coastal states. USA is not party to the Convention but considers it customary international law.

UNCLOS provides rules for the management of living marine resources which are to be managed sustainably and utilized in an optimal manner. These provisions are reinforced by the 1995 UN Fish Stocks Agreement which is an implementing agreement to the Convention. With respect to environmental protection UNCLOS stipulates a general obligation to protect the environment. A number of international treaties, such as the Convention on Biodiversity, pertain to the marine environment, and currently an implementing agreement for the conservation and use of biodiversity in areas beyond national jurisdiction is under negotiation ("BBNJ"). As regards marine scientific research, the main thrust of UNCLOS is that scientific activity is to be promoted.

There are a number of scientific initiatives and bodies in the Arctic. Under the auspices of the Arctic Council an agreement on international scientific cooperation (2016) has been negotiated. Additionally, the working groups in the Arctic Council produce scientific assessments. Since 2016, Arctic Science Ministerial addresses issues of concern in the Arctic. The International Arctic Science Committee (IASC) is a bottom-up scientific cooperation involving scientists from more than 20 countries. In the North Atlantic part of the Arctic, the International Council for the Exploration of the Sea plays an important role, providing scientific advice for the management of fisheries and the marine environment in that region.

The CAO governance regime has been strengthened considerably over the last decade through numerous international agreements. In addition, there is many international agreements besides those mentioned above that pertain to the CAO (Arctic Ocean Review 2011). As regards science in particular, the International Arctic Science Committee represents the scientific community, whereas the Arctic Council science cooperation agreement, the recent Arctic science ministerial, as well as the International Council for the Exploration of the Sea (ICES) and the North Pacific Marine Science Organization (PICES) have important roles in these areas.

Arctic Ocean Review 2011: https://www.pame.is/index.php/document-library/shipping-documents/arctic-ocean-review-documents/347-aor-phase-i-report-to-ministers-2011-nov-2013/file

WGICA

The International Council for the Exploration of the Sea (ICES) is committed to building a scientific foundation for integrated ecosystem understanding. Part of this integrated approach is ecosystem-based management (EBM). EBM requires consideration of the impacts of different marine sectors on marine ecosystems and trade-offs between such activities, in the context of climate change and other forms of environmental change.

The Arctic Council (AC) also promotes the use of EBM. A core component of EBM is Integrated Ecosystem Assessment (IEA), the topic of this report.

The joint ICES/PICES/PAME Working Group for Integrated Ecosystem Assessment of the Central Arctic Ocean – WGICA is undertaking an IEA for the Central Arctic Ocean (CAO), integrating assessment of the changing ecosystem with current and future human activities.

The WGICA was established in 2015 to 1) provide a holistic and integrated view of the status, trends and pressures of key components of the (CAO) ecosystem, and 2) to contribute to the implementation of EBM in the CAO.

The CAO (see black lines in figure 1) is defined by the slopes down to the deep Eurasian and Amerasian basins. The fluxes and properties of water through the Atlantic and Pacific gateways, connecting the Arctic to other oceans, are part of the physical and biological variability of the basins of the CAO.
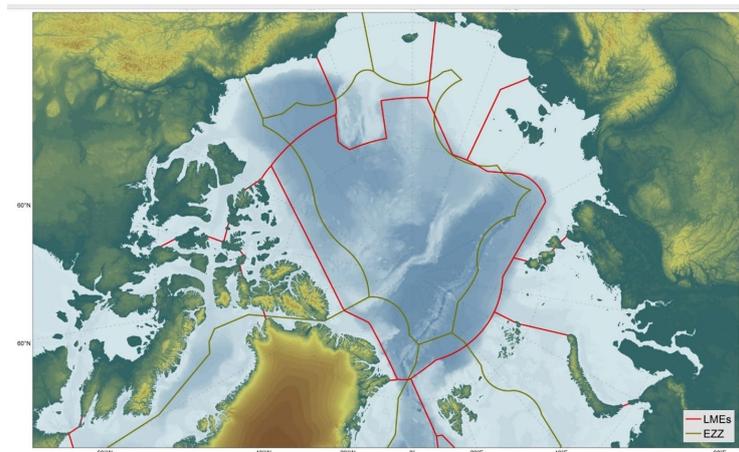
Figure 1. The study area of WGICA is the Central Arctic Ocean (CAO) Large Marine Ecosystem (LME), bounded in red in the center of the map, which includes areas under national jurisdiction (EEZs boundaries are in green) as well as the High Seas beyond national jurisdiction (source: ICES WKICA REPORT 2015 ACOM/SCICOM Steering Group On Integrated Ecosystem Assessments, ICES CM 2015/SSGIEA:11, REF. SCICOM & ACOM).

The WGICA CAO area includes international waters, the High Seas beyond national jurisdiction (see red lines in figure 1,) as well as areas within the exclusive economic zones (EEZs) of coastal states.

Infobox

What is the ARCTIC COUNCIL (AC)? https://arctic-council.org/en/about/

The Arctic Council is the leading intergovernmental forum promoting cooperation, coordination and interaction among the Arctic States, Arctic indigenous communities and other Arctic inhabitants on common Arctic issues, in particular on issues of sustainable development and environmental protection in the Arctic.

The Arctic Council does not and cannot implement or enforce its guidelines, assessments or recommendations. That responsibility belongs to individual Arctic States or international bodies.

The Arctic states: Canada, The Kingdom of Denmark, Finland, Iceland, Norway, The Russian Federation, Sweden and The united States are the members of the AC, while the permanent participants are the Aleut International Association (AIA), the Arctic Athabaskan Council (AAC), the Gwich´in Council International (GCI), the Inuit Circumpolar Council (ICC), the Russian Association of Indigenous Peoples of the North (RAIPON) and the Saami Council.

The working groups in the AC are: Protection of the Arctic Marine Environment (**PAME**), Arctic Monitoring and Assessment Programme (**AMAP**), Conservation of Arctic Flora and Fauna (**CAFF**), Arctic Contaminants Action Program (**ACAP**), the Emergency Prevention, Preparedness and Response (**EPPR**), and the Sustainable Development Working Group (**SDWG**).

Conduct of the meeting in 2020

The 5th annual meeting of the WGICA was planned as a physical meeting at the ICES HQ in Copenhagen, Denmark, but was conducted as a Webex meeting 27-29 April 2020 due to the COVID- 19 travel restrictions.

This meant that the Regional Arctic Ocean Decade Workshop, planned back to back with the WGICA meeting in Copenhagen, was canceled and postponed to an online meeting in October 2020 (http://www.oceandecade.dk/).

The meeting focused on six of the seven action items in the 2018 Terms of Reference for the WGICA, and on finishing Report 1 and starting the work on an Ecosystem Overview (EO) and Report 2.

Before the meeting, one Atlantic and one Pacific lead for each of the action items was tasked to reach out to experts in the WGICA group.

The meeting was built up as two duplicate meetings per 24 hours, with 12 hours in between, allowing participants from around the world to participate.

Norway, Denmark, Finland, Netherlands, USA, Japan, Korea and China, Germany, Russia, Canada, and Sweden are WGICA members and 36 persons participated in the meeting in addition to four participants from the ICES secretariat and one observer.
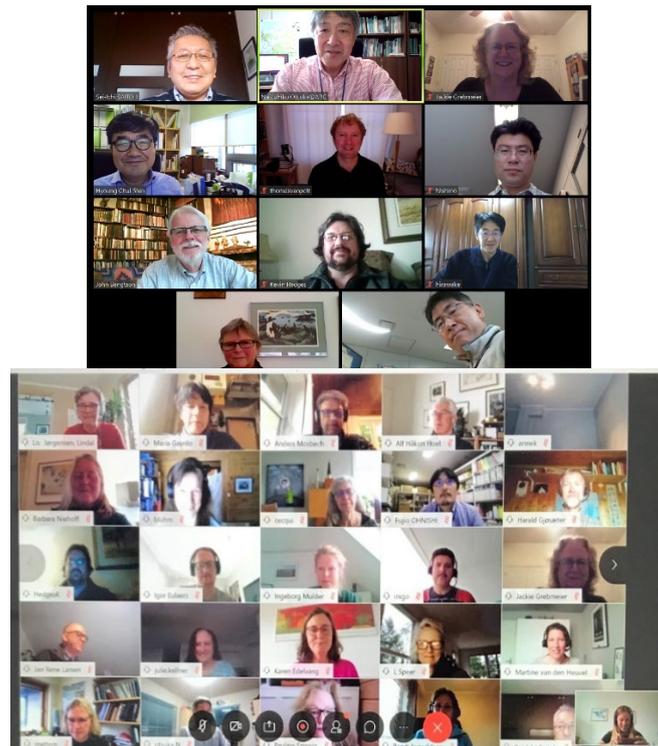
Top photo: the Asian Pacific meeting, Bottom photo: the European and North American meeting

The first two days were dedicated to presentations of the work to address the annual ToRs (see appendix 2), while the final day was used for each of the ToR groups to define the work ahead and discuss the content of the ToR.

During the meeting it was clarified that in 2021 new ToRs must be defined for the next WGICA term (2022-2024). This work includes the writing of the Ecosystem Overview and WGICA Report 2.

WGICA co-lead, Senior Scientist Lis Lindal Jørgensen (IMR), presented the 2020-2024 workplan for the Arctic Monitoring and Assessment Programme (AMAP) Heads of Delegation meeting 18 June 2020. There is interest in co-operation between WGICA and the AMAP/CAFF for the upcoming CAO Climate- and Vulnerability Assessments. The format of such cooperation remains to be decided on.

 Information given as "notes" during the webex meeting:

AMAP will publish "Climate Issues of concern report 2021" in 2021. Draft table of contents:

1) Recent developments in major climate indicators
2) Extreme events and thresholds in the Arctic
3) Future of The Arctic Seen from CMIP6
4) Arctic/Mid-latitude Weather Connectivity
5) Climate change impacts on Arctic ecosystems and ecosystem feedbacks
6) Trends, effects and societal implications of Arctic climate change.

Point 5) above is intended to serve as a basis for a planned AMAP/CAFF assessment of climate change impacts on Arctic ecosystems and ecosystem feedbacks, as part of the 2021-2023 AMAP Work Plan. The scope of this work is tentatively planned also to cover the marine environment

IPCC will release the 6th assessment report in 2021; including both the physical basis and impacts, adaptation and vulnerability. There will be a separate chapter on Polar Oceans

The State of the Arctic Ocean report has been released April 2020: https://www.dfo-mpo.gc.ca/oceans/soto-rceo/arctic-arctique/index-eng.html

"Plastic in a bottle" project is planning five launching sites, and one site is planned from the Eastern coast of U.S.A. And provided report in PAME shows an idea of launching from the Arctic coast of Alaska. The capsule launched in Iceland recently stranded in the northwest of Scotland: https://www.pame.is/projects/arctic-marine-pollution/plastic-in-a-bottle-live-map

ICES Working Group on Shipping Impacts in the Marine Environment (EGSHIP) https://www.ices.dk/community/groups/Pages/WGSHIP.aspx

WGICA work, deliveries and meetings in 2021-24:

WGICA shall produce and deliver annual reports as well as three final reports before year 2024:

- **Annual Reports** (Interim Reports)

The annual report of this year is *this* report. New reports will follow each year answering the ToRs and give the last updates on scientific work from the CAO

- **Final Reports**

Three final reports are planned.

- **Report 1 - Ecosystem description of the CAO**

This report (approximately 350 pages) is in production and details are given in chapter 2 of this annual report.

- **Report 2 – part I: Human activities, pressures and management bodies; part 2: climate- and vulnerability assessment of the Central Arctic Ocean (CAO)**

This report will build on Report 1 and will start in winter 2020 with a deadline October 2024.

- **Ecosystem Overview (EO) –** CAO

Ecosystem overviews provide a description of the ecosystems, identify the main human pressures, and explain how these affect key ecosystem components. Such overviews are approximately 15 pages and updated each third year. We started the EO for the CAO in June 2020 and a first draft will be delivered in November. See Chapter 8 of this annual report for more details.

Planned meetings:

Web-based meeting in subgroups scattered throughout the year, arranged by ToR/sub-groups leaders

2021: Webex-based meeting April early May 2021 to discuss assessment models to be built for data-poor areas, with the Ecosystem Overview (EO) as a first step to develop more methods.

2021: to write part 1 (Human activities and management bodies) by following the structure of the EO

2021: In fall 2021, to have a physical meeting in ICES HQ to discuss the way forward to:

- Finalize the Part 1

- Draft the ToRs for 2022-2024

- Develop Ecological Overview

- Writing of Report 2 - part 2.

2022-2024: to write part 2 (Climate- and Vulnerability- Assessment).

1.1 Terms of Reference

ToR a: Review and consider approaches and methodologies for conducting an IEA of the CAO ecosystem (year 1 - 2019).

ToR b: Review and report on ongoing and recent changes and events in the CAO ecosystem associated with changes such as in sea ice, oceanographic circulation, and hydrographic properties.

ToR c: Continue to examine effects of climate change on the CAO ecosystem by compiling and reviewing information on changes in response to the ongoing 'Great melt', and assess likely consequences to the CAO ecosystem of projected future changes associated with further loss of sea ice and other climate-related changes (i.e. a climate impact assessment).

ToR d: Assess the consequences of recent and ongoing climatic and oceanographic changes on transport pathways (physical and biological) and potential effects of contaminants in the CAO ecosystem.

ToR e: Review and report on new studies on fish as well as other biological components of the CAO ecosystem ("other biological components" not included here, but in ToR c)

ToR f: Continue to identify priority research needs and monitor how identified knowledge gaps (needed to improve IEA and management effectiveness) are being addressed and filled.

ToR g: Prepare an Ecosystem Overview (EO) for the CAO ecosystem as a draft version in interim report in 2020, and final version in 2021 (draft version of EO will be available October-November 2020).

1.2 Summary of work plan

Year 1 **2019**	Review IEA methodologies for IEA of the CAO. Review and report new information and changes in the CAO ecosystem.
Year 2 **2020**	Review and report new information and changes in the CAO ecosystem. Address pathways and effects of contaminants, make an initial list of research needs, and prepare draft Ecosystem Overview.
Year 3 **2021**	Prepare a second version IEA eport for the CAO with information on status and trends, including impacts of climate change, pollution, and other relevant human pressures. Report on research needs and prepare final draft of Ecosystem Overview.

1.3 Summary of achievements of the WG during 3-year term

For 2019:

- The CAO differs from other LMEs in having few biological and oceanographic time series available to describe status and changes of the ecosystem.
- Methodological development: The 'scientific review' method will continue to be a main avenue for compiling information and assessing the changing state of the CAO ecosystem
- Datasets: Satellite-based monitoring of sea ice and some oceanographic parameters provides a very important source of information on the CAO.

2020: *(In bullet form, and as specific as possible – e.g. publications, advisory products, datasets, modelling outputs, methodological developments, etc. These will be used by ICES structures to demonstrate delivery. Typically 1-2 pages).*

Final report on ToRs, workplan and Science Implementation Plan (=to be made in 2021)

(A summary of work done on the ToRs and in fulfilment of the work plan and the ICES (Strategic) Science Implementation Plan; Science Highlights, etc.

Format to include:

- *Progress and fulfilment by ToR*
- *Science highlights*

2 Status for WGICA IEA report in the CAO (CRR) (Report 1)

Report 1: Integrated Ecosystem Assessment of the Central Arctic Ocean: Ecosystem description and vulnerability characterization.

The first final report from the WGICA will be published by ICES in the Cooperative Research Report (CRR) series. This includes peer review and technical editing by ICES prior to publication.

The title of the report is: *Integrated Ecosystem Assessment of the Central Arctic Ocean: ecosystem description*. The plan was to include also a section on *vulnerability characterization*. This part is now moved to the second report where emphasis will be on human activities and their impacts on the CAO ecosystem.

The first report is made up of 9 chapters:

- Chapter 1 – **Introduction**
- Chapter 2 – **Topography, oceanography and sea ice**
- Chapter 3 – **Algae and primary production**
- Chapter 4 – **Zooplankton and invertebrate ice fauna**
- Chapter 5 – **Sympagic and pelagic bacterial communities**
- Chapter 6 – **Arctic benthos**
- Chapter 7 – **Fishes in the Central Arctic Ocean**
- Chapter 8 – **Marine birds: species occurrence and habitat use**
- Chapter 9 – **Marine mammals of and near the central Arctic Ocean**

Draft versions of the chapters have been sent out to the full list of WGICA participants for their review and comments. Chapters 7 and 8 were sent 13 February, chapters 2 and 3 on 1 April, chapters 4 and 9 on 17 April, and chapters 1, 5 and 6 on 22 April. The texts are currently revised and updated based on comments received and graphics are being produced. The aim is to have a complete draft of the report ready to be sent to ICES by the end of 2020 for their further review, editing and publication of the report.

The chapters together provide a description of the ecosystem by ecosystem components following a traditional breakdown into oceanography, plankton, fishes, birds, etc. Each chapter is a review and summary of published information with an emphasis on spatial aspects (where in the CAO) and trophic interactions (prey and predators). This type of information provides some linkages between the chapters. In addition, the text on *Key features of the CAO ecosystem* will be included as a synthesis section of the report. The text that was included in the WGICA 2017 report, will be updated and constitute the main part of the executive summary of the report.

3 ToR b. Review and report on on-going and recent changes and events in the CAO ecosystem associated with changes such as in sea-ice, oceanographic circulation, and hydrographic properties

Contributors: Vladimir Ivanov, Shigeto Nishino and Randi Ingvaldsen.

3.1   Introduction

The purpose of this chapter is to provide up-to-date information on the recent changes in sea ice and oceanographic conditions in the Central Arctic Ocean (CAO) on the basis of open-access sources. The chapter consists of six sections, including the introduction.

Section 2 describes recent changes in sea ice conditions in context of general trends observed in the CAO within the last 20 years. Section 3 examines changes in the Atlantic and Pacific gateways to the Arctic. Section 4 looks at changes in the hydrographic properties of the CAO. Section 5 provides a summary, and Section 6 considers possible ecosystem implications of oceanographic change. Suggested priority research tasks are given at the end of the overall report, in Chapter 7.

A strong seasonal cycle, low temperatures, extensive permanent and seasonal ice cover, a large supply of freshwater from melting ice and rivers, and heat/salt input through the gateways are key physical factors shaping the CAO hydrographic regime. According to the latest report of the International Panel on Climate Change (IPCC, 2019: Chapter 3) over the first twenty years of this century the Arctic surface air temperature has increased more than twice as fast as the global mean. Although attribution studies confirm that greenhouse gases are the primary drivers of global temperature increase, climate change in the Arctic is progressing much faster than in the lower latitudes due to the so-called "Arctic amplification". New mechanisms of Arctic amplification are still being discovered, but the basic ones are well known, with ice-albedo feedback likely to be among the key ones. Rapid reduction of Arctic sea ice area and volume may thus be considered as the ultimate trigger for other physical changes currently taking place in the Arctic domain. Delayed onset of freezing in 'marginal' Arctic seas (Barents, Kara and Chukchi) provides a positive feedback ("atlantification"/"pacification") allowing warmer water to progress further toward the deep interior of the CAO. Besides unprecedented Arctic sea ice loss in summer in the early 21st century, it should be stressed that the last decade was exceptional in terms of record low ice extent at the peak of seasonal minimum relative to 1979-2018 (http://nsidc.org/arcticseaicenews/).

3.2   Changes in Arctic Sea ice

Independent studies confirm that Arctic sea ice extent in summer has substantially decreased in in 1990-2010s (e.g., Serreze et al., 2007; Stroeve et al., 2012; Comiso et al., 2017). According to the IPCC (2019: Chapter 3) Arctic sea ice extent has progressively declined throughout the year with maximum reduction in September (-12.8 ± 2.3% per decade; 1979-2018). However, this average decay is not uniform in time. The strongest decrease happened between 1996 and 2007 (see Fig.

1). After 2007, the summer minimum of sea ice extent has remained fairly stable at -22 ± 8 per cent relative to the mean climatic norm for the available range of satellite observations (1979-2019). Climate models project further decay of the Arctic sea ice with a wide range in expected timing of a seasonally ice-free Arctic Ocean, and in the duration of the ice-free season as a result of the interplay among various affecting factors as well as uncertainties in models and the IPCC's representative concentration pathways (RCPs). This range varies from a 1% chance of brief ice-free years in September by the end of this century (in case of 1.5°C stable global warming) to a 10-35% chance of ice-free summers after 10 years of steady 2°C warming (IPCC, 2019: Chapter 3).

3.2.1   Central Arctic Ocean

The sharp rise of air temperature in the 1990s led to an "instant" (on a climatic time scale) change in the ice regime of the Arctic Ocean - a shift to a reduced area of ice cover at the seasonal minimum (in September) by an average of 22 ± 8% relative to the mean climatic norm for the available range of satellite observations (Fig. 3.1).
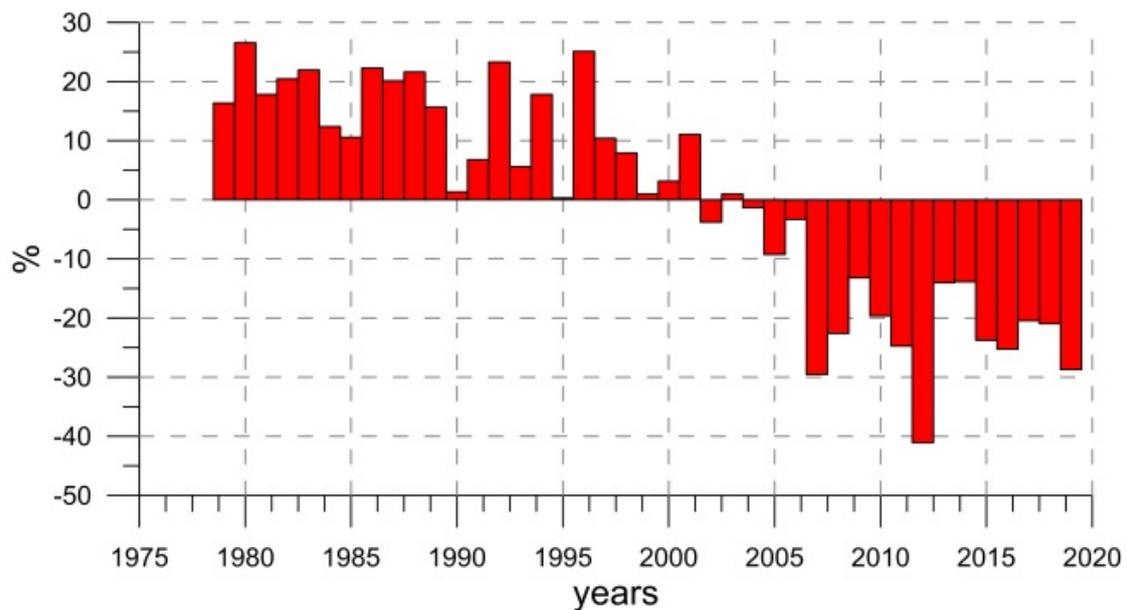
Figure 3.1: Anomaly in the extent of Arctic sea ice in September (%) relative to the mean climatic norm for the period of satellite observations (1979-2019) (based on data from https://nsidc.org/).

The fraction of multiyear ice (5 years and older) decreased from 30% to 2% between 1979 and 2018; while the fraction of first-year sea ice increased from 40% to 70% (Stroeve and Notz, 2018). Average ice thickness declined across the central Arctic by 65%, from 3.59 to 1.25 m between 1975 and 2012 (Lindsay and Schweiger, 2015). Under conditions of thinner and less consolidated sea ice, the speed of ice drift has increased compared with the 20th century. A vivid example of recent changes in ice dynamics seen by comparing drifting ships in the Arctic Ocean. Both the Tara in 2006-2007 (Gascard et al., 2008) and the Polarstern hosting the MOSAiC expedition (https://mosaic-expedition.org/)currently underway approximately followed the drift of the Fram in 1983-1896. The drift that took the Fram three years was completed by Tara in half that time. The Polarstern started about 600 nautical miles closer to Fram Strait due to ice conditions and had nearly reached Svalbard after only nine months.

3.2.2   Arctic seas

The strongest decay of ice cover in summer has occurred in the Eurasian Arctic seas. In the 2000s, the gradual expansion of the ice-free season progressed in two "waves", propagating towards the Arctic interior from the Barents Sea (in the west) and from the Chukchi Sea (in the east). In 2010s this "signal" reached the Laptev Sea (Fig. 3.2), which may be considered as the most remote location along the Arctic coast, far away from the warming influence of either the Atlantic or the Pacific.
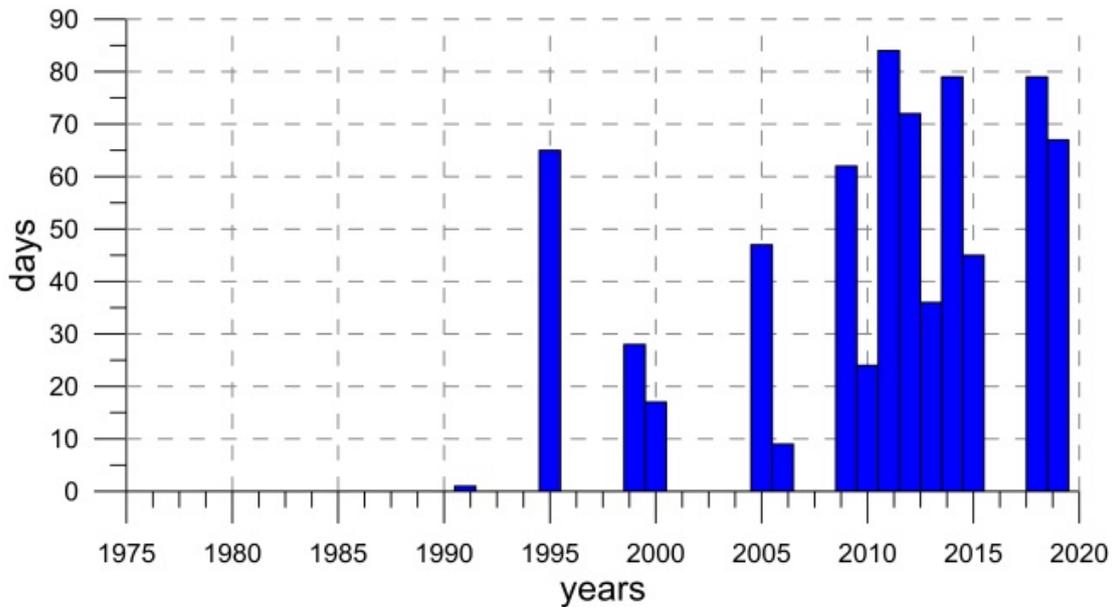
Figure 3. 2: Duration of the ice-free days, defined by spatial mean ice concentration lower than 0.15, in the Laptev Sea. (based on data from https://nsidc.org/).

According to Egorov (2020), in 2004–2018, the area of winter ice thinner than 70 cm increased by 12 % compared to 1997–2003, while the area of thicker ice reduced by 18 %. The area of multiyear ice decreased by about 10 times. On average, in 2004–2018 mean-weighted ice thickness in the Eurasian Arctic seas by the end of cold season decreased by about 40 cm (from 153 to 117 cm) compared with 1997–2003.

Ice cover shrinking and ice thinning leads to enhanced ice-albedo feedback (Stroeve et al., 2014b; Liu et al., 2015a), and to excessive heat uptake by the surface water layer. In the next cold season this extra heat is mostly released to the air, providing a reverse warming influence on the lower atmosphere and delaying onset of freezing. In the 2010s, the thermal impact of the ocean on the ice cover and the Arctic atmosphere had increased (Ivanov et al., 2016; Tetzlaff et al., 2014). This impact is realized either directly, through upward heat flux from the intermediate Atlantic-origin water layer - the so-called "atlantification" (Polyakov et al., 2017; Ivanov and Repina, 2019) - or indirectly, through accumulation of extra heat in the upper water layer in summer, which may affect ice properties during the next cold season (Ivanov et al., 2019) and contribute to earlier break-up the following spring (Stroeve et al., 2012b; Serreze et al., 2016). Another emerging effect of increased duration and extended area of open water in the summer season is thinning of ice in mid-winter, with positive consequences for polynya formation. Arctic polynyas (areas of open water or thin ice inside consolidated ice pack) are the zones of intensive ice production and dense water formation on shallow shelves, where vertical haline convection reaches the seabed in winter (Ivanov et al., 2004; Luneva et al., 2020). While polynyas in the western Arctic show a pronounced variability with varying trends, positive trends in polynya area and ice production are

detected for several regions of the Eurasian Arctic seas, most significantly in the Laptev Sea region as shown in Fig. 3.3 (Preußer et al., 2016).
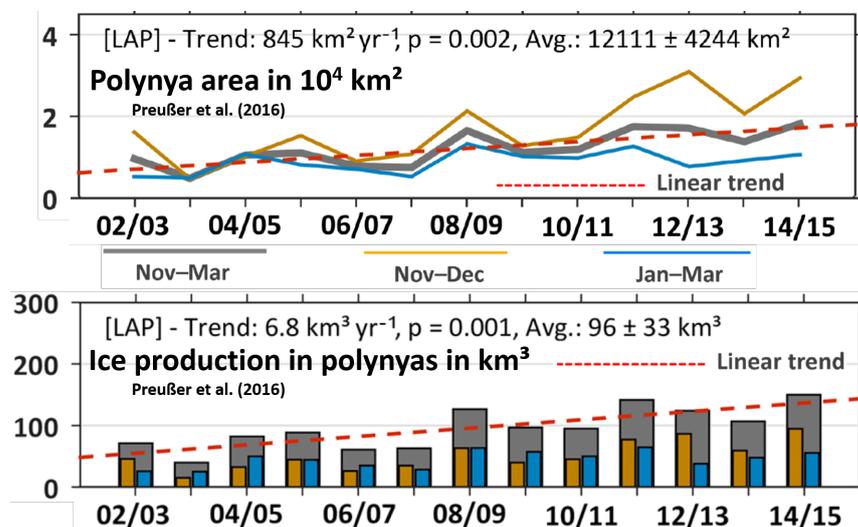
Figure 3.3: Time series of polynya area and ice production of Laptev Sea polynyas from MODIS satellite data showing significant trends in sea-ice production and polynya area (Fig 6 in Preußer et al., 2016).

3.3 Changes in the gateways

3.3.1 Atlantic gateways (Barents Sea, Fram Strait and Western Nansen Basin)

The Atlantic gateways to the Arctic Ocean are strongly influenced by vigorous flow of Atlantic Water (e.g. Schauer et al., 2002), and currently the region is experiencing a greater role for the Atlantic inflows (Polyakov et al., 2017). This "atlantification" is manifested in a warmer ocean (Skagseth et al., 2020; Polyakov et al., 2020a) and atmosphere (Isaksen et al., 2016), loss of sea ice (Onarheim et al., 2018; Ivanov et al., 2018), and the northward and eastwards spread of Atlantic Water in the eastern (Oziel et al., 2016) and northern (Lind et al., 2018) Barents Sea, as well as in the Nansen Basin (Polyakov et al., 2017; 2020a). Changes in stratification and mixing in the upper ocean are also involved (Polyakov et al., 2020b).

Over the last four decades the temperatures of the inflowing Atlantic Water to the Barents Sea have increased by about 1.5oC (Smedsrud et al., 2013; Skagseth et al., 2020). The associated changes include substantial reductions in sea ice cover during winter (Årthun et al., 2012), increases in heat content of the region (Sandø et al., 2010), and a northeastwards shift of the location of the Polar Front (Oziel et al., 2016; Barton et al., 2018). Recent studies have also suggested that this might partly be due to increased velocities in the Atlantic Water surface currents (Oziel et al., 2020). Reductions of about 50% of the March sea-ice area between 1979 and 2018 have been observed, and have been linked to an increase in Atlantic Ocean heat transport, especially through the western part of the Barents Sea (Docquier et al., 2020). When the Atlantic Water passes through the shallow Barents Sea, it is cooled and mixed with the surrounding waters, and the resulting denser water masses that are exported to the Arctic Ocean are an important part of the Arctic thermohaline system. A recent study shows that Barents Sea cooling has become less efficient with reduced ocean heat loss over the southern Barents Sea (Skagseth et al., 2020). According to the study, the outflows from the Barents Sea to the Arctic Ocean have become warmer, although the outflow densities have remained relatively unperturbed as increasing salinity has compensated for the warming. If the trend continues, decreasing salinities in the upstream

Atlantic Water might cause the export of water masses of record-low density from the Barents Sea within a few years (Skagseth et al., 2020).

Despite substantial long-term trends, the inter-annual variability in the Atlantic gateways to the Arctic is substantial, and since 2015/2016 the temperature in the inflowing Atlantic Water has decreased (González-Pola et al., 2019). For the southwestern Barents Sea, the temperature of the inflowing Atlantic Water in 2019 was about at the same level as in the early 2000s (Figure 1). Observations from a recently established standard section (the Hinlopen section) north of Svalbard imply substantial inter-annual variations in Atlantic Water core temperature in this region (Figure 3.4). Maximum temperatures in the period 2014-2019 were observed in 2016. Associated with the decreasing temperatures, both regions have experienced increased sea ice cover since 2016.
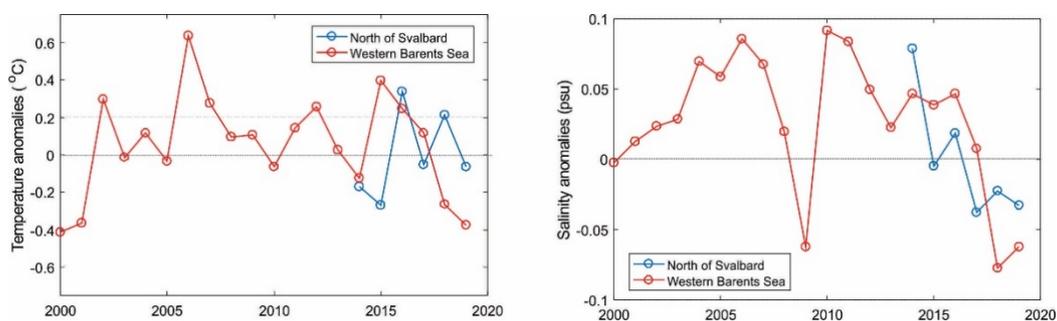
Figure 3.4. Temperature (left) and salinity (right) anomalies in the Atlantic Water flow into the Arctic gateways. The time series sampled in August-September at the Fugløya-Bear Island section at the western entrance to the Barents Sea, and at the Hinlopen section near 20oE north of Svalbard.

Also evident from the time series is a substantial freshening of the Atlantic Water in the Arctic gateways,which started around 2010 in the western Barents Sea (Fig.1). An accelerated freshening is evident from 2016, and similar changes were observed in the eastern subpolar North Atlantic, in the Nordic seas influencing the Greenland Sea, the northern Norwegian Sea to Fram Strait, and the southern reaches of the Barents Sea (González-Pola et al., 2016). Throughout the subpolar region, freshening is accompanied by moderate cooling at just a few sites, indicating that the large changes in salinity are decoupled from changes in temperature (González-Pola et al., 2019).It is likely that the Atlantic Water flowing into the Arctic Ocean has become substantially fresher during recent years, and possibly will do so for some years to come.

3.3.2   Pacific gateway (Bering and Chukchi seas)

The Bering and Chukchi shelves are an important region for fisheries (Van Vorhees & Lowther, 2010) and Indigenous subsistence resources (Suydam et al., 2007). The region has several biological hotspots with high benthic biomasses (Grebmeier et al., 1988, 2006, 2015; Grebmeier, 2012) and congregations of large benthic feeders at high trophic levels, such as grey whales and walruses (Feder et al., 2005). The marine ecosystem in this region is likely influenced by the recent ocean warming and reduction of sea ice.

The Bering Sea recorded unprecedented high sea surface temperatures in 2014 (Stabeno et al., 2017) and the warm condition has persisted into 2019 (Cornwall, 2019; Stabeno & Bell, 2019). Sea water in the winter of 2017-2018 was exceedingly warm and late storms affected sea ice duration and extent, resulting in an unprecedented period of low Bering Sea winter ice (Stabeno and Bell, 2019). Ecosystem surveys there showed that the spring bloom was delayed, zooplankton abundances were low, catches of pelagic forage fishes were low, and seabird die-offs were extensive (Duffy-Anderson et al., 2019).

The Bering and Chukchi seas are connected by the narrow (85 km) and shallow (50 m) Bering Strait. Through the strait, Pacific water carrying heat, freshwater, and nutrients is transported into the Arctic Ocean (Coachman and Aagaard, 1966; Stigebrandt, 1984; Walsh et al., 1989). The Bering Strait throughflow has been monitored by mooring observations (e.g., Woodgate et al., 2012, 2015), and it increased 50 % from 2001 (0.7 Sv) to 2011 (1.1 Sv), driving heat and freshwater flux increases. Enhanced Bering Strait throughflow likely transports more nutrients (Woodgate, 2018) that may help increase the primary production in the Chukchi Sea where the ice-free season has extended in recent decades (e.g., Arrigo et al., 2008). On the other hand, Yun et al. (2016) hypothesized that significant decreases of 30–50% in nutrient concentrations occurred over recent decades in the Bering Strait and the Chukchi Sea, resulting in a decrease of primary productivity that was actually estimated from in situ measurements. As a source of heat, freshwater, and nutrients, the Pacific water that flows through the Bering Strait plays important roles in the sea ice and water mass distributions and ecosystem in the Chukchi Sea and the Canada Basin (e.g., Coachman & Barnes, 1961; Lin et al., 2019; Lowry et al., 2015; Nishino et al., 2011; Shimada et al., 2006; Spall et al., 2018; Steele et al., 2004, 2008; Timmermans et al., 2014, 2018; Woodgate et al., 2010).

In the Chukchi Sea, Danielson et al. (2020) found a significant summer and fall warming of 1.4 °C from climatological data over 1922-2018 (0.14 ± 0.07 °C decade-1), and over 1990-2018 the warming rate tripled to 0.43 ± 0.35 °C decade-1. They proposed a conceptual model that summarized the controlling feedback loop for the Pacific Arctic changes of heat content, sea ice, fresh water distributions, surface heat fluxes, and advective fluxes. Interannual variation in solar heating in the Chukchi Sea over 1999-2015 was examined by satellite-derived sea ice concentration and reanalysis of shortwave radiation (Tsukada et al., 2018). The result showed that solar heating during summer varied from 3.6 to 6.7 ×1020 J and was up to twice the northward heat flux through the Bering Strait. In Barrow Canyon, at the northeastern end of the Chukchi Sea, mooring observations have been carried out since the late 1990s (Itoh et al., 2013; Williams et al., 2014), and the data indicate a significant increase in Alaskan Coastal Water (ACW) temperature in the 2000s (~4 °C to 8°C). The ACW further spreads into the Canada Basin via Barrow Canyon. In addition to the Barrow Canyon throughflow, westward jets along the Chukchi shelf slope are identified with a subsurface warm water transport during winter toward the Chukchi Borderland (Watanabe et al., 2017). Anomalously warm water was found over the Chukchi shelf slope in winter 2016/2017 (Kimura et al., 2019). This warm water was likely derived from the Bering Sea via the Bering Strait and Barrow Canyon.

3.4 Changes in CAO hydrographic properties

3.4.1 Upper ocean layer

ontrasting regional responses to atlantification (related to progression of anomalies from the Atlantic sector) and pacification (associated with influx of anomalous Pacific waters). The analyses revealed strong salinification of the upper Eurasian Basin since 2000, with attendant reductions in stratification, and potentially altered nutrient fluxes and primary production. This was in contrast to the situation in the Amerasian Basin, which showed strong freshening, a thickening of the fresh surface layer, and a deepening of the nutricline and deep chlorophyll maximum. Thus, a divergent (Eurasian Basin) gyre responds altogether differently than does a convergent (Amerasian Basin) gyre to climate forcing (Polyakov et al., 2020a).

The decrease in sea ice contributes strongly to the freshening of the Arctic Ocean, especially in the Beaufort Gyre of the Canada Basin, as a result of freshwater accumulation (Proshutinsky et al., 2009; Wang et al., 2018). Proshutinsky et al. (2019) estimated an increase of more than 6,400 km3 of liquid freshwater content in the Beaufort Gyre from 2003 to 2018, a 40% increase relative

to the 1970s. If the freshwater is released to lower latitudes, it may impact sea ice conditions, ocean circulation, and ecosystems of the Sub-Arctic similar to the influence of the Great Salinity Anomaly observed in the 1970s.

Joint analysis of historical observations in the CAO (from 1950 to 2010) allowed Ivanov and Golovin (2019) to reveal multidirectional changes in the thermohaline parameters of the upper layer in the western and eastern parts of the Arctic basin in different seasons. In the Eurasian Arctic in the winter season, salinification and cooling of surface waters are happening, whereas in the eastern Arctic, to the contrary, there is strong desalination and a corresponding increase of water temperature. One of the main reasons for the desalination of surface waters in the eastern Arctic is a reduction in the area of perennial ice and its replacement by seasonal ice at the same time that riverine water discharge is increasing and there are changes in atmospheric circulation over the Arctic. The salinification of surface waters in the western Arctic is associated with an increase in the supply of saline Atlantic waters from the Fram Strait and their rise to the surface under conditions of increased seasonality of Arctic sea ice.

Significant 'seasonal memory', characterized by consistent change of the ice cover parameters in sequential seasons, was revealed in the Eurasian segment of the CAO (60-120°E, 65-80°N) between 2007 and 2017 (Ivanov et al., 2019). This interconnectivity was hypothetically explained by increased accumulation of heat in the upper layer under present conditions of depleted ice cover.

3.4.2   Halocline layer

The observed reductions in stratification in the Nansen Basin have also caused a weakening of the halocline in recent years (Polyakov et al., 2020b). This, in combination with shoaling of the Atlantic Water, has resulted in a substantial increase of upward oceanic heat flux from Atlantic Water during the winter season, from an average of 3-4 W/m2 in 2007-2008 to >10 W/m2 in 2016-2018 (Polyakov et al., 2020b).

Timmermans et al. (2014) explained the maintenance mechanism of a permanent halocline in the Canada Basin in terms of ventilation by Pacific summer water (PSW) from the Chukchi Sea. Thus, the recent warming and freshening of the Chukchi Sea (e.g., Danielson et al., 2020) could result in increasing trends in integrated heat and freshwater content in the halocline of the Canada Basin. Timmermans et al. (2018) estimated a near doubling of ocean heat content relative to the freezing temperature in the Canada Basin halocline over the past three decades (1987–2017). Pacific winter water (PWW) also spreads into the Canada Basin and forms a cold halocline (Jones and Anderson, 1986). Zhong et al. (2019) suggested that the thickening, deepening, and expansion of the PWW layer in the Canada Basin in recent years is associated with the enhanced and westward-shifted Beaufort Gyre.

The permanent halocline in the Canada Basin generally corresponds to the nutricline, the layer where nutrient concentrations increase rapidly with depth. Freshwater accumulation in the Canada Basin causes deepening of the nutricline (McLaughlin & Carmack, 2010) and can change phytoplankton community structure (Li et al., 2009), decrease phytoplankton production (Coupel et al., 2015), and weaken the biological pump (Nishino et al., 2011; Zhuang et al., 2018). On the other hand, the delay in fall freezing of the eastern part of the East Siberian Sea during the late 2000s compared with the early 2000s might have resulted in the formation of a large water mass through cooling and convection. The spread of this water into the southern Makarov Basin may have caused shoaling of the nutricline (Nishino et al., 2013). Shelf water in the western part of the East Siberian Sea, containing high nutrient concentrations, also spreads into the central Arctic Ocean, forming a shallower nutricline than that in the Canada Basin (Alkire et al., 2019).

These shallow nutriclines could create an advantage for phytoplankton production under decreasing sea ice conditions.

3.4.3 Intermediate and deep layers

Intermediate Atlantic water layer in the CAO experienced two warming episodes in 1990s and 2000s (Polyakov et al., 2005). After peak warming in 2005-2007 (about 1.5°C over the climate norm in the 'core' of this water mass), the temperature decreased, but has not returned to mean climate values. During the most recent 10 years the temperature in the warm 'core' has remained about 0.7-1°C over the climate norm, with seasonal and interannual variations (Baumann et al., 2018). Heat content in the Atlantic water layer (150-900 m) in the CAO continues to increase due to shoaling of the upper boundary of zero-degree isotherm (Polyakov et al., 2017), thus affecting upper layers and, hypothetically, ice cover as a result of weakened vertical stratification in the halocline (Polyakov et al., 2020b). Recent estimates show 2-4 times larger heat fluxes in 2014-2015 compared with 2007-2008. In the Canadian Basin, the maximum temperature of the Pacific Water layer increased by ~0.5°C between 2009 and 2013 (Timmermans et al., 2014), resulting in doubling of integrated heat content over 1987-2017 (Timmermans et al., 2018).

In the Nansen Basin, the Atlantic Water flow is manifested as a narrow slope current. Evaluating its impact and recent changes on the Arctic slopes, Bluhm et al. (in review) show that at the upper slope, climate change is currently manifested in sea-ice retreat, increased heat and mass transport by sub-Arctic inflows, surface warming, and altered vertical stratification, while the lower slope has yet to display evidence of change. Model projections suggest that ongoing physical changes will enhance primary production at the upper slope, with suspected enhancing effects for consumers. A Pan-Arctic monitoring effort of slopes is recommended given that many signals of climate change appear there first and are then transmitted along the slope domain (Bluhm et al., in review).

On the basis of long-term mooring observations in the eastern Arctic Ocean, Polyakov et al. (2020b) have proposed an emergence of new, more energetic state dominated by stronger currents and shear, leading to increased turbulent mixing and larger upward oceanic heat fluxes from intermediate Atlantic waters.

To assess interannual variability of the Atlantic water flow along the Eurasian continental slope Pnyushkov et al. (2020) analyzed observations at long term moorings in the Laptev Sea at five moored stations in 2013-2018. These observations revealed a lack of significant changes in the intensity of heat and water volume transports in this part of the Eurasian Basin, suggesting a steady regime of the slope current in the CAO despite substantial changes in ice cover.

No significant changes have been reported in the deep CAO waters in recent years.

Climate model projections suggest that throughout the 21st century the Arctic Ocean will gradually warm up from surface to deep layers (IPCC, 2019: Chapter 3). The basic mechanisms of this warming are presently acting processes and feedbacks, including: excess summer heating of open water areas, leading to additional ice melt, accelerated due to positive ice-albedo feedback. Rapid transformation of vertical hydrographic structure in the Western Nansen Basin (Ivanov et al., 2018) and in the Barents Sea (Lind et al., 2018) in the 2010s may indicate that IPCC scenarios underestimate the pace of this transformation.

3.5 Summary

After rapid decline between 1996 and 2007, summer sea ice extent remains fairly stable at -22 ± 8 per cent relative to the mean climatic norm for the available range of satellite observations (1979-

2019). The fraction of multiyear ice in CAO and Arctic seas decreased from 30% to 2% between 1979 and 2018; while the fraction of first-year sea ice increased from 40% to 70%. Ice thickness declined across the central Arctic by 65%, from 3.59 to 1.25 m, between 1975 and 2012. The speed of ice motion in the Transpolar drift (towards Fram Strait) roughly doubled between the end of the 19th century and the 2000-2010s.

The seasonal duration of open water has substantially increased in the Eurasian Arctic seas and on the margins of the deep ocean interior (continental slopes). In the Laptev Sea the ice-free season in individual years in the late 2010s reached almost three months. Excessive accumulation of heat in the upper mixed layer in summer started to noticeably affect first-year ice thickness, thus increasing the frequency of polynya events in mid-winter and leading to earlier ice breaking in spring. As a result, the area of winter ice thinner than 70 cm increased by 12 % compared with 1997–2003, while the area of thicker ice reduced by 18 %. On average, mean-weighted ice thickness in the Eurasian Arctic seas at the end of cold season decreased by about 40 cm (from 153 to 117 cm) from 1997–2003 to 2004-2018.

The Atlantic gateways to the Arctic Ocean are strongly influenced by vigorous flow of Atlantic Water, and currently the region is experiencing a greater role for the Atlantic inflows: the so-called "atlantification", which is manifested in a warmer ocean and atmosphere, loss of sea ice, northward and eastwards spread of Atlantic Water in the Barents Sea and the Nansen Basin, and changes in stratification and mixing in the upper ocean. Despite substantial long-term trends, the inter-annual variability in the Atlantic gateways to the Arctic is substantial, and since 2015/2016 the temperature in the inflowing Atlantic Water has decreased, while in the southwestern Barents Sea it remains similar to the early 2000s.

As a source of heat, freshwater, and nutrients, the Pacific water that flows through the Bering Strait plays important roles in sea ice and water mass distributions and ecosystem in the Chukchi Sea and the Canada Basin. The Bering Sea recorded unprecedented high sea surface temperatures in 2014 and the warm condition has persisted into 2019. Sea water in winter of 2017-2018 was exceedingly warm and late storms affected sea ice duration and extent, resulting in an unprecedented period of low Bering Sea winter ice. Anomalously warm water was found over the Chukchi shelf slope in winter 2016/2017. This warm water was likely derived from the Bering Sea via the Bering Strait and Barrow Canyon.

Opposing patterns of salinification/freshening in the upper water layer in different regions of the CAO due to ice melt, freshwater transport and saltwater input through the gateways is detected. Salinification generally happens in the Atlantic sector and freshening generally happens in the Pacific sector. Strong salinification is observed in the upper Eurasian Basin since 2000, with attendant reductions in stratification and potentially altered nutrient fluxes and primary production. In contrast, the Canadian Basin showed strong freshening, a thickening of the fresh surface layer, and a deepening of the nutricline and deep chlorophyll maximum.

Weakening of stratification in the halocline layer in the Nansen Basin in combination with shoaling of the Atlantic Water, has resulted in a substantial increase of upward oceanic heat flux from Atlantic Water during the winter season, from an average of 3-4 W/m2 in 2007-2008 to >10 W/m2 in 2016-2018. Recent warming and freshening of the Chukchi Sea could result in increasing trends in integrated heat and freshwater content in the halocline of the Canada Basin.

After a substantial increase (by about 1.5 deg C) in the early 2000s, intermediate Atlantic water in the CAO has remained at a higher (by 0.7-1°C) temperature than the climate norm of the second half of the 20th century. Interannual oscillations of Atlantic Water temperature around this elevated level are observed. Heat content in the Atlantic Water layer in the CAO continues to increase due to shoaling of the upper boundary of the zero-degree isotherm. A more energetic state of the intermediate water layer in the CAO is projected in future years. This new state will

be presumably supported by stronger currents and shear, leading to increased turbulent mixing and larger upward oceanic heat fluxes. In the Canadian Basin, the maximum temperature of the Pacific Water layer increased by about 0.5°C between 2009 and 2013, resulting in a doubling of integrated heat content over 1987-2017.

Climate model projections suggest that throughout the 21st century the Arctic Ocean will gradually warm up from surface to deep layers. The basic mechanisms of this warming are presently acting processes and feedbacks, including: excess summer heating of open water areas, leading to additional ice melt, and accelerated due to positive ice-albedo feedback.

3.6   Possible ecosystem implications

Currently observed and projected changes in sea ice properties (concentration, thickness, seasonality and drift) may affect primary production with possible impacts on ecosystems through changes in marine species composition, spatial distribution, and abundance.

The general trend of poleward retreat of sea ice cover provides better conditions for penetration of solar radiation in the water column. This will lead to better light conditions in the upper water column for longer duration, higher water temperatures and more intensive vertical mixing – all these factors positively influence primary production.

Expected expansion of winter polynyas may be significant for the early spring phytoplankton bloom. Downslope cascading of oxygenated dense water, originating in polynya zones, frequently triggers compensatory upwelling of nutrient-rich deep waters, thus making continental slope areas favorable for early blooms.

Ongoing "atlantification" in the Atlantic sector of the CAO may have several consequences for biological and ecological conditions in the affected areas (Barents-Kara seas and western Nansen Basin). Direct effects may be linked with northwards and eastwards expansion of the areal extent of Atlantic species. Indirect effect may be caused by a gradual shift of hydrographic conditions to sub-polar type, characterized by intensive vertical mixing in winter and an ice-free regime throughout the year with corresponding impacts on the entire ecological system.

Progressive freshwater accumulation in the Canada Basin causes a deepening of the nutricline and can decrease phytoplankton production. However, spreading of shelf-origin waters with high nutrient concentrations into the CAO may contribute to formation of a shallower nutricline in the adjacent deep basin than that in the Canada Basin, thus allowing relatively high phytoplankton production under decreasing sea ice conditions.

Contrasting changes in surface salinity in the Eurasian Basin (increase) and Canadian Basin (decrease) might have opposite effects on salinity-dependent species. In a general perspective, such changes might lead to opposite trends in vertical mixing in these basins, resulting in more favorable conditions for primary production (in terms of nutrient supply) in the upper water layer of the Eurasian Basin.

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4 ToR c. Continue to examine effects of climate change on the CAO ecosystem

4.1 Arctic microalgae

Contributers: Cecilie von Quillfeldt, Haakon Hop

4.1.1 General introduction

Arctic microalgae can be divided by their habitat; phytoplankton live suspended in the upper layer of the water column, while ice algae live attached to ice crystals, in the interstitial water between crystals, or associated with the underside of the ice. These two types of algae are composed of the same taxonomic groups with considerable overlap in species composition, depending on the area in question (Poulin et al. 2011, Bluhm et al. 2017, Lovejoy et al. 2017, Hop et al. 2020).

The high variability in the number of single-celled algae documented across the Arctic can be related to sampling effort in time and space. On the other hand, knowledge of algal 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). Close to 1276 sympagic algae and other protists associated with sea ice have been recorded (Bluhm et al. 2017) along with 2241 phytoplankton taxa (Lovejoy et al. 2017), dominated by large diatom and dino-flagellate cells that are relatively easy to identify through light microscopy.

While productivity estimates are critically important for understanding food web dynamics, knowledge of which species contribute to production and their size, function, phenology etc., is equally important (Bluhm et al. 2015).

A suite of environmental variables (e.g., sea ice, nutrients, light, water stratification, salinity, temperature) determine abundance, biomass, primary production and taxonomic composition through time (Poulin et al. 2011), but there appear to be ongoing climate-mediated changes in these parameters (von Quillfeldt and Smith 2016) which may have interacting effects on the food web of the CAO. The major changes identified for the ice-associated ecosystem are with regard to production timing and abundance, and biomass of ice flora and fauna, both of which are related to regional changes in sea-ice conditions (Barber et al. 2015). Some examples of reported possible changes in the CAO and adjacent seas are described below. How likely these changes are, and whether they are already ongoing in the CAO, along with possible consequences for the ecosystem, should be further investigated in the second report from WGICA.

4.1.2 Possible effects of climate change

Sea ice

Changes in sea ice (increased amounts of annual sea ice relative to multi-year ice, changes in extent and distribution, etc.) as a result climate change may have substantial effects on primary producers. Sea-ice can be an important driver of the taxonomic structure of protist communities in under-ice and epipelagic habitats of the central Arctic Ocean (Flores et al. 2019).

In general, increased amounts of **first year ice (FYI)** relative to **multi-year ice (MYI)** will influ-ence species composition in an area (Poulin et al. 2011, Bluhm et al. 2017, Hop et al. 2020). MYI is a unique habitat for sea ice protists, particularly diatoms (Poulin et al. 2011, Hardge et al. 2017). The decline in MYI in recent decades has already resulted in a decrease in sea-ice protist diversity in the Arctic Ocean (Hop et al. 2020). Furthermore, changing freeze-up scenarios, as currently witnessed in the Central Arctic, may result in long-term changes in the biodiversity of sea-ice protists, as cryopelagic species and pelagic species of both Atlantic/Pacific and Arctic origin are likely to increase in relative importance under the new Arctic sea-ice regime (Hop et al. 2020). Further,, Hardge et al. (2017) suggest that continued reduction of sea ice extent, and particularly of MYI, will likely lead to diminished protist exchange (e.g. between melt pond water, sea ice and under-ice water and deep-chlorophyll maximum water), which could reduce species diversity in all habitats of the Central Arctic Ocean.

A greater proportion of FYI may offer better growth conditions for ice algae during the shorter ice-covered period due to higher initial nutrient load and brine volume (Leu et al. 2015), but longer seasons of open water, particularly on Arctic shelves, have shifted production from ice algae to phytoplankton in water masses (Wassmann and Reigstad 2011, Barber et al. 2015) and moved the open-water production northwards (Renaut et al. 2018).

Decreasing sea ice extent and thickness may also influence timing of both ice-associated and pelagic algal blooms important for successful recruitment of pelagic grazer species (Søreide et al. 2010, Wold et al. 2011, Daase et al. 2013, Leu et al. 2015). Ecologically important species of the central Arctic Ocean rely significantly on carbon synthesized by ice algae (Brown et al. 2017). Due to the close connectivity between sea ice and the pelagic food web, changes in sea ice coverage and ice algal production will likely have important consequences for food web functioning and carbon dynamics of the pelagic system (Kohlbach et al. 2016; Flores et al. 2019).

Light

Altered light conditions (due to changes in thickness and structure of sea ice, the amount of snow on top of the ice, thawing/freezing, and the increasing length of the open water season), will affect primary producers in the ice and the water column. For example, thinner ice with relatively more snow results in a distinct algal community at the snow-ice interface when the ice becomes flooded (McMinn and Hegseth 2004, Fernández-Méndez et al. 2018). This algal community had previously been only rarely observed in the Arctic (Horner et al. 1992, von Quillfeldt et al. 2009). On the other hand, the sub-ice community, which used to have the high-est biomass in several areas, is less frequent (Eamer et al. 2013, Hop et al. 2020) but can still be observed within the Arctic Basin (Boetius et al. 2013, Hop et al. 2020). However, Boetius et al. (2013) found widespread deposition of ice algae on the ocean floor of the Amundsen Basin at depths of about 4 km in the record low-ice summer of 2012.

The impact of declining sea ice on Arctic sympagic production is large and complex, with con-sequent trophic and phenological cascades expected in the rest of the food web (Tedesco et al. 2019). Thinning sea ice is a factor affecting sympagic algae, and bottom communities develop earlier in the season because light penetration increases with decreasing ice thickness (Van

Leeuwe et al. 2018). Enhanced light availability may allow bottom sea-ice communities to reach higher biomass, though over a shorter period, as nutrients will be consumed more rapidly (Leu et al. 2015).

Overall, sea-ice communities show a high capacity for photoacclimation, but low maximum productivity compared to pelagic phytoplankton (Van Leeuwe et al. 2018). Species-specific mechanisms in coping with high light and high pCO$_2$ (which may reflect ecological niches) could therefore potentially alter the balance between sympagic and pelagic primary production in a future Arctic (Kvernvik et al. 2020). Furthermore, thinner ice and more leads increase light transmission leading to under-ice blooms of phytoplankton (Arrigo et al. 2012, Leu et al. 2015, Assmy et al. 2017). Earlier thawing and later freeze-up also results in a longer growth season for phytoplankton and may result in increased total primary production assuming other requirements (e.g. nutrients and stability) are in place (Arrigo and van Dijken 2015), and at the same time change the relative importance of ice algae and phytoplankton for total primary production in an area (Melnikov 2018). There are also likely to be regional differences in the extent to which primary production in the CAO is affected by climate change (Barber et al 2015). On a pan-Arctic scale, modeling studies indicate both decrease (Dupont 2012, Duarte et al. 2017) and increase in ice algal production (Matrai and Apollonio 2013).

Temperature and salinity

Warming and freshening of the ocean's surface layer due to increased temperature, freshwater runoff (and possibly more precipitation as rain in the ice-free season) may lead to increased stratification of the upper water column, which is likely to favour small species, (e.g. flagellates over diatoms), because they are more effective in acquiring nutrients and less susceptible to gravitational settling than larger species (Lie et al. 2009, Tremblay et al. 2012). Lower and less frequent downward export of biogenic particulate silicate (bPSi) has been observed during a warm anomaly period, also reflecting a shift in phytoplankton community composition towards dominance of small-sized phytoplankton under warmer conditions, but sea ice is a key factor influencing the frequency of export (Lalande et al. 2013). Small species have already become increasingly important in some areas of the Arctic (Sagen and Dalpadado 2004, Tremblay et al. 2012). On the other hand, some small species are specifically adapted to cold water and are likely to be vulnerable to surface-layer warming (Terrado et al. 2012). It has also been predicted that northward movement of Atlantic waters may replace cold-water phytoplankton with more temperate species (Hegseth and Sundfjord 2008, Harrison et al. 2013, Oziel et al. 2020). The effect of this for the CAO is uncertain, but a shift in phytoplankton community structure will have major consequences for carbon cycling and trophic transfer (Wassmann and Reigstad 2011).

Nutrients

Changes in nutrient supply (through mixing/importation/regeneration) will affect primary producers in the CAO. Nutrient concentrations in the upper polar mixed layer are relatively low due to the strong salinity stratification, which limits vertical mixing and upward transport of nutrients from deeper layers with higher nutrient concentrations (Tremblay et al. 2015). In

general, the nutrient concentrations in the upper layer are higher in the Eurasian Basin than in the Canadian Basin (Codispoti et al. 2013, Bluhm et al. 2015), and generally higher on shelves than in the CAO (Randelhoff et al. 2020). Increased freshening and warming of the surface ocean might amplify the permanent halocline and favor a regenerating community (Li et al. 2009).

The winter silicate concentration has declined during the last 20 years in the Atlantic water of the Norwegian and Barents Seas (Rey 2012). Such a decline can have significant consequences for ecosystems (e.g., changes in the spring bloom phytoplankton community due to a decrease in diatom biomass). How a reduced supply of silicate by ocean currents could affect the CAO is unknown, but there are indications that ocean currents are more important for nutrient supply than supply of nutrients from rivers (Holmes et al. 2012).

Concentrations of nutrients have implications for community structure and related primary production. Flores et al. (2019) showed that low-nutrient concentrations in the epipelagic and under-ice habitat of the Arctic Ocean were associated with increasing heterotrophy.

Deeper mixing of the upper ocean, due to less sea ice and an increase in atmospheric low-pressure systems that generate stronger winds, may result in extra nutrient supply supporting primary production if there still is a satisfactory light regime. However, also deeper mixing is likely to favor smaller species (Sakshaug 2004).

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4.2 Invertebrate ice fauna

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Arctic sea ice is habitat for sympagic or ice-associated organisms (Horner et al. 1992; Melnikov, 1997). The diversity of these organisms is largely dependent on the type and age of the ice (Hop et al. 2000; 2011). Habitat complexity ranges from a flat and uniform under-surface in newly formed landfast ice, (via relatively flat areas with brine channels in FYI), to three-dimensional and often very complex habitat in older MYI and pressure ridges of Arctic pack-ice (Hop et al., 2000). Multiyear sea ice provides a more stable and complex environment and therefore often harbors a more diverse community with higher abundance and biomasses (Arndt and Lønne, 2002). In FYI, ridges represent the most important structural habitat for ice-associated fauna, particularly during advanced ice melt (Gradinger et al. 2010).

4.2.1 Sea ice meiofauna

Sea-ice fauna assemblages live within or attached to the ice matrix and consist of bacteria and microbes, the meiofauna community (heterotrophs >20 µm) and ice macrofauna community (macroinvertebrates >0.5 mm) (Melnikov 1997). Ice sympagic meiofauna comprises multicellular organisms such as nematodes, harpacticoid copepods and rotifers, typically ranging from 20 to 500 µm in size (Gradinger and Ikävalko 1998; Gradinger et al. 1999; 2005). Single-celled ciliates are also included as meiofauna in some studies, but in others these are referred to as microfauna (<62 µm; Carey 1985; Bluhm et al. 2017b). In addition to ice-endemic species, both pelagic and benthic meiofaunal species occur in sea ice, often as larvae or juvenile stages. Meiofaunal species or stages settle in sea ice through active migration, are picked up from the water-column during ice formation, disperse from multiyear ice, or are recruited from resting stages (Carey and Mon-tagna 1982).

Besides adding to the biodiversity of the Arctic, many ice meiofauna taxa graze on the seasonally abundant and highly concentrated ice algae (Grainger and Hsiao 1990) that allow for high mei-ofaunal growth rates early in the season before the phytoplankton bloom develops (McConnell et al. 2012).

Meiofauna grazing does not appear to limit ice algal growth despite seasonally high meiofaunal abundances, (often with >200,000 meiofaunal individuals m-2 in landfast ice at peak times (Gradinger et al. 2009; Bluhm et al. 2017a)). The ingestion rates by multicellular meiofauna are estimated at <10 % of ice algal biomass (Gradinger et al. 1999; Michel et al. 2002). Such low grazing pressure may in part be related to the size of the brine channel system, mostly <1 mm in a given channel of solid ice, which may restrict some meiofauna from exploiting niches with high ice algal growth (Krembs et al. 2000). This restriction, however, rapidly changes during the onset of melt when the porosity increases above the percolation threshold of about 5 % brine volume fraction (Golden et al. 1998), and the brine channels connect so that organisms in the ice can move about.

Direct absorption of ice-produced dissolved organic matter has been suggested as an alternative feeding mode for sympagic nematodes (Tchesunov and Riemann 1995). Meiofaunal predators, in turn, appear to be rare (Bluhm et al. 2017b), perhaps due to space limitations within the brine channels and prey patchiness. Exploiting the sea ice as nursery ground can, therefore, be a winning life strategy for those organisms capable of living in this extreme environment due to the high concentrations of food and low predation pressure. During melt, ice-derived organic matter including ice meiofauna is released from the sea ice and provides food for pelagic and benthic biota (Moran et al. 2012).

Sea ice extent in the Arctic Ocean has declined by over 30% since the satellite record began in 1979 (Vaughan et al., 2013; Meier et al. 2014) and the reduction in sea ice has occurred during all months of the year (Barber et al. 2015). The average age of individual Arctic ice floes has decreased, changing from multiyear to mainly first- and second-year sea ice, and the thickness of Arctic sea ice has decreased by about 0.5 m from the 1980s to 2010s (Perovich et al. 2015; Bi et al. 2016). Multiyear sea ice, which covered about 75% of the Arctic in 1983, is currently limited to the areas north of Greenland, the central Arctic, and parts of the Canadian Arctic Archipelago, with as little as 62% of the summer ice cover remaining compared to 1978-1988 values (Maslanik et al. 2007; Stroeve et al. 2012; Meier et al. 2014). First-year ice has concomitantly increased in relative proportion and importance, although dates of its freeze-up and break-up have also shifted substantially (Markus et al. 2009), leaving large parts of the Arctic without sea ice for an increasing amount of time (Arrigo et al. 2011). Consequences for sea ice biota – from bacteria to polar bears – seem inevitable but are largely undocumented (CAFF 2017). Documentation of ice biota composition, abundance and natural variability is critical for evaluating responses to the decline in Arctic sea-ice.

Sea ice meiofauna has been known to occur for over a century (Nansen 1906), and its biodiversity has been documented at various levels (Poulin et al. 2011; Bluhm et al. 2017a, b). Distribution and composition of sea ice meiofauna have been reported from some locations in the Arctic, for example the Canada Basin (Gradinger et al. 2010), Beaufort Sea (Marquardt et al. 2011), Frobisher Bay in Arctic Canada (Grainger et al. 1985; Nozais et al. 2001), Hudson Bay (Grainger, 1988), and Fram Strait (Schünemann and Werner 2005). These studies documented both similar community patterns of ice meiofauna, such as likeness of taxa found at the class and phylum levels and concentration at near-bottom layers of the sea ice, as well as different levels of abundance and dominant taxa. The identified patterns and variations have locally primarily been related to different ice types (landfast, first-year and multiyear ice), seasons, hydrographic conditions, snow cover and sediment load (see Bluhm et al. 2017a for review). Pan-Arctic studies are rare, but a recent study by Bluhm et al. (2018) addressed taxonomic (phylum-level) composition and abundance of sea ice meiofauna at multiple spatial scales, ranging from the vertical distribution within a single ice core at a given location – to the pan-Arctic scale, and at a seasonal scale under landfast ice and pack ice conditions.

Landfast ice regions may be more important for meiofauna than the pack-ice regions. Meiofauna abundance was found to be 1-2 orders of magnitude higher in near-shore fast ice compared to MYI and FYI of both the Beaufort Gyre (median of 990 ind. m-2) and Transpolar Drift system pack-ice (11 180 ind. m-2) (Cross 1982; Kern and Carey 1983; Grainger and Hsiao 1990; Nozais et al. 2001; Gradinger et al. 2005). Meiofauna species are also largely allochthonous and may therefore be less affected by the loss of MYI, although Melnikov et al. (2002) observed a complete lack of sea-ice meiofauna, and also species poor under-ice fauna, in FYI and MYI in the Canadian Basin in October 1997- March 1998. Melnikov blamed the ongoing reduction in sea-ice extent and thickness for this striking difference from earlier studies (Melnikov 1997; Gradinger 1999). Gradinger et al. (2005), however, found a typical sea-ice meiofauna community in the same area in summer 2002. High spatial heterogeneity in sea-ice biota distribution and abundance, methodical differences and seasonal factors may explain this discrepancy.

Meiofauna abundance and ice algal biomass are positively correlated (Gradinger 1999), but the grazing rates of meiofauna are on the order of 1-6% of the ice algal production (Nozais et al. 2001; Michel et al. 2002; Gradinger et al. 2005). Similarly, low grazing rates on ice algal standing stock by ice amphipods in the Laptev and Greenland seas (3% d -1) suggest that food is not a limiting factor for ice-associated fauna (Werner 1997). Thus, changes in the onset and productivity of ice algae blooms may have little effect on ice fauna productivity.

4.2.2 Sea ice macrofauna

Sea-ice macrofauna is mainly comprised of ice amphipods, but also some polychaetes and the copepod Jaschnovia brevis (Gulliksen and Lønne 1991; Lønne and Gulliksen 1991b; Scott et al. 2002). Ice amphipods feed on ice algae, sympagic and pelagic fauna and detritus (Werner 1997; Poltermann 2001). The small gadid, polar cod (Boreogadus saida) is often associated with sea ice, where it feeds on ice-amphipods as well as pelagic amphipods and copepods (Lønne and Gulliksen 1989; Gradinger and Bluhm 2004; Hop and Gjøsæter 2013). Ice amphipods and polar cod (particularly the younger year-classes of polar cod, which can be found in drifting pack-ice) are important prey for marine mammals and seabirds feeding in the MIZ (Bradstreet and Cross 1982; Lønne and Gabrielsen 1992; Welch et al. 1992; Bluhm and Gradinger 2008).

Sea-ice fauna is comprised of authochthonous species that spend their entire life cycle associated with the sea ice, and allochthonous species that spend only part of their life in the ice and other parts in benthic or pelagic environments (Melnikov and Kulikov 1980; Gulliksen and Lønne 1991). The gammarid amphipods Apherusa glacialis, Gammarus wilkitzkii, Onisimus nanseni, O. glacialis and Gammarocanthus loricatus are regarded as true autochthonous sympagic species (Gulliksen 1984; Gulliksen and Lønne 1991; Lønne and Gulliksen 1991b). Some of these species are long-lived with life cycles up to 5-6 years and they feed on algae, fauna, and detritus derived from the ice community (Arndt and Swadling 2006; Werner et al. 2007). Gammarus wilkitzkii in particular, with life cycle duration of up to 6 years, has been associated with MYI, whereas Apherusa glacialis has a shorter life cycle (1-2 years), is more mobile and often associated with FYI (Lønne and Gulliksen 1991b; Beuchel and Lønne 2002). Ice amphipods are able to leave the ice for short excursions into the water column to relocate on neighbouring ice floes (Arndt and Lønne, 2002), but are otherwise largely dependent on the sea ice as a habitat.

The loss of sea ice for parts of the year will have a more detrimental effect on autochthonous species than on allochthonous species. Since long-lived amphipod species depend on persistent sea ice to complete their life cycles, regions where MYI is disappearing may be susceptible to loss of their populations. Observations from north of Svalbard, where MYI ice has decreased over recentdecades, indicate that there are indeed drastic changes in abundance with regard to the large G. wilkitzkii, and less for the smaller A. glacialis. Ice amphipod abundance has been variable, occasionally high (<60 ind. m-2) until the mid-1990's and then lower but variable (10-50 ind.

m-2) until 2005 (Bluhm et al. 2018). Abundance has been very low in later years (from 2010 on-wards) and difficult to sample quantitatively by scuba divers (methods in Hop and Pavlova, 2008). Correspondingly, the biomass has been variable, with high values (> 6 g m-2) until 1996, and then with 1-2 g m-2 until 2005, after which it dropped to very low levels, similar to the pattern in abundance. These results indicate that the sympagic community has declined. A , similar pattern was observed in the Pacific sector by Gradinger et al. (2010). They postulated that pressure ridges in FYI might be crucial for survival during periods of enhanced summer ice melt.

If summer pack-ice disappears in the Arctic Ocean, the sympagic macrofauna will likely vanish from Arctic drift ice, although there may be mechanisms for retaining ice amphipods in the pelagic system (Berge et al. 2012) or shallow water benthic system (Poltermann 1998).Increasing open water areas will likely cause reduction in the ice-associated autochthonous macrofauna as well as their main predators (Bradstreet and Cross 1982), with the exception of local regions in the western Arctic and shallow regions of the Arctic coast where perennial ice remains.

Reduction in ice will also decrease the southward transport of sympagic biogenic material on the European side of the Arctic. The annual biomass transport of ice fauna into Fram Strait and the Barents Sea is in the million-ton range (Wassmann et al. 2006; Hop and Pavlova 2008). There they are released to the pelagic system as the ice melts (Werner et al., 1999; Arndt and Pavlova, 2005). Hop and Pavlova (2008) calculated that 80×10^3 t C yr-1 is released to the pelagic and benthic ecosystem in the marginal seas, with 70% through Fram Strait and 30% into the Barents Sea. The reduction in this carbon export may have repercussions for the pelagic and benthic food webs in these regions. However, in shelf seas, the carbon import by ice amphipods is very low (0.3 %) compared to primary production (Wassmann et al. 2006).

4.2.3 Needs for research and monitoring

Sea ice is a species-rich habitat, and many sea ice taxa are widespread across the Arctic. Sea ice supports some species endemic to the Arctic, some species endemic to sea ice and other taxa that are more widespread. Ice biota generally copes with extreme conditions, although little is known about the tolerance limits and preferences of individual species in this habitat.

Ice amphipod abundance and biomass have declined in the Svalbard area since the 1980s. Amphipods appear to have been more abundant in the late 1970s to mid-1990s than afterwards.

The occurrence and distribution of ice biota is highly variable in time and space related to a suite of environmental conditions. Consequently, monitoring the biota of this variable habitat is challenging.

While no monitoring program currently exists for sea ice biota, various research groups around the Arctic have regular field activities involving select sampling as part of short-term funded projects. The accumulated knowledge base can serve as a baseline for monitoring of sea ice biota. However, monitoring requires coordinated plans for sampling at set locations, with consistent sampling and analyses to ensure comparability (Gill et al. 2011). For sea ice, standardized sampling techniques have, for example, been summarized by Eicken et al. (2009, 2014) and Miller et al. (2015). Consistent methodology is required for monitoring of ice biota. Available protocols need to be more widely implemented for monitoring. Monitoring should be standardized with regard to gear, collections, timing, sample preservation and processing, storage, and data management. A central receiving place as well as long-term funding for monitoring should be considered. Data should be deposited in existing databases and made available to researchers and beyond. Proper monitoring requires seasonal and annual field campaigns as well as sufficient, long-term financial support.

Most (but not all) sea ice sampling for ice biota living within the brine channels has been done using ice cores (methods described for example in Gradinger and Bluhm 2009). The thickness of the ice sections studied typically show high variation, depending on the goals of each study, time constraints and ambient ice thickness to name a few, resulting in different thickness horizons sampled (Hop et al. 2020). Often the bottom 0-4 cm or 0-10 cm were sampled (with 0 cm representing the ice-water interface), sometimes the bottom 20-30 cm and occasionally whole cores. As minimum, the bottom 10 cm of ice cores (which can be split into the lowermost 3-4 cm bottom ice and the next 6-7 cm of the core) should be sampled, because the bottom 10 cm often includes the majority of the biomass and abundance of ice biota (~65 % of ice meiofauna, up to 95% for algae based on the here compiled data sets). The CBMP Sea Ice Biota Expert Network also recommends the 10-30 cm section be included (separately) where feasible, as an average 12% of the meiofauna have been observed in this ice section. Microbes, particularly bacteria, are distributed ubiquitously throughout the ice column and are generally sampled in 10 -cm increments using sterile procedures to avoid contaminating the ice cores (e.g., Collins et al. 2010). Ice algal communities and biomass (chlorophyll a) are concentrated in the bottom few centimeters but have in some studies been determined in 20 cm sections up to the surface of the ice (e.g., Mundy et al. 2011). The need for sampling the entire ice column will depend on project goals, which may also include modelling aspects of biota in sea ice (Duarte et al. 2015).

Regarding the choice of taxa, communities or habitats to monitor, the studies reviewed have usually focused either on a sub-habitat (e.g., ice biota inside brine channels) or on a taxonomic group (e.g., ice meiofauna), a particular method (e.g., morphological taxonomy or genetic analysis), or a combination of the three. Ice biota has rarely been studied as a whole at a given location and time period. The Russian ice-drift studies have likely been the most extensive and comprehensive studies (Melnikov 1997), and there has also been coordinated sampling of ice biota and sea ice physics at some locations in Arctic Canada and Alaska (e.g., Ehn et al. 2011, Hop et al. 2011, Mundy et al. 2011), and more recently during the N-ICE2015 campaign by the Norwegian Polar Institute to the Arctic Ocean. The under-ice amphipod Gammarus wilkitzkii due to its association with MYI may be gradually replaced by the more pelagic, but also ice-associated amphipod Eusirus holmi, which is of similar large size as adult. Both amphipod species should therefore be monitored, since changes in their relative abundance may reflect changes in sea ice conditions.

Under-ice sampling has been more variable in approach. Regularly used tools have included (1) SCUBA-operated suction pumps (Lønne 1988), (2) under-ice in situ or surface-operated still photos (Mundy et al. 2007), (3) video in a fixed location or video transects (SCUBA diver or ROV operated) (Gradinger and Bluhm 2004), (4) under-ice traps (Nygård et al. 2012) and (5) under-ice trawl nets (David et al. 2016; approaches summarized by Gradinger and Bluhm 2009). The most quantitative samples appear to be based on SCUBA-operated sampling of squares with electrical suction pump (Hop et al. 2000) and the under-ice trawl net SUIT (van Franeker et al. 2009), as well as imagery with sufficient resolution.

Themain challenges for monitoring include the relatively low number of people working on sea ice biota and the loss of taxonomic expertise for groups such as ice algae and other protists, but also ice-associated fauna (e.g., meiofauna and ice-associated zooplankton). Another great challenge in attempting to monitor sea ice biota is the large variability of the dynamic sea ice habitat. Ice biota composition and abundance are, as detailed above, highly dependent upon light availability (modulated by day length, ice and snow thickness, sediments in ice, etc.), nutrient availability, temperature, salinity and location. These factors modify the habitat seasonally, even in the same place or the same ice floe. This variability, in combination with historic variability in sampling approach and timing, obscure potential temporal trends. Thus, actual changes in ice biota diversity and community structure need to be substantial enough to rise beyond the existing variability in order to be detected.

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4.3 Zooplankton in the Central Arctic Ocean, a linchpin to keep the system in place

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In a much warmer, continuously warming Arctic Ocean with receding sea ice and stronger stratification, the entire food web is affected. Zooplankton is at the center of these changes. Retreating sea ice, earlier ice break-ups, higher sea surface temperatures are all contributing factors operating in concert. There is already a fair amount of information on zooplankton; nonetheless, the limited access to the region due to the ice cover, and the continually changing ecology warrant a consolidated summary of newly collected information. The focus of this section is on recent and future studies. Below is a list of recent articles describing the zooplankton communities in the higher Arctic.

Wang et al (2019) describes the vertical and geographic distribution of copepod communities inlate summer in the Amerasian Basin. This study investigated species composition and copepod community structures by using geospatial and multiple depth scales, and by using multivariate analyses to evaluate the relationships between sampling stations and layers. During July–August 2010, zooplankton samples were collected with temperature and salinity data from three stations in the Canada Basin and two stations in the Makarov Basin of the Arctic Ocean (maximum distance of approximately 1400 km). A total of 55 copepod species (including 25 species that were solely identified to the generic level) and 7 taxa of copepodites were identified.

Significant differences were detected in copepod community structures among sampling strata and at geospatial scales. At the local scale, copepod compositions responded differently at each of the sampling stations. At the geospatial scale, the distance between stations MS03 and ICE explained variations in the pattern of dominant species and of copepod community richness. This study demonstrated varied spatial distribution which indicates that (1) the abundance of copepods at 0-200 m was significantly higher than at other strata, (2) vertical strata affected the distribution of copepod communities, and (3) the interplay of North Pacific and Atlantic waters is shaping the copepod assemblage structure at geospatial scales in the Arctic Ocean.

The influx and interaction of water masses from the Atlantic and the Pacific are certainly one of the principal factors governing zooplankton changes in the CAO, together with population interactions between shelf and basin. Gluchowskaet al (2017) examined interannual zooplankton variability in the main pathways of the Atlantic water flow into the Arctic Ocean by studying summer zooplankton standing stock and community structure in West Spitsbergen Current (WSC) branch and Barents Sea Opening (BSO) branch. Generally, there was a higher abundance and biomass of *Calanus finmarchicus* in the BSO than in the WSC, where *Oithona* spp. numerically dominated. The observed AW (Atlantic Water) temperature and volume flux modifications measurably affected zooplankton variability, with additional effects likely related to diverse

contributions of advected and local zooplankton production. The high abundances of *Oithona* spp. (predominantly *O. similis*) and *C. finmarchicus* were attributed to warm AW temperature anomalies. These results show the effects of warming on the zooplankton community transported with Atlantic water, before they enter the Arctic Ocean, and this finding will greatly assist the construction and tuning of the plankton components of ecosystem models.

Shelf-basin advection is also essential to the Arctic copepod population in the high basin area, especially for *Calanus hyperboreus*. Xu et al (2018) studied the abundance, population structure and body size of *Calanus hyperboreus* in pelagic layers over a large area of the western Arctic Ocean during summer 2003, in order to evaluate the geographical variation in recruitment pattern. *Calanus hyperboreus* was absent from the shallow areas of the Chukchi Sea and was most abundant in the slope area between the Chukchi Sea and Chukchi Abyssal Plain (CS-slope). These results indicate that *C. hyperboreus* can benefit from primary production increases through accelerated development in the first growth season, and the productive CS-slope area is a potential source for slope-basin replenishment.

There are different ways and mechanisms for warming to generate changes in zooplankton populations. Lower ice cover, early ice retreat and ocean warming can change various facets of the Arctic marine ecosystem, including the biogeographic distribution. Feng et al (2016) coupled a copepod individual-based model with an ice-ocean-ecosystem model to simulate temperature- and food-dependent copepod life history development, using *Calanus glacialis*. Model results agreed with commonly known biogeographic distributions of *C. glacialis*, which is a shelf/slope species that cannot colonize the vast majority of the central Arctic basins. Individuals along the northern boundaries of this species' distribution were most susceptible to changes in reproduction timing and early food availability (released sea ice algae). Early ice retreat and elevated ocean temperatures increased phytoplankton food and prolonged the growth season, creating favorable conditions for *C. glacialis* development, which fueled a remarkable poleward expansion of its distribution.

From a pan-Arctic perspective, despite the heterogeneity in the temperature and food regimes, common biogeographic zones could be identified from model simulations.

Kvile et al (2018) provided a good overview of how living under extreme and fluctuating environmental conditions is made possible by life history strategies such as multiyear life cycles, resting stages and capital breeding, using *Calanus hyperboreus* as an example. This study showed, from statistical analysis of compiled observational data, that abundances are relatively low and later stages and adults dominate in the CAO basins, indicating expatriation. They further demonstrated that the resilience of *C. hyperboreus* to environmental fluctuations enables its life cycle to be completed in the central Arctic basins, while the species can reach higher abundances in areas with greater food availability outside the central Arctic basins. Specifically, the energy level required to reach the first overwintering stage-a prerequisite for successful local production-is likely met in some-but not all-years. This fine balance between success and failure indicates that *C. hyperboreus* functions as a peripheral population in the central Arctic basins and its abundance will likely increase in areas with improved growth conditions in response to climate change. By illustrating a key Arctic species' resilience to extreme and fluctuating environmental conditions, the results of this study have implications for projections of future biogeography and food web dynamics in the Arctic Ocean, a region experiencing rapid warming and sea ice loss.

Lower ice cover in the CAO can affect the major zooplankton species by altering their reproductive ecology. But predation can offset the benefit of improved growth conditions. Darnis et al (2019) studied life cycle and reproduction of *Calanus hyperboreus* during a year of record low ice cover in the southeastern Beaufort Sea. Although vigorous reproduction delivered numerous eggs and nauplii N1-N3 early spring, subsequent CI copepodite recruitment, coincident with the phytoplankton bloom, was only modest in Amundsen Gulf. Consequently, *C. hyperboreus*

abundance and biomass stagnated throughout summer in the Gulf. A mismatch between the first-feeding stages and food was unlikely under the favourable feeding conditions. Rather, predation on the egg and larval stages in late winter probably limited subsequent recruitment and population growth. Particularly abundant copepods *Metridia longa* and *C. glacialis* were likely important consumers of *C. hyperboreus* eggs and nauplii. With the ongoing climate-driven lengthening of the ice-free season, intensification of top-down control of *C. hyperboreus* recruitment by thriving populations of mesopelagic omnivores and carnivores like *M. longa* may counteract the potential benefits of increased primary production over the Arctic shelves and margins for this key prey of pelagic fish, seabirds and the bowhead whale.

During the long Arctic winter, *Calanus glacialis* and *Calanus hyperboreus*, large and lipid-rich copepods dominating the zooplankton biomass in the Arctic Ocean, have been known to enter a form of resting stage called diapause, surviving on lipid reserves accumulated during the short growth season. In this way, copepod lipids can fuel the Arctic marine ecosystem, but information on the fine-scale distribution of copepods and lipids is scarce. Schmid et al (2018) showed that lipid load can trigger migration to diapause in Arctic *Calanus* copepods. They investigated the fine-scale (1 m) vertical distribution of the copepods *Calanus hyperboreus*, *Calanus glacialis* and *Metridia longa* during a Lagrangian drift in the North Water Polynya using the Light frame Onsight Key-species Investigation (LOKI) imaging system. Vertical distribution profiles and individual lipid loads suggested that individuals with lower lipid load continued DVM, while others with high lipid load ceased migrating, remaining at depth. A bioenergetics model showed that *Calanus* females had enough lipids to diapause for over a year, highlighting the significant lipid overhead they use for capital breeding.

Nonetheless, diapause at depth seems a facultative strategy, not a must. Kylie et al (2019) showed based on a large set of pan-Arctic observational data that Arctic *Calanus* has a rather broad depth distribution, not necessarily descending deep for diapause in winter. The larger *C. hyperboreus* has a deeper diapause depth than *C. glacialis*, potentially to alleviate predation pressure or as a result of predation loss near the surface. Moreover, the mean depth of *C. hyperboreus* in winter is negatively associated with latitude, indicating a shoaling of the diapause population in the central Arctic Ocean where predation pressure is lower. In the central Arctic Ocean where visual predation pressure is lower, copepods might be relieved from the incentive to descend and can remain closer to the surface in winter.

With ocean warming, borealization of zooplankton communities might be expected as a matter of natural course. With the reduction in sea ice cover, the Arctic species are likely to have already declined. There are now more studies available that have examined community changes along with documented physical changes. Møller and Nielsen (2020) analyzed a subset of 13 year data from Western Greenland, from the period 1992 to 2018, for trends in the key zooplankton genus *Calanus* during May and June in relation to physical conditions. In the 1990s, the small North Atlantic species *Calanus finmarchicus* and the two larger Arctic species *Calanus hyperboreus* and *Calanus glacialis* contributed equally to the copepod biomass. With the Arctic species having declined, *C. finmarchicus* currently dominates the biomass. Because of the species shift, the *Calanus* community is now dominated by smaller individuals and the lipid content of *Calanus* females during spring and summer has decreased by 34%. Moreover, during the last decade the annual variation in population size has been prominent, *Calanus* virtually being absent in some years. Because of the central role of *Calanus* in the Arctic food web, the changes will likely impact higher trophic levels, including fish, sea birds, and marine mammals.

A year-round study of the relationship between copepod phenology and environmental drivers is a challenge, particularly in the CAO where non-summer season sampling is more difficult. Tokuhiro et al (2019) offered the possibility of using a sediment trap to address this, although their work was from the Pacific Sector of the Arctic. Seasonal changes in the flux (abundance of

swimmers), population structure, lipid accumulation and gonad maturation of four dominant copepods (*Calanus hyperboreus*, *Metridia longa*, *Paraeuchaeta glacialis* and *Heterorhabdus norvegicus*) were studied. *C. hyperboreus* C6Fs were dominated by lipid-rich specimens year-round, and gonad development was observed from February to April, while the *M. longa* flux showed no clear seasonality. From generalized additive models, *C. hyperboreus*, *M. longa* and *P. glacialis* showed relationships with daytime length and/or sea ice concentrations, but the relationship patterns were different. The findings from this trap study were enough to imply that the response to changing environmental parameters could vary with species and that drastic sea ice reductions may affect the copepod phenology in the area.

The Central Arctic will almost certainly be subject to more human activities. One of the consequences of greater human activity is that natural light sources will in many places be masked by the much stronger illumination from artificial light. Berge et al (2020) showed that artificial light during the polar night can disrupt Arctic fish and zooplankton behavior down to 200 m depth. Normal working-light from a ship may disrupt fish and zooplankton behavior down to at least 200m depth across an area of >0.125 km² around the ship. Both the quantitative and qualitative nature of the disturbance differed between the examined regions. Biological surveys in the dark from illuminated ships may introduce biases on biological sampling, bioacoustic surveys, and possibly stock assessments of commercial and non-commercial species and this has ramifications for increased shipping in the future Arctic.

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4.4 Benthos in the CAO

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4.4.1 The seabed

The 3.3 million km2 Central Arctic Ocean (CAO, max. depth of 4,000 m) is divided into two primary basins by a submarine ridge of continental crust (the Lomonosov Ridge, 1,800 km long, 60-200 km wide, min. depth 954m) with steep slopes including canyon structures on each side (figure 4.1). The Amerasian Basin is divided into two unequal basins by the Alpha Ridge, a broad, rugged submarine mountain chain that extends to within 1,402 m of the ocean surface. The Makarov Basin lies between the Alpha Cordillera and the Lomonosov Ridge, and its floor is at a depth of 4,023 m.

The largest sub-basin of the Arctic Ocean is the Canada Basin which has a smooth basin floor interrupted by regions of sea knolls. The average depth of the Canada Basin is 3810 m. In the Canada Basin the sediment magnitude increases from the Chukchi Plateau (see also Mayer et al 2010) toward the Alaskan and Canadian margins with the MacKenzie River delta forming a massive sediment deposit of an estimated 15 km based on geophysical investigations. The Makarov–Podvodnikov Basin forms the second part of the Amarasian Basin and is bordered by the Lomonosov Ridge and the Alpha–Mendeleev Ridge. The Podvodnikov Basin (2,800m) is much shallower than the Makarov Basin (4,000m). They are both covered by a several km thick Cretacious-Cenoozoic sediment layer (Pease et al 2014).

Sediment cores and seismic reflection from the margin of the Lomonosov Ridge in the Lincoln Sea indicates that only a thin sediment cover (less than 50 m) overlies the basement. In the deep passage between the Lomonosov Ridge and the Lincoln Sea continental margin, more than 1 km of sediment is present (Mikkelsen et al., 2005). The rivers also discharge suspended sediment into the seabed. The CAO receives about 10% of the world's fresh-water discharge from the major Arctic rivers (MacKenzie, Yukon, Kolyma, Lena, Yenisey, and. The major part of the suspended sediment discharged from the rivers is deposited on the CAO seabed.

Speculation is ongoing regarding the possibility of exploring for resources in the area, not least because large natural gas reserves are believed to be beneath parts of the CAO's sea floor.
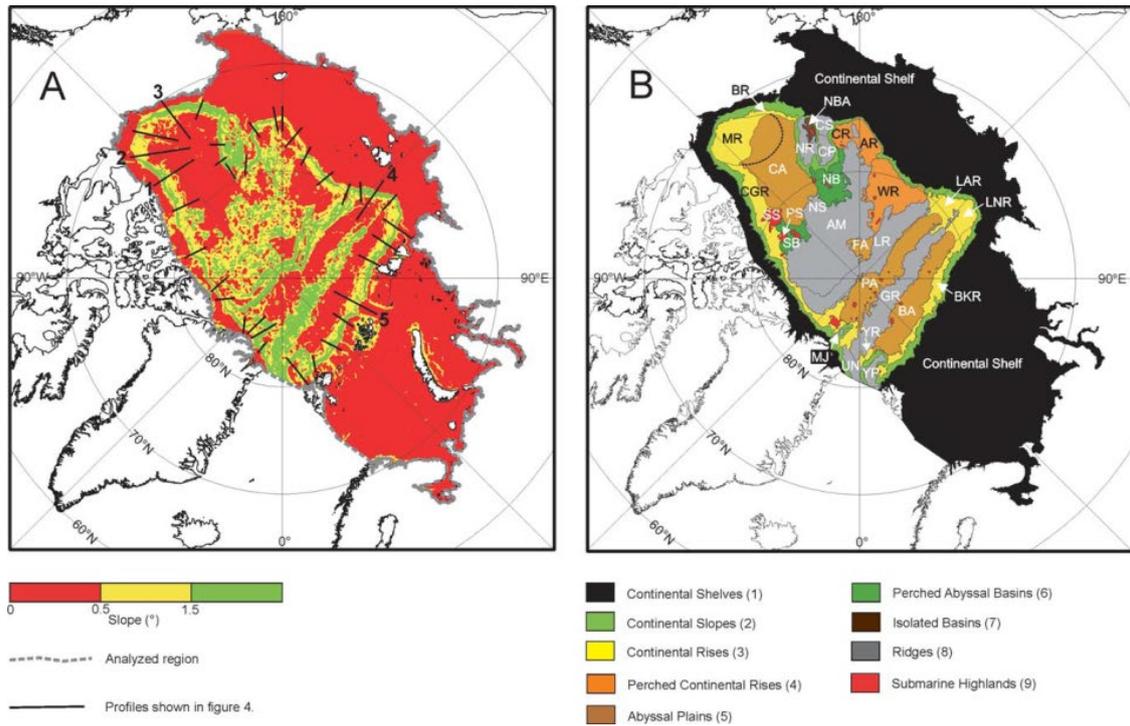
Figure 4.1. The basins of the Central Arctic Ocean (source: Jakobsson, M., Grantz, A., Kristoffersen, Y. and Macnab, R., 2003. Physiographic provinces of the Arctic Ocean seafloor. Geological Society of America Bulletin, 115(12), pp.1443-1455). Permission was granted by Geological Society of America Bulletin for use of the figure.

4.4.2 Bottom temperatures of the Central Arctic Ocean

The bottom temperatures of the Fram Strait Branch of Atlantic Water (T>0oC, 300-500m depth) show large interannual variabilities ranging from 0.4oC to 0.7oC during 2002 to 2018 (Figure 2 left).

The variability of Barents Sea Branch of Atlantic Water (T<0oC, 750-1250m depth) was small until 2016, when the bottom temperature increased up to 0.25 oC (Figure 4.2 middle).

The Deep Water (uniform temperature and salinity, deeper than 2500 m) shows a significant increasing trend of approximately 0.005 oC during the last 16 years in the Canadian Basin (Figure 2 right). This warming contributes significantly to the increasing heat content of the water column.

Further monitoring is needed to evaluate this recent warming trend.
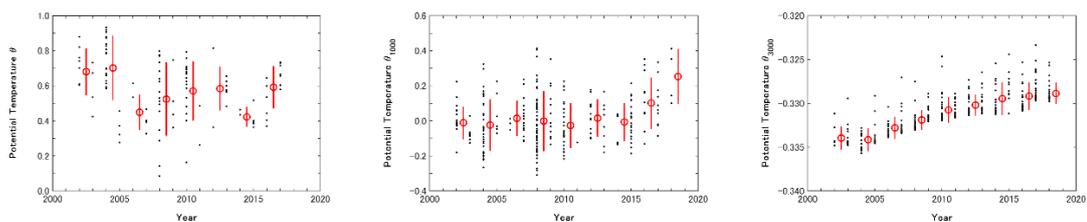
Figure 4.2. Interannual variabilities in bottom temperatures (left) Fram Strait Branch of Atlantic Water at 300-500 m, (middle) Barents Sea Branch of Atlantic Water at 750-1250 m and (right) Deep Water below 2500 m for 16 years (2002 to 2018).

Red open circles show 2-year averages. Red bars indicate standard deviation. (Source: Motoyo Itoh, Shigeto Nishino (JAM-STEC, Japan) and William Williams (IOS, Canada)).

4.4.3 Benthos

Restructuring of the benthic shelf ecosystem in the Arctic region is ongoing and likely to continue in the future (Waga et al 2020), though species expansions into the deep sea are unlikely in the Amerasian Basin given the confinement of Pacific-boreal taxa to the shelf and upper slope (Carey et al. , Ravelo et al. 2020). Atlantic-boreal taxa are already common in the Eurasian Basin (Bluhm et al. 2011, Dilman and Mironov 2011).

Half of the Arctic Ocean is deep sea (>1000 m), and this area is currently changing from being permanently ice-covered to being seasonally ice-free. Studies on sympagic, pelagic, and especially benthic organisms are crucially needed to get a better understanding for the interwoven ecosystem structures in the AO basins, including quantifying the intensity of carbon advection, benthic carbon production, as well as the downward carbon flux in the form of ice algae aggregates. This will help in predicting how changes in the sea ice, the primary production, and the grazer community may change the carbon supply to the benthos in the AO basins (Wiedmann et al 2020)– a system, which is today already affected by anthropogenic waste (e.g., microplastic, La Daana et al 2019).

Awareness is increasing that deep-sea benthic communities are not as homogenous as previously thought, and that 'special habitats' increase biodiversity and add heterogeneity; this finding also holds true for the CAO. Special habitats include seamounts housing unexpectedly rich sponge beds and associated benthic biota (Boetius and Purser 2017), fauna associated with the spreading of Gakkel Ridge including chemoautotrophic biota (Edmonds et a.l 2003; Bünz et al. 2020), fauna on other ridges such as the Alpha Ridge (Schewe 2001), glacial drop stones forming biodiversity islands (Mayer and Piepenburg 1996, Zhulay et al. 2019), a thin benthic boundary layer combining hyperbenthic and abysso-pelagic taxa (Zhulay et al. 2019, Raskoff et al. 2010), distinct density and biomass levels associated with the overlying marginal ice zone (Rybakova et al. 2019), and the more 'typical' meio- and macrobenthos in soft sediment (Paul and Menzies 1974, Kröncke 1994, Renaud et al 2006, Kröncke et al. 2000, Bluhm et al. 2011).

Lower slope and basin benthic community structure is distinct from upper slopes and certainly adjacent shelves. This is true for community structure based on taxonomic identity (Vedenin et al. 2019, Bluhm et al. in review); biogeographic affinity being dominated by Arctic-Atlantic and cosmopolitan fauna all across the basins versus more diverse affinities in shallower water (Mironov et al. 2013, Zhulay et al. 2019); and biological traits characterizing Arctic deep-sea fauna as generally (yet with substantial variation), comparatively small (though gigantism also exists), slow-growing, non-sessile (for epifauna), predatory or deposit-feeding (Iken et al. 2005, Wei et al. 2010, Zhulay et al. 2019).

Given lower overall densities of Arctic deep-sea fauna, sediment oxygen demand is on average one to two orders of magnitude lower in the Arctic basins than on adjacent shelves (Bourgeois et al. 2017, Wiedmann et al. 2020). Data on vertical flux, ice cover and incidental observations suggest carbon supply to the Arctic deep-sea floor covering this oxygen demand is highly variable in time, space and quality (and hence unpredictable and challenging to measure). Short-term events may include quick sinking of large clumps of fresh sea ice algae Melosira arctica (Boetius et al. 2013), increased flux through ballasting (Wollenburg et al. 2018) related to brief blooms (Menge and Nöthig 2020); their contribution to overall carbon flux may be substantial but needs quantifying. In addition, the overlying position of the marginal ice zone influences food availability (Rybakova et al. 2019), enhancing patchiness in flux.

4.4.4 Climate impact on benthos

There are no time series in the CAO. But observations from the HAUSGARTEN observatory in eastern Fram Strait can be used to get a proxy of what may happen in the CAO. Over an 11-year period (2004-2015) epibenthic communities at the seafloor were not static, but instead variable from year to year with no consistent community state (Taylor et al. 2017). Variation was, for example, particularly high for sea cucumber densities. Whether slight increases in Chl a in eastern Fram Strait in summer and in standing stocks of POC in the central AO over the period from 1991-2015 (Noethig et al. 2020) translated to changes in benthic stocks and communities is unclear.

On the Pacific Arctic shelves, there is evidence of declining benthic biomass in the decadal benthic times-series data in both the northern Bering Sea (Grebmeier 2012, Grebmeier and Cooper 2016, Grebmeier et al. 2018) and downstream through Bering Strait in the southern Chukchi Sea (Grebmeier et al. 2015b, 2018). In addition, over the last decade a northward shift in dominant macrofaunal biomass in the persistent northern Bering Sea hotspot south of St. Lawrence Island has been observed related to varying current patterns (Grebmeier and Cooper 2016, Goethel et al. 2018, Grebmeier et al. 2018). This northward shift in the distributional pattern of benthic species, and subsequent changes in community composition has also been recorded at places in the European Arctic (e.g., Svalbard Archipelago and Barents Sea; Kortsch et al. 2015, Jørgensen et al. 2017, Jørgensen et al 2019), including for commercial crab species (Fossheim et al. 2015).

4.4.5 Possible human activities impacting benthos

Characteristics of deep-sea organisms include increased longevity, slow growth rates, reproduction late in life and low fecundity (Carreiro-Silva et al., 2013; Levin et al., 2016; Danovaro et al., 2017b; Montero-Serra et al., 2018). These life history strategies mean that many deep-sea species have an increased sensitivity to human activities such as mining, fisheries and climate change. Much of the Arctic deep-sea floor has until now experienced only a weak human footprint, but a predicted ice-free summer in the Arctic in the near future may change that situation, thus an up-to-date inventory is urgently needed given the last one is a decade old (Bluhm et al. 2011).

4.4.5.1 Pollution and Plastics

Litter in the Arctic (HAUSGARTEN observatory in the Fram Strait, 2500 m depth) has increased from 3635 to 7710 items km2 between 2002 and 2011 and reached densities similar to those reported from a canyon near the Portuguese capital Lisboa (Bergman et al. 2012), with a strong increase in marine litter over the period of 2002–2014 (Tekman et al. 2017). Plastic constituted the majority of litter (47 - 59%) followed by a black fabric (11%) and cardboard/paper (7%). Sixty-seven percent of the litter was entangled or colonized by invertebrates such as sponges (41%) or sea anemones (15%). Litter densities were positively correlated with the counts of ships entering harbor at Longyearbyen, the number of active fishing vessels and the extent of summer sea ice. Sea ice may act as a transport vehicle for entrained litter, releasing it during periods of melting.

There are also indications of a widespread occurrence of high numbers of microplastics (42–6595 microplastics kg−1) at the HAUSGARTEN observatory (Bergmann et a.l 2017). The northernmost stations harbored the highest quantities, indicating sea ice as a possible transport vehicle. The authors postulate that a positive correlation between microplastic abundance and chlorophyll a content suggests vertical export via incorporation in sinking (ice-) algal aggregates. Overall, 18 different polymers were detected. Chlorinated polyethylene accounted for the largest proportion (38%), followed by polyamide (22%) and polypropylene (16%). Almost 80% of the microplastics were ≤25 μm. The microplastic quantities are among the highest recorded from benthic sediments. This 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.

4.4.5.2 Bottom fishing

Most of the CAO is too deep for demersal fisheries. Fishable depths are identified on the Chukchi Borderland (Figure 4.3) and impact on the seabed-fauna is therefore currently unlikely and will most likely be restricted to the Chukchi Plateau of the CAO with depths of 480-2000 m. Here, research suggests taxon richness, biomass and density of epifauna decrease with depth and communities markedly differ between basin and plateau/ridge (Zhulay et al 2019). Echinodermata (e.g. *Ophiopleura borealis*, *Elpidia* sp., and *Pontaster tenuispinus*) and Arthropoda (e.g. *Bythocaris* sp.) dominate the overall taxon richness here. Polynoid annelids and sponges were characteristic taxa of the basin stations. Epifaunal densities were estimated of up to 14,346 individuals and 906 g wet weight /1000 m². The lack of Arctic deep-sea data restricts the evaluation of biological responses to large-scale change in the Arctic environment. In order to provide adequate answers concerning how Arctic deep-sea ecosystems will change, long-term observations are needed also in the Amerasian sector of the Arctic deep sea.
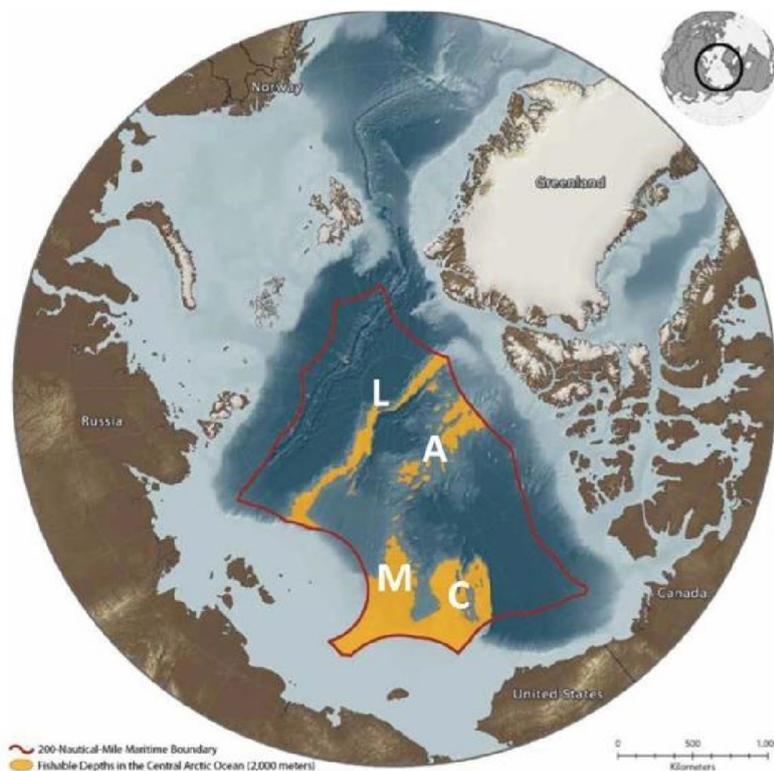
Figure 4.3. Map of the Arctic region showing the High Seas (red line) and the shallower parts of the High Seas (yellow area) that may be more "fishable" than the deep basins. L = Lomonosov Ridge, A = Alpha Ridge, M = Mendeleev Ridge, C = Chukchi Plateau. (Source: Adapted from **PEW map based on fishable depths derived from IBCAO v3 bathymetry (www.ngdc.noaa.gov/mgg/bathymetry/arctic***).*

4.4.5.3 Deep-sea mining

(https://www.iucn.org/resources/issues-briefs/deep-sea-mining) (https://www.isa.org.jm/about-isa)

A concern of many marine scientists is that the mining industry will progress to large-scale extraction without the implementation of adequate measures to avoid significant environmental

harm (Levin et al., 2016; Niner et al., 2018). Seabed mining will damage the marine environment for many centuries (Van Dover et al., 2017). At hydrothermal vent systems, chemosynthesis can play a large role in providing nutrients to deep-sea benthic communities (Sweetman et al. 2013). Even if restoration is part of the wider management of seabed mining, it is highly unlikely that biodiversity will fully recover (Jones et al., 2018).

Direct impacts occur through the removal of target material and associated organisms within the mine site and include the destruction of biota as well as habitat loss, fragmentation, and modification through altered mineral and sediment composition, geomorphology, and biogeo-chemical processes (Ellis, 2001; Van Dover, 2014; Jones et al., 2017). It also includes the smother-ing of habitat and biota, interference with feeding activities, and the release and spread of nutri-ent-rich and toxin-laden water from the generation of plumes (Ellis, 2001; Boschen et al., 2013). The scale over which these indirect impacts are likely to occur is largely unknown and most of the effects remain unstudied (Van Dover, 2014; MIDAS, 2016).

This vulnerable nature of deep-sea environments to mining impacts, currently limited techno-logical capacity to minimize harm, significant gaps in ecological knowledge, and uncertainties of recovery potential of deep-sea ecosystems means that the industry cannot at present deliver an acceptable outcome (Niner et al. 2018).

4.4.5.4   Oil exploitation
(https://atlantic-community.org/petroleum-resources-of-the-arctic-ocean-a-broken-promise/)

Around 22% of the world's undiscovered oil and gas resources is in the Arctic, most of it offshore. The areas of the Eurasian Basin, Amerasian Basin and Lomonossov-Makarov are thought to house an estimated 13.5% of undiscovered Arctic oil reserves, 5 % of total gas and close to7% of total barrels of combined oil and oil-equivalent natural gas (Bird et al. 2008). This assessment means the potential for oil and gas exploration in deep areas exists, though is not considered immediate. However, ongoing and northward moving exploration on shelves may indirectly affect CAO areas also. Russia, Norway and the US have ongoing oil and gas extraction in their Arctic territories   (https://atlantic-community.org/petroleum-resources-of-the-arctic-ocean-a-broken-promise/).

In the south western Barents Sea, drill cuttings released around wells have caused changes in sediment quality and ecosystem structure with partial recovery 15 years after drill cuttings re-leases (Dijkstra et al. 2020).

Effects of drilling discharges are generally limited to within 1 km from the platform but have been observed to impact up to 1.2 km away and impacts persist for at least 6–8 years. Impacts were undetectable in the areas where cuttings (Henry et al 2017).

After oil spills, marine snow on the sediment affects organisms and can be a vector for introduc-ing oil into the food web. Amphipods shows a dose-dependent decrease in survival while gas-tropods were only affected by the highest concentration of oil-contaminated marine snow (van Eenennaam et al 2019).

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4.5 Fish in the Central Arctic Ocean having to cope with unprecedented warming

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In a rapidly warming Arctic, fish populations are faced with major challenges, as are other components of the ecosystem. Receding sea ice, earlier ice breakups and higher sea surface temperatures are contributing factors operating in combination. Fish biodiversity throughout the diverse habitats of the Central Arctic Ocean (CAO) has yet to be explored in detail, and future research is needed.

Since the last update, however, relevant studies are steadily accumulating. Polar cod and Arctic cod, (*Boreogadus saida* and *Arctogadus glacialis)* are known to occur and are likely to be the main forage fish for the apex predators of the CAO. How warming of the Arctic Ocean and the loss of sea ice will affect fish communities of the CAO will depend on several factors, for example the effect on recruitment. A number of studies have been conducted not quite inside the CAO but on the same or related species in nearby waters and are thus highly relevant.

Bouchard et al. (2017) examined, in Canadian coastal waters, whether earlier sea ice break-up and warmer sea surface temperatures (SST) in spring-summer led to higher recruitment of juvenile polar cod, *Boreogadus saida* in late summer by enabling early hatchers to survive and grow larger by late summer. The density (number m^{-2}) and biomass (mg m^{-2}) of age-0 polar cod in August and September, estimated by hydroacoustics over 9 years in 9 areas of the Canadian Arctic, were negatively correlated with ice break-up week and positively correlated to SST. Ice breakup, in some areas, has occurred earlier by as much as 9.3 days per decade since 1979.

Bouchard et al. project an increase in polar cod biomass, at least transiently, over the first part of the present century. Whether this will be sustained is not clear, however. It is possible that the ongoing migration of sub-Arctic and boreal forage fish northward in response to the moderation of extreme climatic conditions in the Arctic may cause the replacement of the hyper-specialized cod species. If that were to happen, cascading impacts would be expected on the unique pelagic ecosystems and biodiversity of the CAO.

LeBlanc et al. (2019b) investigated whether, apart from a longer growth season, an earlier ice breakup can also provide superior feeding conditions for young polar cod, *Boreogadus saida* by enhancing microalgal and zooplankton production over the summer months. Earlier breakups resulted in earlier phytoplankton blooms. Zooplankton backscatter in August increased with earlier breakup and bloom and plateaued at chlorophyll a > 1 mg m^{-3}. Juvenile cod biomass in August increased with earlier breakup and plateaued at a zooplankton backscatter > 5 m^2 nmi^{-2}, supporting the hypothesis that higher food availability promotes the growth and survival of age-0 fish in years of early ice melt. Intense avian predation could explain the lower biomass of juvenile cod in the polynya complex, which is known to be a biological hotspot for energy transfer to higher trophic levels.

There are other aspects to the question of how changing sea ice (with a static photoperiod) will impact planktivorous fish in a future Arctic Ocean. Climate change will drive fish and plankton species toward the poles, but the distribution of fish may also be governed by less acknowledged mechanisms. For example, ice limits access to air for physostomous fish filling their swim bladders at the surface. Kaartvedt et al. (2018) hypothesized that reduction of ice constraints may facilitate northward expansion of physostomes, with implied impacts on their zooplankton prey. On the other hand, even in a changing Arctic, the extreme high-latitude photoperiod will persist.

The abundance of mesopelagic fish is low in the Arctic Ocean. Feeding conditions may be inferior during the darkness of winter and in bright summer nights. If the photoperiod is constraining distribution, biogeographic boundaries of mesopelagic fish may be relatively unaffected by climate change. Alternatively, if low temperatures are the main constraint, it is hypothesized that northward extensions in a warmer ocean may be detrimental to key Arctic copepods if their current success relates to low mortality during overwintering in the absence of mesopelagic fish. It is therefore critical to distinguish the effects of light at high latitudes from those related to temperature in assessing future biogeographic boundaries.

Salinity change associated with sea ice melt can also impact early life stages of Arctic fish species by changing the dispersal potential of marine organisms, salinity change can do so for most fish species, if not any. Spencer et al. (2018) examined whether loss of sea ice and salinity changes associated with warming in Alaskan waters have a strong effect on the distribution and survival of eggs and larvae of key fish species at the Pacific-Arctic interface, such as polar cod (*Boreogadus saida*) in the Chukchi Sea and walleye pollock (*Gadus chalcogrammus*) in the northern Bering Sea. Laboratory experiments were conducted to investigate how changes in ontogeny and salinity influenced the buoyancy and survival of eggs and larvae of these and two other gadids (Pacific cod, *Gadus macrocephalus* and saffron cod, *Eleginus gracilis*). Polar cod egg density varied among family groups, but eggs were more buoyant than those of walleye pollock overall. After hatching, polar cod and walleye pollock larvae were similar in density and were notably more buoyant than the larvae of species with demersal eggs (Pacific cod and saffron cod). Larvae of the two Arctic species (polar cod and saffron cod) were less sensitive to salinity challenges than the sub-Arctic gadids, but polar cod became more sensitive at 6 weeks post-hatch. These results highlight possible adaptations of polar cod to ensure that their eggs are positioned under or near ice after spawning so that larvae hatch in productive surface waters during ice break-up. The synergistic effects of environmental variables on vertical distribution of eggs and their survival potential

will be important biogeographic mechanisms to consider with climatic warming and continued loss of sea ice.

The pan-Arctic population structure of polar cod can provide insights as to how the species may respond to environmental change and allow for establishment of meaningful management units. Nelson et al. (2020) examined the population genetic structure of *Boreogadus saida* by analysing nine microsatellite DNA loci in 2269 fish collected at 19 locations across the species' range. Genetic differentiation was detected ($FST = 0.01$, $p < 0.01$), in concordance with geography.

A Canada East group consisted of fish collected from Resolute Bay to the Gulf of St. Lawrence. The Canada West group contained specimens from the Canadian Beaufort Sea and Amundsen Gulf. The Europe group contained specimens from the Greenland Sea, Iceland and the Laptev Sea, and a US group consisted of specimens collected in the North Bering, Chukchi and Western Beaufort seas. Very little genetic differentiation was detected within the identified groups. Physical distance, geophysical structure and oceanography all appeared to have the potential to influence levels of genetic divergence. The population genetic structure is likely to be important for the response of *B. saida* to environmental change and should be considered in management of human activities that may impact this foundational species.

Characterizing the condition of fish in dynamic seasonal environments requires an understanding of their energy allocation strategies. Varying energy sources for the early life stages of fish in relation to prey organisms is also an important aspect associated with Arctic Ocean warming. Copeman et al. (2020) examined the ontogenetic patterns in lipid and fatty acid biomarkers of juvenile polar cod (*Boreogadus saida*) and saffron cod (*Eleginus gracilis*) from across the Alaska Arctic, as changes in lipid allocation could have important implications for overwintering survival as well as energetic value for predators. A combination of laboratory and field approaches was employed to describe allometric relationships in lipid storage of polar cod and spatial patterns in field-caught juvenile gadid condition were explored in consecutive years. Lipid density in wild juvenile Arctic gadids increased with size leading into the first overwintering period, but age-1 + fish showed a reduction in lipid density with size prior to the 2nd overwintering period. Fatty acid biomarkers from the total lipid pool indicated that polar cod have a higher reliance on calanoid copepods than saffron cod. Collectively, these data suggest polar cod as well as saffron cod will likely respond differently to regional warming depending upon the shift in zooplankton communities, such that the energetic contribution of these fish to higher trophic levels could be transformed with ocean warming in coming decades.

With the CAO becoming more accessible and hence subject to enhanced human activities, fish populations will also have to deal with a number of new circumstances they have not experienced before. Several recent studies on CAO fish species may be relevant, although not necessarily undertaken inside the CAO.

Increased human presence in and close to the CAO will mean a higher plastic pollution load, and plastic litter is among the recently recognised stressors in Arctic ecosystems. With increasing human activity, plastic ingestion may act as an increasing stressor on polar cod in combination with ocean warming and sea-ice decline in peripheral regions of the Arctic Ocean. Any ingestion at any trophic level will go up the food web with cascading effects.

Kühnet et al. (2018) investigated the plastics in the stomachs of juvenile polar cod (*Boreogadus saida*), one of the key species in the Arctic ecosystem. The stomachs of 72 individuals collected both directly from underneath the sea ice in the Eurasian Basin and in open waters around Svalbard were analysed. Two stomachs contained non-fibrous microplastic particles. According to µFTIR analysis, the particles consisted of epoxy resin and a mix of Kaolin with polymethylmethacrylate (PMMA). Fibrous objects were excluded from this analysis to avoid bias due to contamination with airborne micro-fibres. Based on the two non-fibrous objects found in polar

cod stomachs, it was shown that ingestion of microplastic particles by this ecologically important fish species is possible. To fully assess the significance of this stressor and its spatial and temporal variability, future studies will need to apply a rigorous approach to avoid secondary contamination.

Increasing Arctic shipping will definitely affect the behaviour of fish and influence the underwater soundscape. Anthropogenic noise associated with shipping has emerged as a major disruptor of aquatic animal behavior worldwide. The Arctic marine realm is no exception, and indeed may be more vulnerable in that it has historically experienced little noise-generating human activity.

Ivanova et al. (2019) used a combination of acoustic telemetry and modeling of ship noise to examine the temporo-spatial habitat use of a key arctic forage fish, polar cod (*Boreogadus saida*), in the presence and absence of vessels in Resolute Bay, Canada, a high latitude Arctic embayment. The presence and movement of vessels induced a horizontal shift in the home ranges of Arctic cod with low core overlap when compared to periods without vessel activity. Results indicate that Arctic cod perceive vessel noise and presence as a threat and react by moving away and decreasing exploratory activities. These changes in fish behavior also coincide with the critical open water feeding period, suggesting an interruption in exploitation of important and seasonally abundant food resources, and carry broader implications for dependent seabirds and marine mammals, and indirectly for all Arctic indigenous peoples' subsistence and long-term cultural traditions.

The soundscape is an important habitat feature for marine animals, and sea ice loss and increased human activity may cause large changes to the Arctic marine soundscape. Halliday et al. (2020) examined the marine soundscape over eight months near Ulukhaktok, Northwest Territories, Canada, and assessed the relative contribution of the geophony (wind and wave sounds), biophony (marine mammal and fish sounds), and anthrophony (noise from vessel traffic). Sound pressure levels (SPL) were significantly higher during the summer than during the autumn and winter, and these differences were caused by increased wind/waves and vessel traffic in the summer. Increased wind speed drove increased SPL, while increased ice concentration resulted in decreased SPL. When vessel traffic was closer, SPL was higher. Overall, the marine soundscape near Ulukhaktok varied greatly through time and may be prone to large changes in the future as the ice-free season continues to lengthen and more vessels travel through the region.

With the disappearance of sea ice that provides refuge for many fish and zooplankton species, the interaction between forage fish and top predators will likely respond. LeBlanc et al. (2019a) tested the hypothesis that thick-billed murre (*Uria lomvia*), northern fulmar (*Fulmarus glacialis*) and black-legged kittiwake (*Rissa tridactyla*) congregate in areas of high polar cod food abundance and low ice concentration at different spatial scales across the marginal ice zone in Baffin Bay. At a large spatial scale (western versus eastern Baffin Bay), thick-billed murre, northern fulmar and their polar cod resource proxy were generally more abundant on the western ice-covered side of Baffin Bay. No clear spatial match was found, however, when comparing seabird abundances and their food-resource proxy in different ice concentrations across the marginal ice zone or at small scale (5 km). A lack of schooling behavior and a successful strategy to avoid predation by hiding under the ice could explain the absence of any strong spatial match between polar cod and its seabird predators at these different scales.

It will be important for the CAO ecosystem and marine living resources management to synthesize results from observations, laboratory experiments and models to showcase how the integration of scientific methods and indigenous knowledge can improve our understanding of (a) past and projected changes in environmental conditions and marine species; (b) their effects on social and ecological systems in the respective communities; and (c) support management and planning tools for climate change adaptation and mitigation.

Steiner et al. (2019) used an integrated approach by linking climate-ecosystem-economic (CEE) models for the key forage fish *Boreogadus saida* and subsistence fisheries in the western Canadian Arctic and discussing uncertainties within those models by changing "this" to "an", it will be a general, beginning statement. Arctic cod can be trophically linked to sea-ice algae and pelagic primary producers and are key vectors for energy transfers from plankton to higher trophic levels (e.g., ringed seals, beluga), which are harvested by Inuit peoples. Fundamental changes in ice and ocean conditions in the region affect the marine ecosystem and fish habitat. Model simulations suggest increasing trends in oceanic phytoplankton and sea-ice algae with high interannual variability. The latter might be linked to interannual variations in Arctic cod abundance and mask trends in observations. CEE simulations incorporating physiological temperature limits data for the distribution of Arctic cod result in an estimated 17% decrease in Arctic cod populations by the end of the century (high emission scenario) but suggest increases in abundance for other Arctic and sub-Arctic species. Uncertainties remain with respect to detailed future changes, but general results are likely correct and in line with results from other approaches. This makes a case for the involvement of Arctic communities both in monitoring and decision making and illustrates the need for a precautionary and adaptive approach.

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4.6 Marine mammals in the CAO

11 species of marine mammals in the Northern hemisphere may be considered ice dependent based on the criterion that maximum population size is recorded in areas with at least seasonal sea ice cover. This list comprises seven species of pinnipeds (ringed seals (*Pusa hispida*), bearded seals (*Erignatus barbatus*), harp seals (*Pagohilus groenlandicus*), hooded seals (*Cystophora cristata*), spotted seals (*Phoca largha*), ribbon seals (*Histriophoca fasciata*), and walrus (*Odobenus rosmarus*), three species of whales (bowhead whales (Balaena mysticetus), beluga (*Delphinapterus leucas*), and narwhal (*Monodon monodon*), and polar bears (*Ursus maritimus*). Detailed descriptions of distribution, biology and population history of these species are found in the upcoming report 1 of WGICA.

All of the listed species have been observed in the CAO. In addition, some more temperate large pelagic-feeding cosmopolitan species like blue whales (*Balaenoptera musculus*), fin whales (*Balaenoptera physalus*), humpback whales (*Megaptera novaeangliae*) and minke whales (*Balaenoptera acutorostrata*). are increasingly observed off northern Svalbard during summer (Storrie et al. 2018). The same species are found in the North Pacific, but are rarely north of the Bering Strait (Moore et al. 2019). Pacific endemic gray whales (*Eschritius robustus*) are more commonly found in the Northern parts of the Chukchi Sea and Southern Beaufort Sea, but are not observed or expected to move off the shelf because they are primarily benthic feeders (e.g. Iwahara et al. 2016, Moore et al. 2019).

Based on current knowledge, the slopes and high seas of the CAO appear to be relatively scarcely populated by marine mammals. However, with increasing sea temperatures, the importance of the CAO may increase, especially for ice dependent species in adjacent areas. The importance of the WGICA focus area for any species can therefore only be adequately assessed if information on population status in adjacent areas is also taken into consideration. Updated summaries of known effects of climate change and other anthropogenic pressures on ice dependent marine mammal species observed in the CAO are given below.

4.6.1 Ecological Effects of Climate Change

4.6.1.1 Walruses
The community of ice dependent marine mammals in the Pacific Arctic region is dominated by benthic-feeding species, including a population of around 200000 walruses (Lowry 2016a, Beatty et al. 2019), which has been severely affected by reduced ice cover in their summer feeding habitat in the Chukchi Sea. Female pacific walruses (*Odobenus rosmarus divergens*) depend on the sea ice over shallow waters as a platform for nursing their calves and resting between feeding bouts. Over the past decades, the summer ice cover has retreated faster to deep waters off the shelf, where female walruses cannot successfully combine feeding and nursing (McCracken 2012). This has led to increased calf mortality due to abandonment on the ice or trampling and predation at crowded terrestrial haul-outs (Cooper et al. 2006, McCracken,2012). Panics leading to stampedes may be caused by human disturbance or polar bear attacks (Garlich-Miller et al. 2011).

Ovsyannikov (1995) described intensive harassment of walrus by polar bears on Wrangell Island in 1990, which was a year with severely reduced availability of sea ice haulouts. Numerous attacks were made by polar bears, but the direct success rate was low. Such attacks may, nevertheless, increase the mortality rate of walruses due to stampedes or stress/exhaustion and make them easily available for scavenging bears (Ovsyannikov 1995). Cases of killer whale predation on Pacific walruses have also been reported by Russian scientists and Alaska natives (Fay 1982; Kryukova and Kochnev 2014). Of 52 walrus carcasses washed ashore on St. Lawrence Island in 1951, 17 (33%) were estimated to have died from injuries consistent with killer whale predation (Fay 1982). Passive acoustic data collected from 2009 to 2016 in the southern Chukchi Sea showed an increase in the occurrence of killer whale vocalizations over time (Stafford 2018). Killer whale calls were detected every year and with increasing frequency in fall months (September - November). The earliest signals were detected in early June and the latest in November. Incidental sightings of killer whales have been reported since the 1950s, but the majority of reported sightings are from the period 2008-2015 and are primarily made in areas far offshore in the Northern Chukchi Sea. Reduced sea ice cover also weakens the benthopelagic coupling in the Chukchi Sea leading to reductions in the benthic prey base for walruses (Grebmeier et al. 2015). Walruses may diversify their diet and forage partly on pelagic species including seals and birds (Seymour et al. 2014, Clark et al. 2019), but movement studies have so far not indicated significant feeding off the shelf of the CAO (Jay et al. 2012). Surveys in the Eastern Chukchi Sea corroborate this finding (Kuletz et al. 2015). Very little is known about the ecology of the Laptev Sea population of pacific walruses, but they are generally reported to be rather stationary within polynyas on the Laptev Sea shelf (Spiridonov et al. 2011).

Atlantic walruses (Odobenus rosmarus rosmarus) in the Atlantic gateway area only number in the low thousands and appear to be slowly recovering after historical hunting pressures (Lydersen and Kovacs 2014, CAFF 2017). Due to low densities, calving and nursing in terrestrial summer haul-outs are likely not associated with significantly increased mortality in the East Greenland -Franz Josef Land area (Lydersen and Kovacs 2014). Telemetry data are available for males in these areas and show strong association with coastal waters during the summer feeding period and heavy ice during winter (Freitas et al. 2009). None of the available data, however, suggest significant use of waters off the slope of the CAO. Diet data show a predominantly low trophic benthic diet, but some individuals also feed on birds and mammals (Fox et al. 2010, Lydersen and Kovacs, 2014). Feeding on higher trophic levels is a strategy that could allow some walruses to forage from summer haul-outs on the ice edge in the CAO, but so far this does not appear to happen. A possible hint of more pronounced non-benthic feeding in walruses may, however, be suggested by the observed wintering of Atlantic walrus males on thick ice over relatively deep waters in the Barents Sea (Freitas et al. 2009). The males are not feeding during winter, but they are courting females, which are believed to be feeding during winter.

4.6.1.2 Bearded Seals

Bearded seals are generally considered benthic feeders, but they can also adopt more pelagic feeding strategies in areas with high availability of fish (Hindell et al.2012, Hamilton et al. 2018) and/or significant competition with other benthic feeders like walruses (Lowry et al. 1980).

Pacific bearded seals (*Erignatus barbatus nauticus*) tagged along the coast of the Eastern Bering and Chukchi Seas appear to aggregate in the Bering Strait region during winter and adopt a more northern distribution during summer, but few animals appear to use the slope areas of the CAO and Beaufort seas as summer feeding areas (Citta et al. 2018, Cameron et al. 2018). Bearded seal vocalisations have, however, been recorded year-round over the slope of the southern Beaufort Sea (MacIntyre et al. 2014). Call activity increased with the formation of pack ice in the winter and peaked in April-June, coinciding with the mating season. Mating usually occurs at the end

of a 3-4 week lactation period, suggesting that pupping may take place in this pack ice habitat. Studies of bearded seals harvested in the Bering and Chukchi Seas over the recent period of declining sea ice cover have not found clear signs of a shift towards a more pelagic prey composition (Crawford et al.2014). Biological parameters like residual length, blubber thickness and proportions of pups have also not shown any significant relationship with ice cover (Crawford et al. 2014). A decline in age at maturity by 1.6 years has, however, been observed along with an increased proportion of pups in the harvests, indicating increased postweaning reproductive success (Crawford et al. 2014).

In Svalbard, Atlantic bearded seals (*Erignatus barbatus barbatus*) have responded to a dramatic decline in fjord ice by pupping and nursing on small pieces of calved glacier ice. Estimates of pup survival, growth and condition has not changed between periods of contrasting ice conditions (Kovacs et al. 2020a). Bearded seal pups swim with their mothers within hours from birth and are thus much more robust than other arctic seal pups (Hamilton et al. 2019). At few months of age, they may dive down to 300m. Juveniles continue to dive deeper than adult seals during their first year, possibly due to competition with adult seals in the more lucrative shallow waters. Bearded seals may haul out on land, but so far, have not been observed to pup and nurse on land. As fjord ice and glaciers retreat from the coast, ice may therefore become a limiting factor for bearded seals in several of their current pupping areas (Kovacs et al. 2020a, McCracken et al.2012). Based on the general affiliation of bearded seals with shelf waters, it seems unlikely that pack ice over deep waters of the CAO could be used as pupping areas, but little visual survey data are available from these and other pack ice areas during the pupping period.

4.6.1.3 Ringed seals

Ringed seals have a circumpolar distribution with little genetic structure (Lowry 2016b, Martinez-Bakker et al. 2013). Tagging studies have nevertheless suggested pronounced female philopatry in some areas (e.g. Kelly et al. 2010) providing some stability to management units. Few estimates of ringed seal abundance are available, but the total population in the circumpolar Arctic is thought to number at least 1.4 million in the circumpolar Arctic (Lowry 2016b). They are the single most important prey of polar bears in throughout their range (e.g. Wiig et al. 2015). Due to their small size, ringed seal pups require snow cover for insulation for several weeks after birth (Lydersen and Kovacs 1999). Successful breeding therefore requires stable snow -covered ice, where ringed seal females can dig out a cave under the snow with underwater access through a hole in the ice beneath. These caves also offer protection from visual predators like gulls and to some extent polar bears and arctic foxes (Lydersen and Smith 1989).The breeding habitat must, however, also offer feeding opportunities for the female during the 6-7 week long lactation period (Lydersen and Kovacs 1999). The size of the foraging range of lactating females during winter has been found to vary in response to thickness of ice cover, which could be driven by changes in prey distribution (Harwood et al. 2015). Ringed seals are known to be able to maintain breathing holes in ice up to 2 meters thick, but the extra effort needed for maintaining holes in thick ice could also affect the foraging range. During the past decades of increasing temperatures in the Arctic, suitable pupping habitat has become scarce in many areas, including the west coast of Svalbard, where landfast ice has almost ceased to be formed in fjords that were previously prime breeding habitat (Lydersen et al. 2014). The degree to which, the pack ice area of the CAO is used as a breeding substrate is currently unknown. Pack ice breeding is, however, known to occur in the Barents Sea and eastern Canada (Finley et al. 1983, Wiig et al. 1999).

During the summer and fall feeding period, subadult ringed seals tagged in western Svalbard migrate to the ice edge to the north of Svalbard in summer (Hamilton et al. 2015), while adult ringed seals generally remain in Svalbard coastal waters (Hamilton et al. 2016). The increasingly long summer migrations of subadult ringed seals are expected to reduce their energy balance and potentially their growth rates and life-time reproductive output (Hamilton et al. 2015).

Glacial fronts are highly productive and appear to be a preferred habitat for ringed seals staying close to land (Lydersen et al. 2014, Weslawski et al. 1994). Ringed seals have, however, also been observed and sampled along the ice edge in the Barents Sea (Wathne et al. 2020). For these samples, occurrence of krill and amphipods in gastrointestinal tracts was almost as high as for polar cod, but a strong preference was shown for the latter (Wathne et al. 2000). Diet studies in western Svalbard in the 1980s also found a higher preference for fish (mainly polar cod but also some redfish (Sebastes spp) than for pelagic crustaceans (mainly Pandalus spp and amphipods) (Weslawski et al. 1994). Mysids were not eaten although they were abundant and of high energy density. No substantial changes in ringed seal diets around Svalbard were found by Labansen et al. (2007) during the period 2002-2004 or Bengtsson et al. (2020) for the period 2014-2017. So far no diet data are available for the pack ice areas of the CAO.

In the Pacific gateway region, the main breeding areas of ringed seals appear to be located close to the Bering Strait on both sides, with some breeding also occurring along the North Slope and in the Amundsen Gulf region bordering on the Southeastern Beaufort Sea (Kelly and Quakenbush 1990, Kelly et al. 2010, Citta et al. 2018). Surveys in the post breeding season for ringed seals in the Chukchi Sea showed highest densities in the southern areas and densities were expected to decline further towards the East, due to much lower overall productivity (Bengtsson et al. 2005).

Long term data series of ringed seal vital rates are available from the eastern Beaufort Sea and Amundsen Gulf area and offer insights to effects of environmental change on growth and reproductive rates. One data series uses a growth index based on relative thickness of cementum growth layers in teeth from ringed seals killed by polar bears (Nguyen et al. 2017. These data showed a general negative trend in body growth over the period 1965-2007. Among candidate ice-related explanatory variables, only timing of ice break-up was retained in the final model (Nguyen et al. 2017). This parameter was, however, only available from 1992. Galley et al. (2016) did not find any trend in timing of sea ice break-up over the period 1983-2014, but a significant linear decline in date of break-up was found by Harwood et al. (2020) based on local data for the eastern Amundsen Gulf. The significant effect of break-up time was, however, due to reductions in growth index in years with late ice break-up. These years also coincided with years of reduced ovulation rates of ringed seals in the Amundsen Gulf area (Harwood et al. 2012). In a later study based on an extended data series, Harwood et al. (2020) found a decline in blubber depth over the period 1991-2019 in both males and females. Ovulation rates were generally around 100 % but showed episodic reductions to 60-70% and even 40% in years of unusually late ice break-up. The ovulation rates correlated well with observed proportions of pups of the year in the summer harvest, which is a more reliable indicator of recruitment. The declines in blubber depth may suggest a negative trend in energy balance, but a similar trend is not seen in asymptotic lengths, which increased slightly for both males and females between the periods 1991-2011 and 2012-2019 (Harwood et al. 2020). Estimated age at first pregnancy was also lower in the latter period by 0.5 year. The effects of ice conditions on the fitness of ringed seals in the eastern Beaufort Sea area therefore appear to be complex.

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 in this study spent winter in the Bering Sea, but appreciable numbers also stayed in the southern Chukchi Sea (Von Duyke et al. 2020). Crawford et al (2014) found significant increases in body growth rate and blubber thickness of harvested ringed seals with reduced sea ice cover in the Bering and Chukchi Seas between the periods 1975-84 and 2003-2012. Ringed seals also matured 2 years earlier in the latter period and there was an increase in the proportions of pups in the harvests (Crawford et al. 2014). Both growth of young

seals and the proportion of pups in the harvest were significantly negatively correlated with ice concentration. Diet studies over the same period showed a considerable increase in occurrence of fish species, particularly rainbow smelt (*Osmerus mordax*) and a decline in the occurrence of invertebrates, including the sympagic *amphipod Gammarus wilkitzkii* (Crawford et al. 2014). Polar cod, however, remained the dominant prey item across the sampling periods.

4.6.1.4   Ribbon seals and spotted seals

Satellite telemetry shows that some ribbon seals summer on the northern slope of the Chukchi Sea, where they may forage on several hundred meters depth (Boveng et al. 2013). Based on available evidence, however, the number of ribbon seals using this area appears to be small. The capacity for deep diving, however, suggests that ribbon seal could potentially increase their use of the waters off the shelf. Spotted seals are found in the Northern Chukchi Sea in summer, but appear to stay on the shelf (Citta et al. 2018). Abundances of these Pacific species in the Bering Sea area have been estimated at about 180000 for ribbon seals (Conn et al. 2014) and about 460000 spotted seals (Conn et al.2014).

4.6.1.5   Harp seals

Harp seals have both been observed in low numbers in the pack ice areas on the slopes of the CAO close to the Atlantic gateway (Haug et al. 2017) and may be potential prey for polar bears in the area. It is assumed that only harp seals from the Northeast Atlantic populations enter the CAO, as the access from to the CAO for the Northwest Atlantic populations is much more restricted.

The Barents Sea/White Sea harp seal population pups on ice in the White Sea and moults in a larger area also including the southern Barents Sea (Sergeant 1991). During spring they migrate through the Barents Sea to the edge of the sea ice (Nordøy et al. 2008). During the past decades, the summer ice edge has retreated from the Barents Sea to areas north of Svalbard (Hamilton et al. 2015). Harp seal diets along the ice edge during summer and autumn is mainly comprised by krill and amphipods but also some polar cod and capelin (e.g. Wathne et al. 2000, Lindstrøm et al. 2013). The increased distance to the ice edge may have played a role in the 50% reduction in pup production of Barents Sea/White Sea harp seals since 2003 (ICES, 2019). No pup production surveys have been conducted since 2013, but projections of previous data estimates current abundance at 1497189 (SD=104209) (ICES, 2019).

Harp seals from the Greenland Sea population breed and moult in pack ice areas off Northeast Greenland during spring and then embark on a feeding migration towards the Northeast along the ice edge into the Fram Strait, Barents Sea and to some extent also the waters north of Svalbard (Folkow et al. 2004, Haug et al. 2017). This population was estimated at 426 808 (SD =58 063) in 2018 (ICES, 2019). Studies within the Greenland Sea have shown diets dominated by amphipods, polar cod and some capelin (Haug et al. 2004, Enoksen et al. 2017). During winter, both harp seal populations typically switch to a more fish dominated diet close to the pupping area (Haug et al. 2004, Nilssen et al. 2000). Pup production of Greenland Sea harp seals also declined by 50% in 2018 compared to previous surveys over the period 2002 to 2012 (ICES 2019), but it is not yet known if this was just a single bad year. Over the past decades, killer whales have been observed to prey on harp seal pups from the Greenland Sea area (Foote et al.2013). The overall extent of this behavior is unknown but currently not thought to be extensive (Jourdain et al. 2019).

4.6.1.6   Hooded seals

Hooded seals are known to occur in low numbers in the pack ice areas on the slopes of the CAO close to the Atlantic gateway (Folkow et al. 1996, Haug et al. 2017). These seals likely belong to the Greenland Sea hooded seal population, which breeds and moults on the pack ice off northeast

Greenland. This population is currently on a historically low level of about 76 623 individuals (SD=9348) (ICES, 2019). A dramatic decline by about 80% occurred from the 1940s to the 1980s for this stock, probably due to overexploitation (Øigård et al. 2014). The lack of recovery after full protection since 2007 is, however, likely related to environmental changes. Increased predation from polar bears may be part of this explanation, but likely not all (Øigård et al. 2014).

Hooded seals forage over continental slopes of the northeast Atlantic during most of the year (Folkow et al. 1996, Folkow et al. 2010, Vacquie-Garcia et al. 2017a). A satellite-tracked pup of the year has even been tracked to the North Pole (Vacquie-Garcia et al. 2017a). Hooded seals are deep diving specialists foraging on a wide range of prey including arctic species like polar cod, the squid *Gonatus fabricii*, Greenland halibut and redfish (Folkow and Blix 1999, Enoksen et al. 2016). Three observations of vagrant hooded seals were made in the Beaufort Sea between 1970 and 1975 underlining the dispersal potential of this species (Burns and Gavin, 1980). Reductions in sea ice cover in the CAO should facilitate this type of dispersal, but no cases appear to have been recorded recently. It has, however, been noted that outbreaks of phocine distemper virus among marine mammals in the Pacific Arctic region have been caused by virus strains spread from the North Atlantic, presumably by a live vector (VanWormer et al. 2019).

4.6.1.7   Polar bears

Polar bear neonates only weigh about 0.7 Kg and depend on an insulating maternity den of snow for several months after birth in mid-winter (Blix and Lentfer 1979, Spady et al. 2007). Dens are generally dug into snow drifts on land but denning on sea ice is also observed in the Beaufort and Chukchi Seas, the CAO and off the coast of North Greenland (Laidre et al. 2020). Reproducing polar bear females may spend up to 7 months fasting in the den (Rode et al. 2018). Growth and early survival of the suckling cubs are therefore highly dependent on maternal resources accumulated prior to denning (Robbins et al. 2012, Rode et al.2014) as well as resource availability immediately after emergence. In all of the world's 19 subpopulations of polar bears, choice of denning habitat and timing of emergence appears to have evolved to ensure access to ringed seal pups for the lactating females. Still, there are important ecological differences between subpopulations and habitats, also among the 8-11 subpopulations bordering on or situated in the CAO (e.g. Regehr et al. 2016). An important habitat characteristic is whether sea ice is divergent or convergent i.e. retreating from land during summer or available close to land all summer (Amstrup et al. 2008). Both of these regimes are represented in the Pacific and Atlantic gateway regions (see Fig.1). These are also among the most intensively studied areas with respect to polar bears and their interactions with physical, biological and anthropogenic elements of the Arctic ecosystem.

The Southern Beaufort Sea polar bear subpopulation is known to den both on land and on sea ice. Some of the recorded den locations are far off the shelf and located within the CAO (see Fig.2). Rode et al. (2018) found that survival was higher among cubs born in dens on land than in dens on sea ice over the period 1985–2013. Part of this difference was explained by longer denning duration, later emergence from dens and thicker snow cover on land-based dens. Some of these factors may, however, also have been influenced by prey availability prior to denning, which is thought to be greater close to shore than at the sea ice edge (Rode et al. 2018). In the southern Beaufort Sea in particular, bowhead blubber and carcasses left on the shore by hunters may imply a nutritional advantage to bears summering on land (e.g. Atwood et al. 2016, Olson et al. 2017). Both behavioural studies and stable isotope analyses confirm that shore-based bears use this resource to a considerable extent (Olson et al. 2017; Ware et al. 2017). The carcasses are shared with grizzly bears, which appear to be dominant when both species are present (Miller et al. 2015). Summer habitat is tightly linked to the choice of denning habitat. Olson et al (2017) found that all tagged females summering along the shore also denned on land and 61% of the females summering on the sea ice denned on the ice.

Between the periods 1985-1995 to 1996-2006, the proportion of Southern Beaufort Sea polar bears denning on sea ice declined by 20 % and then remained stable up to the end of the study in 2013 (Olsen et al. 2017). An average abundance of 907 (95% CI = 548 – 1,270) individuals was estimated for the Southern Beaufort polar bear population over the period 2001-2010 (Bromaghin et al. 2015) The decline in sea ice denning coincided with retreat of the sea ice and a decrease in the availability of multiyear ice preferred for denning (Fischbach et al. 2007, Olson et al. 2017). It also coincided with a decline in pup survival (Bromaghin et al. 2015) and several reports of nutritionally stressed bears in the sea ice habitat (Cherry et al. 2009, Rode et al. 2010). Polar bear survival returned to previous levels after 2006, but the proportion of females denning on sea ice has not changed (Rode et al. 2014, Olson et al. 2017). The females that do den on sea ice tend to do so further north, probably because availability of suitable multiyear ice has decreased in the southern areas (Olson et al. 2017). Significant differences in activity budgets and diets have been found between females summering on land and along the ice edge of the Beaufort Sea (Rogers et al. 2015, Olson et al. 2017, Ware et al.2017). For example, more than half of the female polar bears summering in coastal areas of the Beaufort Sea visited bowhead carcasses on the shore and likely fed on whale blubber (Ware et al. 2017). Analyses of fatty acid composition of 569 polar bears from 2004-2012 show high seasonal variability in prey composition and better condition among adult males and females that had fed on bowhead carcasses in one or more seasons (McKinney et al. 2017). Coastal polar bears also preyed more on bearded seals during summer and autumn (McKinney et al. 2017). Overall, alternative prey types like bowhead whales, seabirds, bearded seals and beluga whales have made up about 50% of the diets of polar bears in the Southern Beaufort Sea from 2004-2014 (Bourque et al. 2020).

A separate polar bear subpopulation resides in the northeastern Beaufort Sea (=Northern Beaufort Sea subpopulation, PBSG 2019) but there is some overlap in distribution with the Southern Beaufort Sea population and the geographic delineation of these subpopulations is currently being revised (Stirling 2002, PBSG 2019). The habitat of the Northern Beaufort Sea subpopulation is classified as a convergent ice region (PBSG 2019), but the sea ice transport into this area by the Beaufort gyre is highly variable (Galley et al. 2016). In the past decade mainly annual ice has been present and the open water season has increased (Galley et al.2016). Polar bears from the Northern Beaufort Sea subpopulation den both on land and on sea ice (Stirling et al. 2002), but less is known about trends in habitat use for this subpopulation than for the Southern Beaufort Sea subpopulation. Polar Bears from the two subpopulations tagged over the period 1970-1998, partly overlapped in summer distributions in the Amundsen Gulf, but Northern Beaufort Sea polar bears were more prone to using the northern and eastern areas overlapping the harvesting areas of the ringed seals studied by Harwood et al. (2020) mentioned in the previous section. Stirling et al. (2011) estimated the abundance of Northern Beaufort Sea polar bears over the period 2000-2006 at 980 ± 155 (mean and 95% CI) and this estimate has not since been updated. This subpopulation is, however, expected to be in decline (PBSG 2019), due to indications of poor body condition and very few observed polar bears in previous high use areas (PBSG, 2019).

A third Pacific region subpopulation of polar bears is found in the Chukchi Sea. Based on mark-recapture data collected 2008-2016, the abundance of this subpopulation has been estimated at 2937 95% CI = 1552-5944 (Regehr et al. 2018) in the American part of their distribution range. A similar number may be found on the Russian side based on surveys of denning areas in the 1980s (Belikov, 1993). In spite of increased rates of sea ice retreat, the body condition of Chukchi Sea polar bears was improving or stable between the periods 1986–1995 and 2008–2013 (Rode et al. 2014). This may be because suitable ice for hunting did not completely disappear from the productive shelf waters during spring and summer. Increased condition of ringed seals reported by Crawford et al. 2014 probably also had a positive effect on the polar bears. Between the periods 1986–1995 and 2008–2013, the proportion of polar bears spending > 7 days on land between August and October increased from 20.0% to 38.9%, and the average duration of their stay on land

increased by 30 days (Rode et al. 2015). Most of the bears came to Wrangel and Herald Islands (Russia), which are also important denning areas (Rode et al. 2015). These islands are also increasingly used as summer haul-outs by walruses and polar bear predation on walruses has been reported by Ovsyannikov (1995) and Kochnev (2002). According to the latter, polar bears killed at least 226 walruses between 1989 and 2006, mainly by causing stampedes. About 20% of the Chukchi Sea polar bears summered on mainland Chukotka, where they were observed to feed opportunistically on marine and terrestrial mammal carcasses, such as gray whales, muskox (*Ovibos moschatus*) and reindeer (*Rangifer tarandus*) (Kochnev 2002). In addition, predation on live lemming (*Synaptomys* spp.) has been observed during lemming peak years. The population effect of these supplements to ringed and bearded seals is uncertain, but expected to be small, especially for terrestrial food resources (Rode et al. 2015).

The polar bear subpopulation inhabiting the Barents Sea area has experienced the fastest loss of sea-ice habitat of all the 19 recognized polar bear subpopulations (Laidre et al. 2015). Surveys around Svalbard and in the pack ice to the North of Svalbard have nevertheless indicated a stable population size over the period 2004 to 2015 of ~1000 bears (95% CI = 334 – 1026), possibly because the population was well below carrying capacity, when the sea ice reductions began (Aars et al. 2017). Retreat of the ice edge in the Barents Sea has led to abandonment of previous prime breeding habitat such as the Island of Hopen (Derocher et al. 2011). In addition, there has likely been an eastward shift in the distribution of dens from the east side of Svalbard to the Franz Josef Land archipelago (Aars et al. 2017). No recent counts are available from the Russian components of this subpopulation.

Polar bears around Svalbard are split into a smaller component summering in coastal waters and a larger offshore component summering along the edge of the pack ice, which has recently been situated over the slope of the CAO (Aars et al. 2017). Pregnant females summering offshore appear to return to Svalbard to breed 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 the coastal resident strategy (Blanchet et al. 2020). There are so far no signs of temporal trends in body condition or pup production in any of the two polar bear ecotypes in the Svalbard area (Aars et al. 2017). The resident bears also swim a great deal between feeding areas along the shores of Svalbard (Lone et al. 2018, Blanchet et al. 2020). Females with cubs of the year swim significantly less than other females, but they do in fact swim considerable distances, possibly carrying the pups on their back (Aars and Plumb 2010, Lone et al. 2018). Even cubs of the year appear to be able to survive being displaced several tens of kilometers through water (Lone et al. 2018). This may be a crucial factor for the ability of mothers to maintain sufficient resources for lactation after emergence from the den. Currently, many females are thus able to pursue an offshore life style even during the cubs first summer. With continued ice retreat, however, this will eventually become impossible and more of these females may have to stay on land, choose denning sites less affected by warm Atlantic water, or den on the drift ice itself.

Telemetry and observational data suggest that some polar bears around Svalbard have developed new foraging strategies suitable for extended periods in ice free coastal waters (e.g. Lone et al. 2018). These strategies rely on alternative hunting techniques like "aquatic stalking" of bearded seals and hunting for harbour seals, which are not ice-associated (Lone et al. 2018). These skills appear to be rare but could become the target of strong selection. Even so, predation on harbour seals likely cannot sustain the current number of polar bears in Svalbard as the Svalbard harbour seal population was only estimated at ~1800 individuals in 2010 (Merkel et al. 2013). Polar bears are also known to feed on harp seals, which are, however, generally only available, when ice is present. Smith and Stirling (2019) noted that harp seals react very slowly or not at all to polar bear attacks when hauling out on the ice in summer. In 2014, several polar bears were found to be scavenging on 9 different carcasses of white-beaked dolphins from spring through early autumn in three different areas in Northern Svalbard (Aars et al. 2015). One bear appeared

to be hiding left-overs with snow for later use (Aars et al. 2015). The dolphin carcasses were likely a significant food source for the polar bears in the area that year, but similar incidences have not been reported since. The dolphins are believed to have been entrapped by ice while foraging in early spring in previously ice-covered areas. With increased presence of southern cetacean species in Svalbard, whale and dolphin carcasses could become an increasingly important food supply for polar bears, although they are likely to be only scarcely and sporadically available. Reindeer, seabirds and eggs are also occasionally consumed by polar bears in Svalbard (Stempniewicz et al. 2014, Prop et al. 2015, Aars et al. 2015, Lone et al. 2018). As terrestrial prey generally does not have as high a fat content as marine prey, these resources are likely of less energetic value, especially for adult females depending on fat accumulation for winter gestation and lactation (e.g. Rode et al. 2015). For cubs and subadults they may be more useful supplements, although not outweighing the loss of sea ice habitat.

The East Greenland subpopulation of polar bears inhabits a convergent sea ice region (PBSG, 2019). The southern and eastern extent of the ice has nevertheless decreased over the past decades and changed the hunting habitat of the polar bears (e.g. Strong 2012, AMAP 2017). Polar bears in East Greenland are believed to den primarily on land (Born et al. 2011). Recently, however, denning on sea ice off North and Northeast Greenland has been documented (Laidre et al. 2020). Precipitation is scarce in this area, but sufficient snow for denning is found around calvings of glacier ice stuck in the sea ice. The movement pattern of these northern polar bears is unknown, but areas bordering on the CAO could potentially be part of their habitat. Interviews with local hunters suggest that the occurrence of polar bears near settlements in East Greenland has increased in recent years (Laidre et al. 2018), possibly indicating an increase in abundance or a change in distribution pattern. The latter could be driven by ongoing changes in sea ice and snow cover, also noted by the hunters (Laidre et al. 2018). Changes in polar bear foraging patterns are supported by analyses of fatty acids, stable isotopes and contaminant profiles in blubber samples from East Greenland collected over the period 1984-2011 (McKinney et al. 2013). These analyses show a change from a diet dominated by ringed seals to a diet dominated by pack-ice seals, mainly hooded seals.

Overall, recent studies of polar bears in the gateways to the CAO reveal considerable levels of ecological plasticity and opportunistic behavior both with respect to habitat use, foraging strategies and diets. This could be important for the survival chances of polar bear species in the face of severe expected reductions due to climate change (Lone et al. 2018, Molnar et al. 2020). Understanding potential new foraging strategies and changes in denning habitat as they occur or change in frequency is also important for efforts to mitigate the effects of climate change on polar bears and their prey species (e.g. Prop et al. 2015) and their interactions with humans (e.g. Wilder et al. 2017).

4.6.1.8 Bowhead whales

Bowhead whales feed efficiently on small crustaceans both pelagically and on the sea floor (Simon et al. 2009). Relatively shallow waters may therefore be an optimal habitat for them as also suggested by their successful recovery from overexploitation in the Pacific Arctic region to recent estimates of ~16000 animals (Givens et al. 2016). Bowheads overwintering in the Bering Sea follow the ice edge through the Bering Strait and feed on copepods and krill in the Chukchi and Beaufort seas during summer (Citta et al. 2015). In this area, reduced sea ice cover has been accompanied by improved body condition of bowhead whales, especially juvenile whales (George et al. 2015). There has also been a considerable increase in the number of observed bowhead calves in recent years (Clarke et al., 2017). These responses are likely driven by increased pelagic productivity, partially due to increased coastal upwelling (Moore 2016).

The bowhead whale population around the Atlantic gateway is believed to be slowly recovering from historic overexploitation and is estimated to number in the low hundreds (Vacquie-Garcia

et al. 2017). A survey in 2015 estimated bowhead abundance to the North of Svalbard at 343 (CV = 0.488) (Vacquie-Garcia et al. 2017b). Many of these whales inhabit the pack ice over the slope of the CAO to the north of Svalbard (see Fig. 3). This summering habitat differs somewhat from typical bowhead habitat in the Pacific Arctic region where the whales are more strongly associated with the shelf waters (Citta et al. 2018). Observations of very large groups of bowheads have also been reported in the Fram strait pack ice areas in recent years (de Boer et al. 2019). Although bowhead whales may be responding positively to recent levels of sea ice reduction, they are nevertheless strongly ice associated and prefer waters below 2°C (Kovacs et al. 2020b). Modelling of future availability of preferred habitat for bowhead whales suggest that suitable areas may be reduced by 50% by 2050 (Kovacs et al. 2020b).

4.6.1.9   Beluga whales

The Pacific gateway region is one of the most important habitats for beluga whales globally with an estimated total of at least 60000 individuals during summer and fall. The majority of these belugas belong to the Beaufort Sea population, which was estimated at ~39000 individuals in 1992 (Muto et al. 2018). Subsequent studies of relative abundance have shown an increasing trend within a selected index area, but at least part of this is thought to be due to distribution changes (Harwood and Kingsley 2013). The genetically distinct Chukchi Sea population was estimated at 20752 (CV = 0.70) individuals in 2012 (Lowry et al. 2017).

There are significant differences in spatiotemporal distribution both between populations and between sexes within stocks in the Pacific Gateway region (Hauser et al. 2014). For all groups, however, dive data suggest that the main foraging depth is 200-300 meters (Hauser et al. 2015), which is consistent with a diet primarily composed by polar cod as indicated by fatty acid analyses (Loseto et al. 2009). On the shelf, most dives extend to the bottom and significant amounts of benthic organisms appear to be consumed including shrimp, octopuses, eciurid worms and amphipods (Quakenbush et al. 2015). Stable isotope values from Beaufort Sea and Chukchi Sea belugas suggest important contributions of both pelagic and benthic prey (Dehn et al. 2006, Horstmann-Dehn et al. 2012). This fits the mixed pattern of benthic and pelagic diving in the summer and fall dive data (Hauser et al. 2015). No diet data are available from the wintering areas in the Bering Sea.

Males generally spend most time in waters on and off the slope of the Beaufort Sea and Chukchi Plateau. Chukchi Sea males were particularly prone to explore waters in the central and northern Beaufort Sea bordering on the CAO (Hauser et al.2014). In deep water areas, belugas occasionally dive down to 900m depth, but the function of these dives is unclear (Hauser et al. 2015). Females spent more time than males in nearshore areas around the Mackenzie Estuary and Kasegaluk bay, which are the main moulting and nursing areas for the Beaufort Sea and Chukchi Sea belugas, respectively. Beluga habitat use of belugas in the Chukchi and Beaufort seas appears to be driven mainly by bathymetry and oceanographic features rather than ice cover (Hauser et al. 2018). Hence little change in home ranges and habitat use was observed over a period of retreating ice cover between 1998-2002 and 2007-2012. Longer ice- free season has, however, triggered a month delay in the migration of Chukchi Sea belugas from the western Beaufort Sea in 2007-2012 (Hauser et al. 2018). Chukchi Sea belugas also spent more time at greater depths than during 1998-2002. This could be indirectly driven by ice retreat, which may change the depths of productive zones through effects of increased wind exposure and resulting changes in frontal systems and mixing depths (Stafford et al. 2016).

Harwood et al. (2014) found some signs of decreasing size at age in belugas harvested in the Beaufort Sea from 1989-2008. This was mainly due to a trend over the period 1998 to 2008, which was, however, not separately analysed. Data on blubber thickness also showed a decline over the period 2000-2008, albeit not statistically significant. Moore and Kuletz (2019) noted that the potential decline in beluga blubber thickness co-occurred with negative responses in ringed seals

and black guillemots (*Cepphus grylle*) in the same area and suggested that a common factor may have affected pelagic food availability for these species. Interestingly, the same factor does not appear to have affected bowhead whales, which also feed pelagically albeit on a lower trophic level. The distribution areas of both Chukchi and Beaufort Sea beluga whales overlap with areas, where killer whales have been observed over the past decades (Stafford 2018). Very few cases of killer whale predation on belugas have, however, been reported for the Chukchi Sea from the 1950s to the 1990s (Lowry et al. 1987, George and Suydam 1998) and the present status is unknown.

In the Svalbard area, abundance of beluga whales has been estimated at 549 individuals (95% CI: 436-723) in 2018 (Vacquie-Garcia et al. 2020). They are almost exclusively inhabiting coastal waters and often forage along glacier fronts (Vacquie-Garcia et al. 2018). Fatty acid analyses suggest that polar cod is their primary prey (Dahl et al. 2000). Karlsen et al. (1999) found that Belugas in Svalbard waters were unusually quiet during summer and suggested this was due to a perceived threat from killer whales. This is also suggested to be a possible explanation for their strong preference for waters close to shore (Vacquie-Garcia et al. 2018). No instances of killer whale predation on belugas or other cetaceans have, however, been reported over the past decades from this area.

Beluga whales are also thought to be quite common around Franz Josef Land and even more so in the Kara and Laptev Seas (Belikov and Boltunov 2002, Solovyov et al. 2012). Some observations have also been made in the CAO to the north of these areas (Belikov and Boltunov 2002). Few belugas have been observed in the East Siberian Sea (Belikov and Boltunov 2002).

4.6.1.10 Narwhales

The Atlantic gateway to the CAO is dominated by the deep waters of the Northern Norwegian Sea, the Greenland Sea and the Nansen Basin, which are home to the Arctic-Atlantic endemic narwhals (Ahonen et al., 2019). This deep-diving species inhabits the ice-covered waters of the Fram Strait year-round and 837 (95% CI 314–2233) narwhals were estimated to occur in the western Nansen basin pack ice in summer 2015 (Vacquie-Garcia et al. 2017b, See Fig. 3). This estimate is thought to be negatively biased, as narwhals were still observed at the end of the transects (Vacquie-Garcia et al 2017b). Narwhals have generally been found to summer in coastal habitats and the presence of narwhals in the Nansen basin during this time of year is therefore very atypical for the species (Heide-Jørgensen et al. 2015, Vacquie-Garcia et al. 2017b). Narwhals generally feed most intensively during winter and spring (Watt et al. 2015), but it is not known, if the narwhals summering in the Nansen basin were feeding. Typical prey of narwhals are polar cod, *Gonatus fabricii*, shrimp, capelin, Greenland halibut and redfish. While narwhals in the Northwest Atlantic feed mainly on Greenland halibut, East Greenland narwhals have a broader niche and feed more on capelin than the Northwest Atlantic narwhals (Watt et al. 2013). The genetic affiliation of the narwhals in the Nansen basin is not known, but narwhals sampled in coastal waters of East Greenland and Svalbard appear to belong to genetically differentiated populations (Louis et al. 2020).

Abundance of narwhals in East Greenland was recently estimated at ~700 individuals, which is substantially less than a previous estimate of ~2700 individuals (NAMMCO 2019) and much less than an estimate of 6,444 (95% CI: 2,505–16,575) reported by Heide-Jørgensen et al. (2010) based on surveys in 2008. It is not clear, if these apparent reductions are due to a genuine decline, low precision in the estimates, or a shift in distribution. It is notable, however, that the recent survey did not detect any narwhals in the southernmost management region in southeast Greenland (NAMMCO 2019). The surveyed area only extended northward to Scoresby Sound fjord. Groups of at least 100 narwhals have been observed in areas further to the North along the coast, but no

abundance estimates exist for this area (Boertman et al. 2009, NAMMCO 2019). There are also no abundance estimates for narwhals in the Russian Arctic, but it is quite clear that the narwhal abundance in the area from eastern Greenland to Franz Josef Land is vastly lower than in the Northwest Atlantic, where total abundance is estimated around 170000 individuals (Lowry et al. 2017).

Overall, narwhals are characterized by very low genetic diversity, which has likely been maintained over long periods of their evolutionary history (Westbury et al.2019). A threefold increase in effective population size is, however, estimated to have occurred at the start of the Holocene in response to deglaciation (Louis et al.2020). According to Polyak et al. (2010) this period was in fact warmer than recent decades in the Arctic. Future climate scenarios are however predicted to reduce suitable narwhal habitat by 25 % (Louis et al. 2020). This result is partly due to the strong preference shown for cold waters in narwhal telemetry studies.

4.6.2   Effects of anthropogenic noise

Cetaceans and pinnipeds rely on passive and active acoustics for prey location, detection of predators, identification of conspecifics, and navigation. Sounds emitted from ship engines, seismic airguns, military, fisheries and research sonars may interfere with these vital behaviours and in some cases inflict physical hearing damages of temporary or permanent nature (Gomez et al. 2016, Southall et al.2019). Adverse effects are mainly expected within the auditory range of the animals although in rare cases very powerful directed sounds may generate other trauma at close range (Gray and Van Waerebaek, 2011)). With the exception of fisheries and research sonars, the listed sources of anthropogenic noise are primarily in the low-mid- frequency range (PAME 2019, Kvadsheim et al., 2020).

For many species, evaluations on sensitive hearing ranges are mainly based on recorded frequencies of sound production and sounds eliciting behavioral responses documented by visual observations, acoustic monitors or telemetric devices (Southall et al. 2019). Controlled experimental studies of total hearing range are only available for pinnipeds and a few toothed whales but no baleen whales. For several species analyses of auditory anatomy have played an important role in sensitivity evaluations. However, significant gaps still remain in our understanding of the biophysical principles of hearing in cetaceans, particularly in baleen whales. Hence, it was only recently discovered, that baleen whales likely receive sound impulses in water partly through a fat organ located on the sides of their heads (Yamato et al. 2012).

Based on a comprehensive review of available data on hearing ranges, Southall et al. (2019) assigned marine mammals to 6 different hearing groups of which 4 are known to be regularly present in the gateways to the CAO. These are 1) Low Frequency cetaceans (all baleen whales), 2) High frequency cetaceans (killer whales, narwhals, belugas and more), 3) Phocid carnivores (all phocid seals) and 4) Other carnivores (walrus, polar bears and more). Somewhat counterintuitively, several high frequency cetaceans are highly sensitive to low frequency anthropogenic sounds. This is illustrated by the strong response to shipping noise reported for belugas (Erbe and Farmer, 2000). High sensitivity to seismic noise for both belugas and narwhals is also suggested by recent studies in the Baffin Bay area (Kyhn et al. 2019). Both species appear to vacate ensonified areas at distances of more than 10 km from the source. Depending on the timing, location and duration of the disturbance, this may significantly affect feeding or other important behaviors. Little is, however, known about the actual behavioral state of the animals during the reported noise exposures. Narwhals are generally known to feed little during summer, which is the main season of anthropogenic noise in their habitats (Ahonen et al. 2017, Kyhn et al. 2019).

Bowhead whales are also more likely to move away from seismic airgun noise when they are migrating (Richardsson et al. 1999) than when they are feeding (Koski et al. 2009). Feeding

bowheads whales exposed to seismic airgun noise have, however, been found to reduce their surfacing and respiration rates (Robertson et al. 2016), which could affect the energetic costs of diving. It could also affect their foraging efficiency by disturbing the pattern of short exploratory dives before longer lasting feeding dives reported by Simon et al. (2009). Exposure to low frequency anthropogenic noise has also been shown to increase the levels of stress hormones in baleen whales even in the absence of clear behavioral responses (e.g. Rolland et al. 2012).

In some cases, observed noise tolerance levels in marine mammals may pose a risk of temporary or permanent hearing disabilities (threshold shifts). This was suggested by Harris (2001) for seals (mainly ringed seals) observed to remain close to a seismic survey vessel during a full range seismic operation in the Beaufort Sea. No differences in dive rates were observed between seals within 150 from the ship and >250 m from the ship.

Phocid seals exhibit the most sensitive low-frequency hearing abilities among marine mammal species for which audiometric data are available (Reichmuth et al., 2013; Erbe et al., 2016). They could therefore be especially vulnerable to seismic airgun noise, which is predominately concentrated below 1 kHz. No signs of temporal threshold shift were, however, recorded by Reichmut et al. (2016) exposing 2 ringed seals and 2 spotted seals to single pulses of seismic airgun noise of 100 Hz at levels predicted to generate TTS by Southall et al. (2007). Unlike the reported studies on seismic exposures, Kvadsheim et al. (2010) found strong evasive reactions to simulated sonar signals between 1-7 kHz at source levels from 134-194dB (RMS, re1uPa@1m). The sound pressure level inside the net cage was 10-27dB below the source level. Initial responses included rapid surface swimming away from the sound source. The horizontal escape reaction soon stopped but the seals generally remained at the surface with their heads out of the water. Heart rates were increased compared to pre-exposure levels during surface time, but not during dives (Kvadsheim et al. 2010). More studies using comparable metrics for exposure levels are, however, needed to understand thresholds for auditory effects in seals exposed to low frequency noise. Depending on temporal overlaps, there is also a clear potential for masking of phocid vocalizations, which has not received much attention.

The calls and mating songs of bowhead whales and other baleen whales are also prone to masking by low frequency anthropogenic noise. At low levels of masking noise, singing bowhead whales respond by increasing the volume, but beyond a certain threshold level, the whales stop vocalizing (Blackwell et al. 2015). Critical levels of this type of disturbance are unknown, but past levels in the Pacific Arctic region have not prevented an observed population increase (Givens et al. 2016). In contrast to the Pacific Arctic soundscape, almost no overlap between bowhead mating displays and anthropogenic noise occurs in the western Fram Strait, which is the preferred mating area of the endangered East-Greenland Spitsbergen bowhead whale population (Ahonen et al. 2017, Hiemer et al. 2020). Distant seismic noise and occasional local shipping noise is, however, heard during summer, concurrently with vocalizations by narwhals and mating calls from bearded seals. This study is an important base line study of a critical habitat for arctic marine mammals prior to a potential increase in anthropogenic activity due to reduced ice occurrence. Similar studies are available for the Pacific Arctic region (Moore et al. 2012, Stafford et al. 2018, Halliday et al. 2020) and would be highly valuable other areas of the CAO close to areas of high biological activity such as the Nansen basin, Laptev Sea and East Siberian Sea.

4.6.3   Knowledge gaps and monitoring needs for marine mammals

Among the research and monitoring needs for marine mammals in the CAO are:

1.Continued and expanded monitoring of marine mammal occurrence in the CAO

Monitoring of geographic and seasonal occurrence patterns is of fundamental importance for the understanding of highly mobile species in a changing environment. Historically, monitoring of

marine mammals in the CAO has mainly relied on opportunistically collected data from ice breakers, aerial ice monitoring programs and various research and tourist expeditions (e.g. Belikov and Boltunov 2002). Collection, collation and analyses of this type of data is highly valuable and should continue and expand with the increase of human activities in the region. Efforts should be made to optimize the quality, synthesis and dissemination of opportunistic observations. In addition, passive acoustic monitoring stations within the CAO would valuable tools for the majority of the arctic marine mammals. Based on prior indications and judgement of ecological habitat suitabilities, reconnaissance surveys should be carried out in selected areas to evaluate the need and feasibility of specialized abundance surveys.

3. Continued and expanded dedicated abundance surveys in the CAO

Continued and geographically expanded dedicated abundance surveys for ice dependent species like narwhals, polar bears, seals and bowheads around the CAO ice edge are needed for responsible management of human activities. In particular, a more complete survey of narwhals in the Nansen basin should be a near future priority as this population component has shown high affinity to conditions prevailing in the CAO. It is furthermore likely to constitute a significant proportion of the total abundance of a distinct grouping of narwhals to the East of Greenland.

4. Telemetry based studies of marine mammal movements in the CAO

Satellite telemetry, preferably with oceanographic tags, provide highly valuable information on movement patterns, habitat selection, diving behavior, potential diets and population affiliation. Currently available telemetry data for marine mammals in the CAO are generally based on animals originally tagged outside the area, which may be biased towards short term visitors. Tagging animals already within the CAO would be more likely to reveal information on potential long-term residents of the CAO. Elucidating the population affiliation of Nansen basin narwhals is of particularly high importance as these animals are likely to represent a significant proportion of the total abundance of narwhals to the East of Greenland.

5. Genetic studies

Genetic assignment of population affiliation of marine mammals observed in the CAO is a high priority for all species. In addition, genetic samples may provide information on sex and some physiological parameters through quantitative analyses of gene expression (Sigsgaard et al. 2019). High quality DNA from individual biopsies provide the most straightforward technical basis for these analyses, but faecal dna or environmental DNA from targeted areas may provide similar information with extended protocols (Sigsgaard et al. 2019). In addition, eDNA may provide community data on suites of species.

6. Studies of life history, health and ecology based on biological material

For marine mammals observed in the CAO access to biological material from live animals for assessment of health, age and reproductive status are generally limited to biopsies, faeces, cells in exhaled air, and occasional live sampling of blood samples, epithelial cells, hair and whiskers. These samples can provide useful data on reproductive status (sex hormones), health (stress hormones, contaminants, pathogens and antibodies), trophic information (stable isotope and fatty acid analyses). With the exception of data collected from live-captured animals for tagging, many of these techniques are, however, highly opportunistic and time consuming and unlikely to be widely operational for realistic levels of field time in the CAO. For abundant species like ringed seals, lethal sampling may be defendable for more detailed analyses of health and reproductive status, contaminant levels, age and diet. Similar data derived from indigenous and commercial hunting have previously proven highly useful for arctic populations (e.g. Nguyen et al. 2017, Beatty et al. 2019). The relevance of available hunted samples for CAO related studies, should be assessed.

7.Analyses of soundscapes relevant for marine mammals within the CAO

In addition to data on occurrence patterns of vocal marine mammals, general analyses of CAO soundscapes are important for the overall understanding of marine mammal acoustic ecology in the area. This is because levels of both anthropogenic noise and sounds from natural sources like wind and wave action are likely to change in response to changes in ice cover (Stafford et al. 2018). Soundscape data can be obtained from passive acoustic monitoring devices. Baseline studies for the pacific and arctic gateways are available (Moore et al. 2012, Ahonen et al. 2017, Stafford et al. 2018).

8.Studies of arctic mammal sensitivity to low frequency anthropogenic noise

Although several studies are available on the sensitivity of bowhead and beluga whales to seismic airguns and vessel noise, there are still considerable gaps in the knowledge base required for vulnerability assessments of marine mammals in the CAO. Very few studies of behavioural responses to noise exist for other arctic marine mammals and no studies appear to exist on effects of military sonars on arctic marine mammals (Gomez et al. 2016). With expected increases in industrial and military activity in the CAO and other parts of the Arctic, these gaps need to be filled.

Since marine mammals in the CAO are most likely closely connected with larger populations outside the core area of the CAO, continued monitoring of these more central populations are important in order to put the information from the CAO into a population and species-wide context. Generally agreed circumpolar research and monitoring recommendations for arctic mammals are summarized in CAFF (2017).

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4.7 Marine birds in the CAO

Contributor: Thomas Van Pelt and Kathy Kuletz

Marine birds occur in relatively low densities throughout the Central Arctic Ocean (CAO), but are substantial ecosystem components along the continental edges of the CAO, particularly in the 'gateway' ecosystems; as such they are sensitive to a wide range of current and future climate and anthropogenic impacts. Marine birds breed on coasts and islands, so terrestrial aspects of their life cycles are not be directly impacted by change in the open-ocean Central Arctic. But as highly mobile predators, their foraging range in the breeding season can include open water areas hundreds of kilometers from land, and large numbers of non-breeding or migratory individuals use open water habitats in marginal waters of the Central Artic region during summer and fall. Marine bird species also play a role in linking marine and terrestrial habitats by returning nutrients from offshore waters to the coast. Marine birds thus span a large breadth of ecological and management considerations.

The *Circumpolar Seabird Monitoring Plan* (CSMP; Irons et al., 2015) recognizes 64 marine bird species in the Arctic ecosystem; about half of these breed in the Arctic while others visit in summer and fall to forage on zooplankton, invertebrates and forage fish. About a dozen seabird species comprise over 90% of total individual birds in the broader "Arctic" region (following the Arctic Council geographic definition of Arctic); of those, only a few species have been regularly recorded in the CAO, and about two dozen species recorded overall. In the Pacific sector of the CAO, murres *Uria spp*], black-legged kittiwakes (*Rissa tridactyla*), and jaegars (*Stercorarius* spp) are most frequently encountered, while Ross's gull (*Rhodostethia rosea*) and ivory gull (*Pagophila eburnean*) predominate in the Atlantic sector. Throughout the CAO, numbers of birds are extremely low, defined largely by lack of open water, but perhaps also related to water depth and prey availability. In contrast, the adjacent continental shelves, and in particular the gateways linking the CAO with adjacent seas, have high densities of marine birds and high species richness. A comprehensive resource for further marine bird information in the Arctic Ocean and surrounding areas can be found in the seabird chapter of the 2017 SAMBR report (CAFF 2017).

For this WGICA 2020 annual report, we first provide a very brief summary of recent information relevant to marine birds in the context of climate and human impacts in the basin waters of the Central Arctic region that are the WGICA core area. Then we briefly refer to related ICES and other programs that support marine bird information in marginal seas and coastlines and gateway regions.

4.7.1 Recent information on marine birds in the CAO

Historically, there have been few formal at-sea surveys for upper-trophic organisms (fish, marine birds and mammals, etc.) in the CAO, largely due to near-total ice coverage year-round. Now, with the combination of recent Arctic warming and consequent sea ice reductions allowing greater access to the Arctic Ocean, and increased scientific, commercial, and political interest motivating greater research presence, some new information is emerging from deskwork and fieldwork. A European Commission-funded review of "fish populations and related ecosystems" published in 2020 (Snoeijs-Leijonmalm et al., 2020) provides an up-to-date review of information on prey species important for marine birds in the CAO, with select examples of potential impacts connected to climate change and to human impacts. New fieldwork with some marine bird focus includes surveys from transarctic icebreaker cruises, documenting expected low densities of marine birds and mammals (e.g. Joiris et al., 2016).

4.7.2 Climate and anthropogenic impacts on marine birds in the future CAO

As reviewed in the SAMBR report and in other sections of this WGICA annual report, an array of climate and human impacts are predictable for the future CAO region. The most prominent of these is the projection of ice-free summer and fall conditions in the CAO within the next ~20-30 years (Notz & Stroeve 2018), and related changes in freshwater inputs, currents, water column structures, and primary and secondary productivity. These changes will impact marine bird prey species such as polar cod (*Boreogadus saida*; e.g. Huserbråten et al. 2019). Considering that marine birds reproduce on land, an ice-free CAO is unlikely to result in rapid changes in marine bird habitat use in the region. However, unexpected effects may result across a range of scales, from reductions in certain very ice-dependent species like ivory gulls and Ross's gulls (Joiris 2017) to extreme changes in longstanding migration and distribution patterns of northern hemisphere marine birds (Clairbeaux et al. 2019).

Decreasing sea ice is likely to be followed by increased shipping traffic, seabed exploration, and tourism, with consequential impacts on marine birds and the prey resources upon which they depend. Increased use of the CAO by post-breeding and migrating marine birds in newly ice-free waters would overlap with increased vessel traffic, which could lead to more bird-ship collisions, such as occurs in sub-Arctic and Arctic seas during poor weather and fog, when birds are attracted to ship's lights. Pollution and oily or plastic debris dumped illegally from vessels can also be detrimental to marine birds. In summer 2020, dead seabirds have washed up with trash and non-petroleum oil on beaches in the northern Bering Sea, coincident with increased fishing activity in the region (Kuletz, pers. comm.); similar risks could increase in the CAO.

4.7.3 Marine bird research, management, and monitoring resources in adjacent seas

The circumpolar northern continental shelf regions support enormous populations of marine birds, with high ecological, economic, social, and cultural values— the marine bird chapter of the SAMBR report (CAFF 2017) is a current and authoritative resource for marine bird information in the areas adjacent to the CAO. Shelf and Atlantic 'gateway' ecoregions within the ICES framework provide assessments and information on marine birds as components of the Barents, Norwegian, and Greenland Seas (http://www.ices.dk/community/groups/Pages/IEASG.aspx). In the Pacific gateway region, the North Pacific Marine Science Organization (PICES) and its working groups and programs, in partnership with ICES, are building an integrated ecosystem assessment for the Bering and Chukchi Sea Large Marine Ecosystem that encompasses marine birds and their prey (https://meetings.pices.int/members/working-groups/wg44). The Arctic Council's Circumpolar Seabird Expert Group (CBird;https://www.caff.is/seabirds-cbird) support an array of circumpolar initiatives and programs including the Circumpolar Biodiversity Monitoring Program— which generated the recent SAMBR report (CAFF 2017)— and the Circumpolar Seabird Monitoring Plan. Other practitioner-based research programs and networks include marine bird studies and surveys in conjunction with physical and biological studies, e.g.: the Distributed Biological Observatory program in the Pacific gateway region (https://arcticdata.io/catalog/projects/DBO); the Synoptic Arctic Survey (https://synopticarcticsurvey.w.uib.no/); the Pacific Arctic Group (https://pag.arcticportal.org/); and the Arctic Marine Biodiversity Observation Network in the Chukchi Sea (AMBON; https://www.uaf.edu/cfos/research/projects/arctic-marine-biodiversit/).

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5   ToR d. Assess the consequences of recent and on-going climatic and oceanographic changes on transport pathways and potential effects of con-taminants

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5.1   Introduction

In the Central Arctic Ocean (CAO), rapid climate-driven sea ice loss is putting pressure on the highly sensitive ecosystems, while also opening the area for an unprecedented expansion of human activities (De Lucia et al 2018).

For the ecosystem of the CAO, five main pressures have been identified, such as sea-ice decline and pollution. In this chapter, we focus on pollution, including both chemical pollution and marine litter. Pollution in the Central Arctic Ocean is primarily a consequence of activities in other regions of the northern hemisphere, with long-range transport by air or sea bringing pollution into the CAO. Additionally, some human activities that generate pollution occur within the Arctic. Both types of sources, and both current and predicted future pollution, are reported here.

5.2   Pollution pressures in the present-day CAO

5.2.1   Contaminants

The CAO is relatively unpolluted compared to other marine regions of the world. However, the Arctic is a sink for global pollutants transported from lower latitudes via the atmosphere, oceans and rivers, and local sources of pollution are also increasing. Winds provide a relatively fast route to the CAO for volatile contaminants and for substances that adhere to small particles. With rain and snow, contaminants are washed from the air and deposit on the sea ice, open water, or on the ground. Rivers carry contaminants to the coasts bordering the Arctic Ocean, where processes of sedimentation and re-suspension of particles occur. Both ocean currents and sea-ice drift also carry contaminants (partly dissolved in water or in ice) to and from the CAO.

It is indicated that ongoing climate change in the Arctic will increase the potential of long-range atmospheric transport of contaminants such as Hg and POPs (AMAP, 2011; Armitage et al., 2011; Ma et al., 2011; Wöhrnschimmel et al., 2012a, b, 2013). At the same time, POPs in the Arctic may be influenced by warming, resulting a shorter lifetime of the POPs in the environment (AMAP 2016). Changes in ocean currents may affect ocean transport (AMAP, 2011; Kallenborn et al., 2012; Grannas et al., 2013), as well as transport caused by sea-ice drift.

5.2.2   Chemical pollution

Emissions of chemical compounds from the Northern Hemisphere mid-latitude (from Europe, Asia, and North America) are currently the main source of Arctic air pollution. These include toxic contaminants (e.g. mercury) and certain persistent organic pollutants (POPs), along with particulates and emerging pollutants (AMAP 2017).

While levels of many POPs are declining in the Arctic due to tighter global regulation, other pollutants have been listed as 'chemicals of emerging concern" for the Arctic (AMAP 2017). Examples include pharmaceuticals and personal care products, a large number of per- and polyfluoroalkyl substances (PFASs), new brominated, organophosphorus-based and chlorinated flame retardants (BFRs, PFRs, CFRs), hexachlorobutadiene (HCBD), siloxanes, byproduct polychlorinated biphenyls (PCBs, e.g. PCB11), phthalates, halogenated natural products (HNPs), and pesticides (AMAP 2016).

In addition, increasing industrial activity in the Arctic region itself, such as oil and gas development, mining, shipping, and industrial runoff from onshore facilities, will likely result in higher levels of pollution in the Arctic Ocean.

Since 1991, AMAP has been investigating the transport of pollutants to the Arctic, as well as their fate and effect. AMAP (2016) provided maps of modeled estimates of changes in concentrations of γ-hexachlorocyclohexanes (γ-HCH), PCB52, and PCB153 in the atmosphere and oceans between 1995–1999 and 2095–2099. In the CAO, future γ-HCH concentration is estimated to be stable or to slightly increase, whereas concentrations of PCB52 are predicted to decrease.

5.2.3 Plastic pollution

Plastic debris, including microplastics, have been documented in Arctic marine habitats, sea ice, and wildlife (Obbard et al 2014). Debris are transported by rivers and ocean currents from regions south of the CAO. Additionally, debris can result from human activities onsite, such as shipping activities (see figure 5.1).

Plastic microparticles and nanoparticles are entering food webs in poorly understood ways (IP-BES 2019). Plastic debris can be divided into three categories: macro-, micro- and nanoplastic. Particle analyses suggests that microplastics in the Arctic may either result from the breakdown of larger items (transported over large distances by prevailing currents, or derived from local vessel activity), or from direct input of microplastics in sewage and wastewater of coastal areas (Lusher et al 2015). Recently, transport and deposit of microplastics from air has received more attention as microplastics have been found in snow in the Arctic and in the alps (Bergmann et al., 2019). Ingestion of plastic by Arctic marine species has been recorded in organisms ranging from blue mussels (Mytilus, Lusher et al 2017; Kühn et al 2018), polar cod (Kühn et al 2018), marine mammals (Martin and Clarke 1986), to seabirds (Lydersen et al 1989; Mallory 2008; Provencher et al 2010; Trevail et al 2015).

The effects of climate change are expected to alter the amount of plastic debris present in the Arctic (AMAP 2016). In the future, the incidence of plastic ingestion in Arctic food webs is likely to increase as plastic pollution rises in the Arctic (Tekman et al 2017). The likely increased influx of Atlantic water and accelerated ice drift may enhance the advection of microplastic particles into the CAO (AMAP 2017), and possible toxic contaminants adhered to microplastics (Karlsson et al. 2018). In addition, recent analyses of ice cores from across the Arctic found levels of microplastic pollution in sea ice up to three orders of magnitude greater than previously thought, suggesting that Arctic sea ice is an important sink for microplastic pollution (Peeken et al 2018).

5.3 Human activities in the CAO related to pollution: present and future

Two main activities that are currently occurring in the CAO and adjoining regions are ship traffic and fisheries. Human activities that may increase in the future— when the CAO becomes ice free in summer— are oil and gas activities, offshore mining and tourism.

5.3.1   Ship traffic

See also: PAME's Shipping Expert Group (SEG) Arctic Ship Traffic Data (ASTD) System. Data from this system could be used to conduct an assessment of ship traffic in the CAO.

 Smith and Stephenson (2013) modeled shipping routes under several climate change scenarios and concluded that September sea ice will have retreated in the Northwest Passage by midcentury, allowing approximately 30% geographic distance savings in shipping between western North America and Europe.

Potential vessel traffic growth in the Arctic could result in higher rates of noise and air pollution, vessel discharges (sewage, graywater, etc.), non-native species introductions, small vessel interference, oiling, and other concerns related to the wellbeing of humans and environment (Huntington et al 2015).

Cooperation among the Arctic states, the non-Arctic shipping states, and the global maritime enterprise will be critical to effective protection of Arctic people and the marine environment and developing sustainable strategies for the region (Safety 2018).

PAME has been monitoring ship activities in the Polar Code governed area under the Arctic Ship Traffic Data Project. The latest report (PAME 2020) indicates that the number of ships and total distance sailed has been increasing continuously since 2013. Fishing vessels are the dominant group, accounting for 45% of total sailed distance by vessels in the Polar Code area (Figure 5.1). At the same time, large cargo vessel activity is taking place as LNG transport from the Yamal Peninsula and crude oil transport from the Kara Sea occurs via the Northern Sea Route along the Russian Arctic coast. However, most of these activities are limited to nearshore and shelf areas. In the CAO itself, a limited amount of ship activity is currently taking place, mainly involving tourism and scientific research.

The Arctic Marine Shipping Assessment (AMSA 2009) identified oil spills and disturbance of wildlife as the two main potential effects of shipping. Shipping as a local source of pollution was not considered to be significant, because discharges to water and emissions to air are governed by IMO regulations and are negligible. On the other hand, if vessel traffic in the Arctic Ocean increases, oil spills from maritime accidents was thought to become a major threat to the Arctic marine ecosystems.

Oil and gas activities in the Arctic were assessed by AMAP in 2007-2010 (e.g. AMAP Assessment 2009). In that assessment, oil spills were regarded as the major environmental threat, particularly in ice-covered waters. The likelihood of a major spill in the Arctic is increasing as vessel traffic rises and offshore oil development accelerates (Eckle et al., 2012; Nevalainin et al 2016). The effects of a major spill depend on the physical and chemical composition of the oil or other chemical spilled; spill size, location, and season; and the vulnerability and sensitivity of affected species and ecosystems. Oil will last a long time when spilled in ice (or transported into ice-covered waters). Therefore an oil spill will have a large total geographical range as it drifts with the ice, although its spatial extent at any one time may be limited, even for a large spill.

IMO (2020), MARPOL Convention Annex IV, gives a set of regulations for the discharge of sewage into the sea from ships. And its Annex V prohibits the discharge of all garbage into the sea except as provided in regulations that are related to food waste, cargo residues, cleaning agents and additives, and animal carcasses. The IMO Polar Code applies these regulations into polar waters.
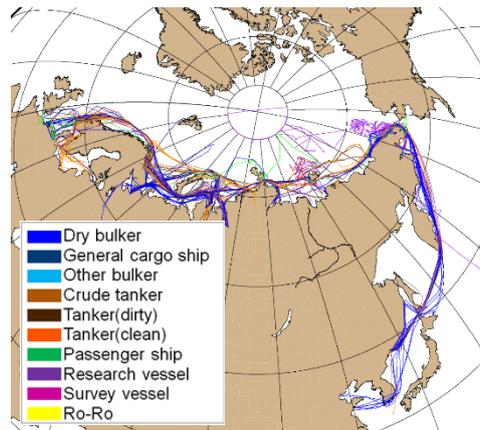
Figure 5.1. Ship tracks (#75) along the NSR (larger than 5,000DWT, Jun.~Nov.2014). Navigable speed related to ice condition along the Northern Sea Route, The 5th International Symposium on Arctic Research (ISAR5) (Source: Otsuka, N., Izumiyama, K. and Tateyama, K. (2018)).

From Annual Report 2017:

The following species or groups of organisms are identified as the key **ecosystem components to consider in a shipping vulnerability** context:

• Polar bear with relevant subpopulations: Barents Sea, Kara Sea, Laptev Sea, Chukchi Sea, southern, and northern Beaufort Sea, and CAO subpopulations;

• Ringed seal, as the anticipated food base for polar bears;

• Bowhead of the Critically Endangered Spitsbergen stock, and the large migratory Bering-Chukchi-Beaufort stock; • Beluga whale of several stocks in the Atlantic and Pacific gateway areas;

• Narwhal of the stock (or stock complex) found in the Atlantic gateway area;

• Ivory gull, which uses the peripheral pack ice of the CAO as feeding habitat in summer and autumn; • Ross's gull, similar habitat use as ivory gull;

• Polar cod *Boreogadus saida*, presumably with large migratory populations surrounding the CAO and spawning under ice;

• Arctic cod *Arctogadus glacialis*, possibly occurring with a migratory population in the Canada Basin;

• Sea ice amphipods, living on the underside of ice and being an important part of the CAO food-webs.

5.3.2 Fisheries in the CAO

The "Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean" bans commercial fishing in the CAO until there is scientific evidence that fishing can be done in a sustainable manner. Of the nine nations (USA, Canada, Russia, Norway, Denmark, Japan, China, Korea, Iceland) and one party (EU), eight have currently ratified the agreement as of May 2019. Ratification by China and Iceland remains to be completed.

Capture volume of the Arctic Ocean (FAO major fishing area 18) yields only up to 589 tons annually in 2000-2018 (FAO 2018). This survey however does not mention the CAO specifically, and might also include adjacent shelf seas. By another estimation, the fish catch of Alaskan Arctic coast yields 89 thousand tons, Canadian commercial and small-scale local fishery yields 94 thousand tons, and Russian Arctic waters yield 770 thousand tons from 1950-2006 (Zeller et., al. 2011). In all cases, fishery activity in the Arctic Ocean is small-scale and limited to coastal waters and brackish nearshore waters.

Today, the problem of Abandoned, Lost or otherwise Discarded Fishing Gear (ALDFG) is causing great concern for marine environment. It is estimated that ALDFG accounts for less than 10 percent of global marine litter by volume (Macfadyen et al 2009). ALDFG has a number of negative environmental impacts, including ghost fishing, entanglement, and being a vector for invasive species. ALDFG should be taken into account when assessing effects of high seas fisheries in the CAO. In the Barents Sea, where extensive fisheries occur, fishery-related macro litter encompasses approximately 40-60 % of litter as bycatch in trawls (Prokhorova and Grøsvik, 2019).

5.3.3   Oil and gas activities and related shipping

Oil- and gas-related shipping activity in the Northern Sea Route (NSR) is increasing year-round mainly in the Kara Sea area, with increasing oil and Liquefied Natural Gas (LNG) production planned from coastal areas. By 2024, Russia plans to quadruple cargo shipment volume compared to 2018, mainly due to natural resources shipments.

From the coast off the Kara Sea and Pechora Sea of the Russian Arctic, crude oil and LNG is extracted and transported by tankers to the non-Arctic regions. Additionally, the new LNG development project in the Ob Bay (Arctic LNG 2) is about to start. For Arctic LNG 2, most of the LNG tankers are powered by LNG, without carrying heavy fuel oil. However, the overall increase of large vessel traffic along the NSR is becoming a reality.

There are currently no crude oil developments in the CAO area, but oil spills from activities on the shelves (e.g. in the Russian Arctic) may affect the CAO ecosystem and should be taken into account in an assessment of potential impacts of oil and gas activities on the CAO ecosystem.

5.3.4   Offshore mining

Ocean mining, while relatively small, has expanded and likely will expand into the Arctic and Antarctic regions as sea ice melts (IPBES 2019).

There is increasing interest worldwide in the potential for deep-sea mining to serve as an engine for "Blue Growth" and to drive sustainable economic development (European Commission, 2012; Wedding et al., 2015). There is also an increasing concern that the direct and indirect impacts of mineral extraction in the deep sea will result in a significant loss of biological diversity (CBD, 1992; Wedding et al., 2015).

Direct impacts occur through the removal of target material and associated organisms within the mine site, and include the destruction of biota as well as habitat loss, fragmentation, and modification through altered mineral and sediment composition, geomorphology, and biogeochemical processes (Ellis, 2001; Van Dover, 2014; Jones et al., 2017).

Potential indirect impacts on the seabed and water column, both within and outside of the directly mined area, include the smothering of habitat and biota, interference with feeding activities, and the release and spread of nutrient-rich and toxin-laden water from the generation of plumes (Ellis, 2001; Boschen et al., 2013).

Additional potentially harmful diffuse effects include those from light, noise, and electromagnetic disturbance (Van Dover, 2014; MIDAS, 2016). The scale over which these indirect impacts are likely to occur is largely unknown, and most of the effects remain unstudied.

While biodiversity loss is recognized as a major global environmental problem (Weikard, 2002), the importance of biodiversity in the deep ocean merits clarification, particularly given that most species in the CAO remain undiscovered or unidentified (Bluhm et al 2011).

The seafloor of the CAO is not fully defined in geographical terms, pending decisions on the claims by coastal states for extended jurisdiction of mineral resources on their continental shelves. The "Area", also in the CAO, is governed by the International Seabed Authority (ISA), which is a UN body based in Jamaica. ISA has the duty to ensure the effective protection of the marine environment from harmful effects that may arise from deep-seabed related activities.

5.3.5 Tourism

In the 21 century, international tourists in the Arctic region has been increasing to reach 6 million including 1.2 million cruise tourists in 2015 (National Ocean Economics Program) (Tanaka et., al. 2018). Some Arctic tourism cruise routes are beginning to enter the CAO. Tourism in the CAO is likely to generally be associated with ships, although tourists are flown in to the Russian Barneo station established at the North Pole in spring.

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Proposed assessment products currently include:

- AMAP Assessment Report on "POPs – climate interactions" (possible targets for release include scientific conferences in 2021/2022, e.g. SETAC meetings)
- Summary for Policy Makers (target for release/delivery: Arctic Council Ministerial meeting 2021)

The scope of this work is not just 'central arctic ocean' and not just marine.

A scoping document is posted on the AMAP website on the following link: https://www.amap.no/work-area/document/2918. A table of contents is found in Annex 1. Timeline is found in Annex 2.

Mercury Assessment 2021

Proposed assessment products currently include:

- AMAP Assessment Report on "AMAP Assessment 2021: Mercury in the Arctic" (possible targets for release include Minamata COP (fall? 2021) and International Conference on Mercury as a Global Pollutant (South Africa, July 2021))
- Summary for Policy Makers (target for release/delivery: Arctic Council Ministerial meeting 2021)

The scope of this work is not just 'central arctic ocean' and not just marine.

A scoping document is posted on the AMAP website on the following link: https://www.amap.no/work-area/document/2917. A table of contents is found in Annex 1. Timeline is found in Annex 2.

POPs-climate interactions: https://www.amap.no/work-area/document/2918 (upcoming)

Mercury Assessment 2021: https://www.amap.no/work-area/document/2917 (upcoming)

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6 ToR e. Review and report on new studies on fishes in the CAO ecosystem

Contributing: Hauke Flores, Harald Gjøsæter, Kevin Hedges, Pauline Snoeijs-Leijonmalm, Ingeborg Mulder, Barbara Niehoff, Hyoung Chul Shin

6.1 Introduction

Over the years, several – partly overlapping – initiatives have been undertaken to describe, review, map, and monitor fish populations living in the CAO. It is worth noting that some experts are active in several of these initiatives.

Various working groups under the Arctic Council, such as AMAP, CAFF, and PAME have produced comprehensive reports dealing with Arctic biota, including fishes. The ten Signatories to the "Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean" established a group of scientific experts, including experts on fishes (the Scientific Experts on Fish Stocks in the Central Arctic Ocean group; FiSCAO), who met five times and produced reports summarizing the current knowledge about fishes in the CAO (FiSCAO 2017[1], 2018[2]). In 2019, when most Signatories had ratified the Agreement, the group of experts was re-established as the "Provisional Scientific Coordinating Group (PSCG)" to the Agreement and tasked to develop a monitoring plan for the CAO under the Agreement. The EU, one of the signatories to the Agreement mentioned above, published a report in spring 2020 titled "Review of the research knowledge and gaps on fish populations, fisheries and linked ecosystems in the Central Arctic Ocean (CAO)" (Snoeijs-Leijonmalm et al. 2020). The WGICA, established in 2016, was tasked to report on the current knowledge about all ecosystem components and the physical environment of the CAO ecosystem, to develop advice on IEA and to develop an Ecosystem Overview for the CAO. The two latter tasks distinguish the WGICA from the other groups. To accomplish its tasks, it is vital that the WGICA utilizes the knowledge already collected about fishes in the CAO, to the extent possible, including knowledge that has been summarized and reviewed by FiSCAO, the PSCG and AMAP, CAFF and PAME working groups.

In this chapter we summarize some of the fish research that has been carried out in recent years (2017-2020) in or adjacent to the CAO. We also compiled a list of peer-reviewed articles and reports covering the period 2017-2020, and new knowledge that has been gained through recent and ongoing research activities that have been reported in peer-reviewed journals as well as in cruise reports and project reports.

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[1] FiSCAO, 2017. Final Report of the Fourth Meeting of Scientific Experts on Fish Stocks in the Central Arctic Ocean. Tromsø, Norway, September 26-28, 2016, 82 pp. https://www.afsc.noaa.gov/Arctic_fish_stocks_fourth_meeting/default.htm.

[2] FiSCAO, 2018. Final Report of the Fifth Meeting of Scientific Experts on Fish Stocks in the Central Arctic Ocean. Ottawa, Canada, October 24-26, 2017, 45 pp. https://www.afsc.noaa.gov/Arctic_fish_stocks_fifth_meeting/pdfs/Final_report_of_the_5th_FiSCAO_meeting.pdf.

6.2 An analysis of literature published in the past three years (2017-2020)

The Fifth FiSCAO Report (FiSCAO 2018) provides a summary of literature on marine fishes in the CAO up to 2017. To provide an overview of literature on fishes published during 2017-2020, Alf Hakon Hoel and Pauline Snoeijs Leijonmalm prepared a list of relevant literature prior to the WGICA Meeting on 27-29 April 2020 and attendees updated the list during the meeting . The final list was analyzed by geographical area (shelf areas, gateways, CAO), number of species investigated (one species, multiple-species), and research topic (e.g. abundance, diet, genetics, experimental study). In this analysis, the Beaufort Sea is characterized as outside the CAO (as defined by PAME in 2016), even though parts of the Beaufort Sea are deeper than most shelf areas, and in that respect those parts are more similar to the CAO than to shelf areas. For consistency, the common name "polar cod" is used for the species *Boreogadus saida*, even though this species is also known as "Arctic cod" in some areas. Altogether, 109 publications were included in the analysis.

6.2.1 Shelf area

Most of the studies published during 2017-2020 focus on the shelves and slopes surrounding the CAO where mainly Arctic and Arctic-boreal fish species occur (***Figure 6-1***). The circumpolar genetic variation of polar cod has been assessed (Gordeeva & Mishin 2019, Nelson et al, 2020). Trawl surveys have been carried out in the Siberian shelf LMEs (Kara Sea, Laptev Sea, and East Siberian Sea) to study the role of polar cod in these ecosystems (Chernova 2018), and to assess the size composition and distribution of larval and juvenile polar cod (Mishin et al. 2018). Other studies focused on specific areas within the Siberian shelf such as the Kara Sea (Figure 1) (Antonov et al. 2017; Borodavkina et al. 2019; Dolgov & Benzik 2017; Prokopchuk 2017). Research included diet studies of polar cod (Prokopchuk 2017) and Greenland halibut (*Reinhardtius hippoglossoides*; Dolgov & Benzik 2017), visual observations of Greenland shark (*Somniosus microcephalus*; Borodavkina et al. 2019), and the abundance of polar cod and its fishery potential in the Kara Sea (Antonov et al. 2017).
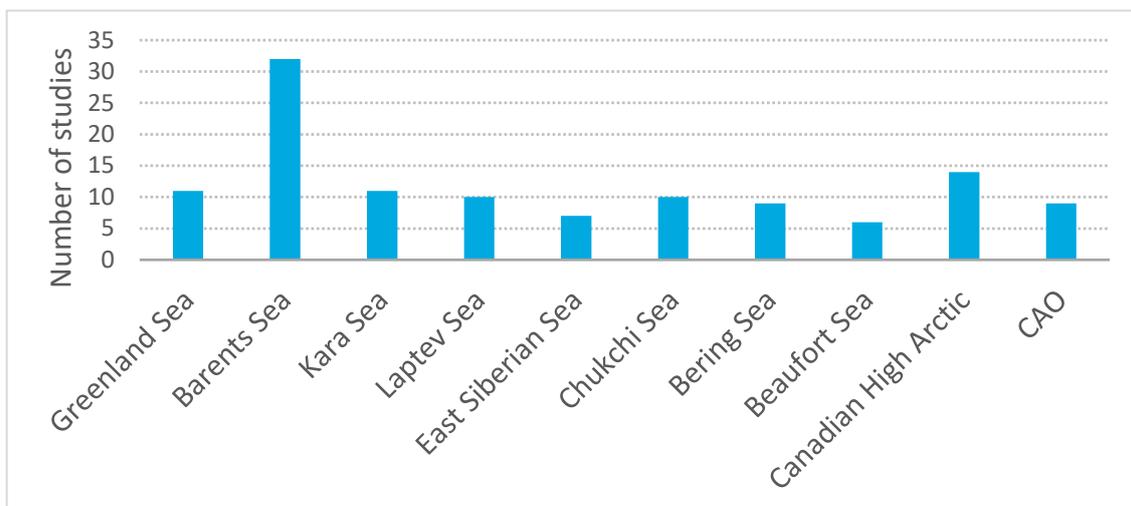

Figure 6-1. Number of studies on fishes in the CAO and adjacent shelf seas by geographical area.

Bouchard & Fortier (2020) studied the diet composition and feeding success of young polar cod in the Kara Sea and extended their research into other Arctic seas: the Laptev Sea, Beaufort Sea and parts of the Canadian High Arctic. Understanding the polar cod's feeding ecology is

important for predicting its response to the ongoing borealization of the Arctic seas. In the Canadian High Arctic, new research on polar cod in 2017-2020 includes genomics, thermal limits, movement and distribution (Drost 2017, Kessel et al. 2017, Wilson et al. 2017, Nelson et al. 2020). Other studies focused on boreal species that are currently expanding their range into the Canadian Arctic Archipelago (e.g. sand lance, *Ammodytes hexapterus*, Falardeau et al. 2017) and the continental slope of northeast Greenland (e.g. northern wolffish, *Anarhichas denticulatus*, Karamushko et al. 2017).

A recent study by Steiner et al. (2019) illustrates how combining physical, biological and socio-economical models in a common framework can help assess the impacts of climate change on an ecological keystone species, and resulting effects on subsistence fisheries by local communities. Steiner et al. conducted a case study focusing on polar cod, applying a comprehensive framework of linked Climate, Ecosystem and Economic (CEE) models. The study applied two scenarios for future climate projections, the so-called "business as usual scenario" (Representative Concentration Pathway, RCP, 8.5), and a scenario representing the Paris Agreement target limiting global temperature rise to 1.5°C (RCP 2.6). Regional models show declines in sea-ice concentration and sea-ice thickness throughout the whole Canadian High Arctic region over the past three decades. Associated with these changes, phytoplankton primary production increased. Ice-algae primary production also shows a somewhat positive trend, albeit with large inter-annual variability. A pronounced increase in sea-ice velocity indicates decreasing accessibility of hunting grounds for local coastal communities.
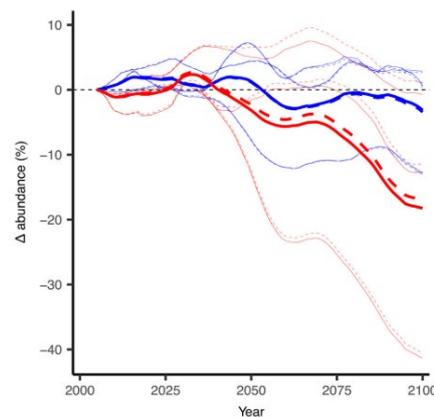
Figure 6-2. Projected changes in abundance for polar cod relative to the 2001–2010 average, as simulated with a Dynamic Bioclimatic Envelope Model (DBEM). Thin lines indicate the individual DBEM results with forcing input from three earth system models. Thick lines represent the averaged results from the respective three runs. Dashed lines indicate DBEM results that include impacts of ocean acidification. Red indicates DBEM results using the high CO2 emission scenario (RCP8.5), and blue indicates results for the low emission scenario (RCP2.6). Modified from AMAP (2018).

Future projections show continued rise of ocean temperature, and declines in oxygen concentration, pH and sea-ice concentration until the end of this century. The magnitude of these changes varies according to the scenario applied (RCP 8.5 or RCP 2.6). Model projections for the future (2100) development of polar cod abundance show an average 17% decrease under the RCP 8.5 emission scenario, and ~ 5% in the RCP 2.6 scenario, but the model uncertainty is high (*Figure 6-2*). Steiner et al. (2019) hypothesize that the demise of polar cod will negatively impact specialised predators, such as ringed seals and beluga whales, and therefore will also affect subsistence fisheries. In conclusion, Steiner et al. (2019) recommend that future decisions regarding commercial fisheries need to be precautionary and adaptive in light of the many uncertainties. Furthermore, inclusion of indigenous knowledge and the interests of local communities are essential.

6.2.2   Gateways

Increasing water temperature and loss of sea-ice trigger shifts in species distributions causing community-wide reorganizations and subsequent changes in ecosystem functioning. Ecosystems prone to fauna shifts are located on Arctic inflow shelves (major gateways into the Arctic), such as the Northeast Greenland shelf (Andrews et al. 2019), Barents Sea, and the northern Bering Sea and Chukchi Sea. To characterize potential future variations and changes in ecosystems, baseline information is needed. Several studies have reported such baseline information, including current demersal fish community structure and distributions (Bergstad et al. 2018, De Robertis et al. 2017, Vestfals et al. 2019), seasonal variations in biomass, species assemblages and trophic relationships (Geoffroy et al. 2019, Kortsch et al. 2019, Sigler et al. 2017), and the structure of water masses and plankton in the Atlantic Water Boundary Current (Hop et al. 2019). Other studies focused on the impacts of environmental variables (e.g. temperature, ice-cover), the behavior of individual fish species, and the functioning of fish communities (Frainer et al. 2017, Huserbraten et al. 2019, Marsh et al. 2019, Mueter et al. 2017, Schmidt et al. 2017). Recently recognized stressors for polar cod include plastic litter. Kühn et al. (2018) showed a 2.8 % frequency of occurrence of ingested non-fibrous microplastic particles among 72 polar cod specimens, which is similar to levels in previous studies. In combination with ocean warming and sea-ice decline, plastic ingestion might act as an increasing stressor on polar cod (Kühn et al. 2018).

The deep scattering layer (DSL, >200 m) south of the CAO was described by Gjøsæter et al. (2017) and Knutsen et al. (2017), as documented from most other oceans. Species (zooplankton, small fish) occurring in these layers play a key role in carbon sequestration (Knutsen et al. 2017). Gjøsæter et al. (2017) showed that these layers display diel vertical migration with a clear ascending movement during nighttime and a descending movement during daytime. Berge et al. (2020) showed that artificial light can influence the vertical distribution of fishes and zooplankton.

6.2.3   CAO

Some studies published on the CAO in the last three years used previous collected publicly available data to make model predictions about near future and longer-term (decreased) development of sea-ice cover (Screen & Williamson 2017, Serreze & Meier 2019) and northward movement of sub-Arctic and boreal fishes and shellfish with climate-induced environmental change (Hollowed et al. 2017).

Other studies combined and summarized previous datasets to understand general structures or movement patterns of zooplankton and small fishes (Hobbs et al. 2018) or compiled an organic carbon budget for the deep Arctic Ocean (Wiedmann et al. 2020). Others collected new expedition data in the CAO. Kohlbach et al. (2017) examined the contribution of ice algae-produced carbon to the carbon budget of polar cod and Flores et al. (2018) reported on the biodiversity of sea-ice associated habitats, with emphasis on polar cod and its ice-associated and pelagic prey species, using data from the Polarstern expedition "IceArc" in 2012. Melnikov (2018) used data obtained during Pan-Arctic ice camp expeditions (PAICEX) in 2007-2011 and 2015 to characterize the biodiversity of ice-associated flora and fauna. Most samples in the above-mentioned papers were collected at the outer edges of the Amerasian and Eurasian Basins (Hobbs et al. 2018, Kühn et al. 2018), a few were collected near the Lomonosov Ridge (Hobbs et al. 2018), and some were collected around 89 oN (Kohlback et al. 2017, Hobbs et al. 2018, Melnikov 2018).

6.2.4 Experimental studies

Several experimental studies have been published on Arctic fish species and species that are showing a northward shift in their distribution, such as Atlantic cod (*Gadus morhua*). Most of these studies have looked at the impacts of temperature on lipid allocation (Copeman et al. 2017), habitat loss (Dahlke et al. 2018), condition, survival and growth (Koenker et al. 2018a, Koenker et al. 2018b, Laurel et al. 2017, Laurel et al. 2018), metabolism and swimming performance (Kunz et al. 2018), and behaviour (Schmidt et al. 2017). Most of these studies focused on polar cod, but some also examined saffron cod (*Eleginus gracilis*) (e.g. Copeman et al. 2017) and walleye pollock (*Gadus chalcogrammus*) (e.g. Koenker et al. 2018a). Another well-studied topic is the effect of oil exposure on the long-term survival, growth, lipid allocation, lipid metabolism and biotransformation, and reproductive development of polar cod (Bender et al. 2018, Laurel et al. 2019, Vieweg et al. 2017).

6.2.5 Policy

The opening of the Arctic Ocean provides many opportunities for both Arctic and non-Arctic states. Therefore, several policy papers have examined the challenge of researching sustainable management of living resources (Crépin et al. 2017, IPCC 2018, Landriault 2018, Vestergaard et al. 2018). As climate change is expected to transform the CAO ecosystem, research has focused on how these changes might impact geophysical variables and as a result directly or indirectly impact socio-economic activities like transportation, marine sea food production and resource exploitation (Crépin et al. 2018, IPCC 2018). Other publications focused mainly on fisheries in the CAO, including gaps in fisheries research (Papastavridis 2018, Van Pelt et al. 2017), science coordination (Van Pelt 2017), effective tools for fisheries enforcement (Papastavridis 2018), the role of law (Rayfuse 2019), ocean governance for species on the move (Pinsky et al. 2018), determination of total allowable catch given certain restrictions (Richter et al. 2018), and how social-ecological cross-scale interactions affect the development of Arctic fisheries (Niiranen et al. 2018).

6.2.6 Research topics

The literature on fishes in the Arctic Ocean published in the last three years (2017-2020) covers a wide variety of topics, from life history to food web interactions and policy (*Figure 6-3*). Most studies report the abundance and distribution of certain species or fish assemblages in particular areas – in some cases to assess fishery potential. The number of studies that investigated a single species (N=38) or multiple-species (N = 32) are relatively similar. Several studies focus on the effects of climate change (warming ocean, retreating ice-cover and acidification) in the Arctic region both from an ecological and policy perspective (Figure 2). Topics such as growth, condition, life history, genetics and conservation were little studied in the last three years.
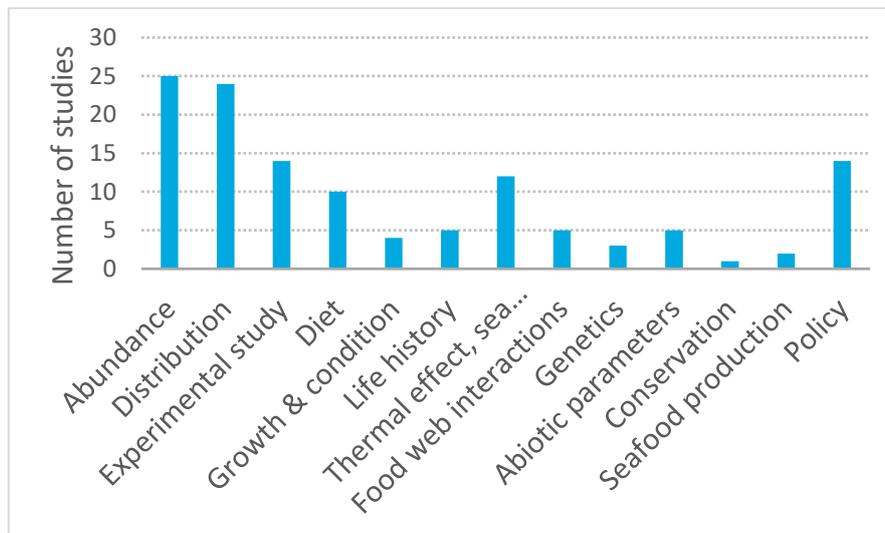
Figure 6-3: Number of studies on fishes in the CAO and adjacent shelves by research topic.

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7 ToR f. Continue to identify priority research needs and monitor how identifies knowledge gaps are being addressed and filled

Leads: Jacqueline Grebmeier[1] and Randi Ingvaldsen[2] - with text and additions from chapter 3, 4, 5, and 6 (see authors of each of the chapters).

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7.1 Introduction

The goal of ToR f is to identify priority research needs and questions to understand the impact of ongoing environmental change and human activities on the Arctic ecosystem, and to assess whether ongoing and planned activities will address the identified knowledge gaps.

The report is organized as follows; first we describe important case studies from ongoing research, mapping and monitoring (7.2), as well as some new tools and methods necessary for conducting the needed research including recent experience with sampling gear (7.3). Thereafter we list the identified research questions and monitoring needs for each of the ToRs b-e (7.4), before we summarize the overall conclusions and discuss them in relation to earlier assessments as the SAMBR report (CAFF, 2017) and the reports from the FISCAO process (FISCAO 2016 and 2018, PSCG 2020) (7.5).

7.2 Examples of Case studies form ongoing research, mapping and monitoring in the CAO

n inventory of monitoring programs can also be found in PSCG 2020.

7.2.1 Distributed Biological Observatory (DBO)

Variations in upper-ocean hydrography, light penetration, lower and upper trophic levels, pelagic-benthic coupling and carbon cycling are being evaluated through the Distributed Biological Observatory (DBO), which was initiated in 2010 in the Pacific Arctic (Moore and Grebmeier 2018). The DBO sampling approach emphasizes annual standardized sampling by an international suite of ships occupying agreed-to transect lines in order to measure the status and developing trends in key measurements for the marine ecosystem. Continuous data are also obtained through mooring and satellite observations. The first decade of DBO sampling has revealed seasonal and interannual hydrographic changes are driving shifts in biological species composition and abundance, northward range expansions for some temperate species and negative impacts for some ice dependent species. This model of change detection is being expanded to other Arctic regions beyond the initial implementation in the Pacific Arctic. An Atlantic DBO is in development through coordination of ongoing international field activities in the Eurasian Arctic, and planning has started for an effort in Davis Strait/Baffin Bay. The FISCAO process identified the use of standard measurements and section lines in the shelf to outer slope in the DBO network as a potential model for coordinated international activities for the Central Arctic Ocean (CAO), including the developing Synoptic Arctic Survey (SAS) to include a suite of Essential Ocean

Variables (EOVs) to be collected by multiple ships sampling in the CAO in a pan-Arctic effort, including associated data exchange (PSCG 2020, Paasche et al. 2019). Information on the DBO can be found at https://dbo.cbl.umces.edu/.
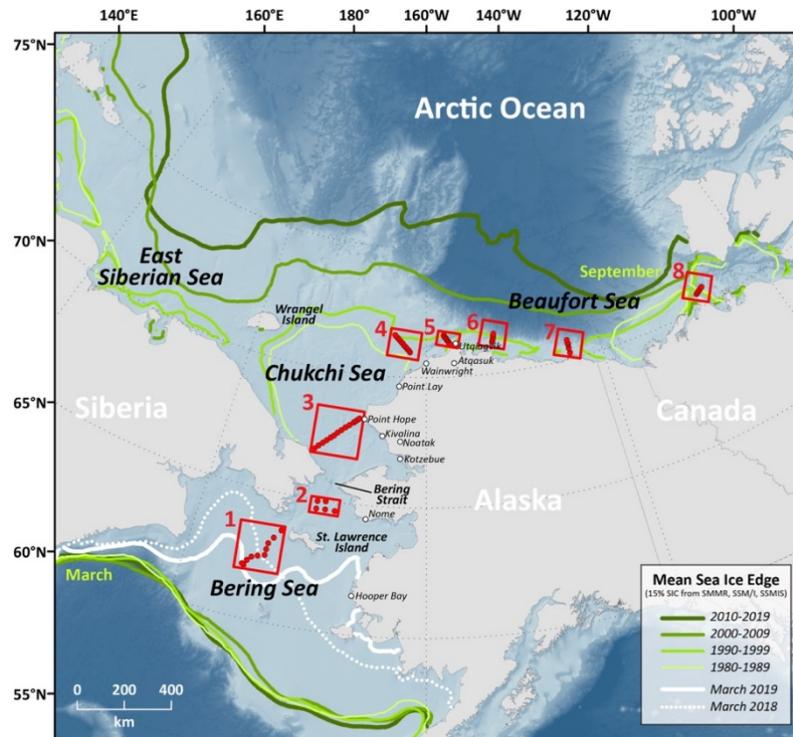

Figure 7.1 The eight sampling regions of the Distributed Biological Observatory (DBO) extending from the northern Bering Sea into the Beaufort Sea in the Pacific Arctic Region that are focused on 'hotspots' of biological productivity and biodiversity. Maximum and minimum median ice extent based on SMMR, SSM/I, and SSMIS satellite-derived sea-ice concentrations (1979–2018) are also shown on this figure (from Grebmeier et al. 2019).

7.2.2   Pacific Arctic Climate Ecosystem Observatory (PACEO)

The Pacific Arctic Climate Ecosystem Observatory (PACEO) is a developing long-term monitoring Pacific Arctic Gateway (PAG) activity in the high Pacific Arctic and CAO (Figure 7.1). PACEO includes a set of climate-ecosystem lines extending from west of the Chukchi Borderlands into the Canada Basin in the CAO. This developing international initiative is coordinating multiship operations in the Pacific Arctic Ocean that are including standard physical, biochemical and biological measurements, similar to the DBO. The PACEO sites are occupied by international entities in the CAO with a shared data plan. Key fisheries measurements are also planned to understand the Pacific CAO's marine ecology and the potential impacts of climate change before fishing becomes widespread and to prevent unregulated high seas fisheries in the CAO. Figure 7.2a provides a schematic of the PACEO, multi-ship effort for sampling in the Pacific CAO. Figure 7.2b shows the 10-yr time series stations undertaken as part of the Korean Polar Research Institute (KOPRI) efforts over the Chukchi Borderland into the CAO as part of the PACEO effort.
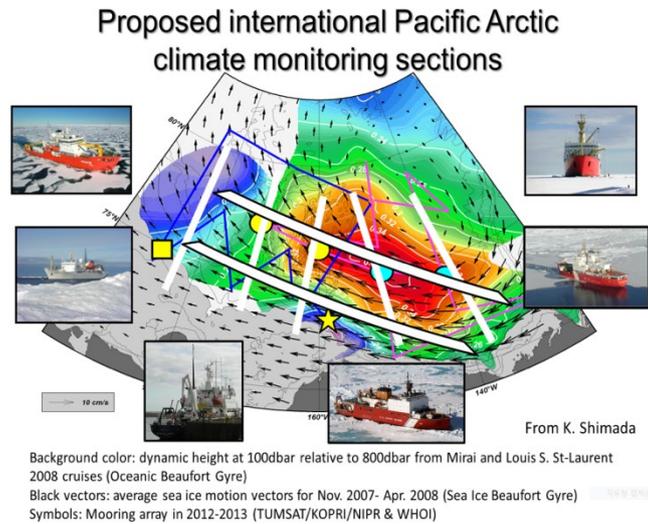
Figure 7.2a Developing international Pacific Arctic climate monitoring sections as part of the Pacific Arctic Climate Ecosystem Observatory (PACEO).
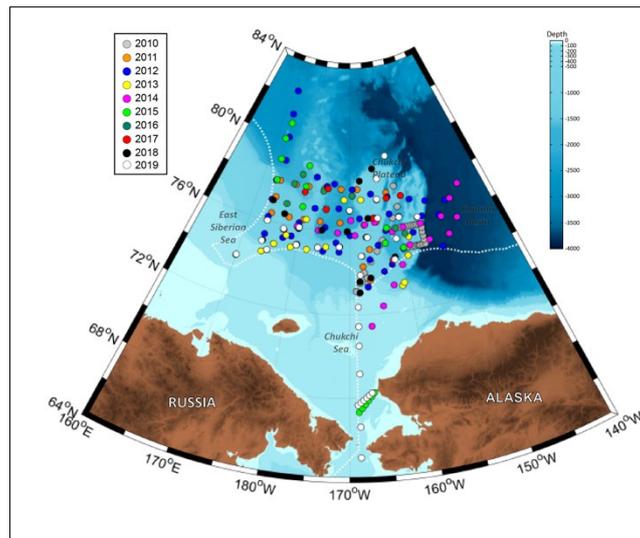
Figure 7.2b. Time series stations occupied on the RV ARAON as part of the PACEO program.

7.2.3 Joint Ocean Ice Studies (JOIS)

Canada has conducted a variety of studies in the Beaufort Sea and adjacent waters since the early 2000s (Figure 7.3). The Joint Ocean Ice Studies (JOIS) program is an international collaboration among Canada, the United States and Japan; the program provides ongoing assessment and monitoring of oceanographic and sea ice conditions through a combination of ice buoys, CTD casts, XCTDs, bongo net tows and closing nets. JOIS program cruises collect data for the Arctic Observing Network - Beaufort Gyre Observing System (AON-BGOS) and more recently represent an important part of Canada's contribution to SAS (Paasche et al. 2019). Information about the 2018 JOIS cruise can be found at: https://www.dfo-mpo.gc.ca/science/atsea-enmer/missions/2018/jois-eng.html.
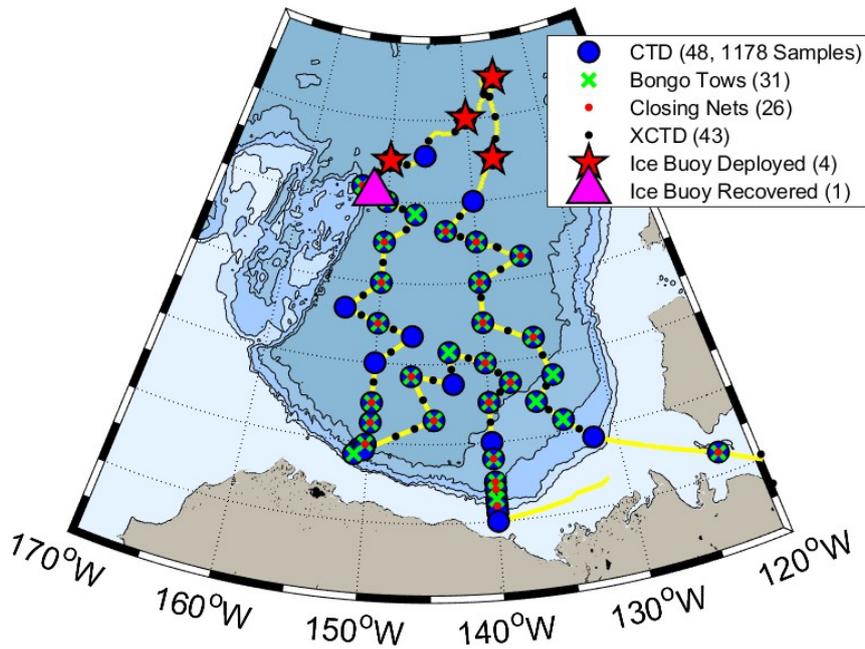
Figure 7.3. Sampling and observation locations from the 2019 Joint Ocean Ice Studies - Arctic Observing Network - Beaufort Gyre Observing System– Synoptic Arctic Survey cruise in the Canadian Beaufort Sea and adjacent waters.

7.2.4 Canadian Beaufort Sea Marine Ecosystem Assessment (CBS-MEA)

Surveys of phytoplankton, zooplankton, marine invertebrates, fishes and mammals have been less regular in the Canadian Beaufort Sea, but significant data have been collected through short term (typically 1-3) year programs. The Canadian Beaufort Sea Marine Ecosystem Assessment (CBS-MEA) is a multi-year program that represents a resumption or continuation of the Beaufort Regional Ecosystem Assessment–Marine Fishes Project that was conducted during 2012-2014. CBS-MEA is collecting baseline data on phytoplankton, zooplankton, marine invertebrates and fishes throughout the Canadian Beaufort Sea (Figure 7.4) and supports long-term monitoring. CBS-MEA links to the JOIS program as well as coastal, community-based research programs to integrate data throughout the Beaufort Sea ecosystem and across trophic levels. Sample collection includes rosette and CTD casts, box coring, bongo/multi-net collections, benthic and midwater trawling and ship-based hydroacoustics (EK80). Information about the 2019 CBS-MEA cruise can be found at:

https://www.dfo-mpo.gc.ca/science/atsea-enmer/missions/2019/beaufort-eng.html.
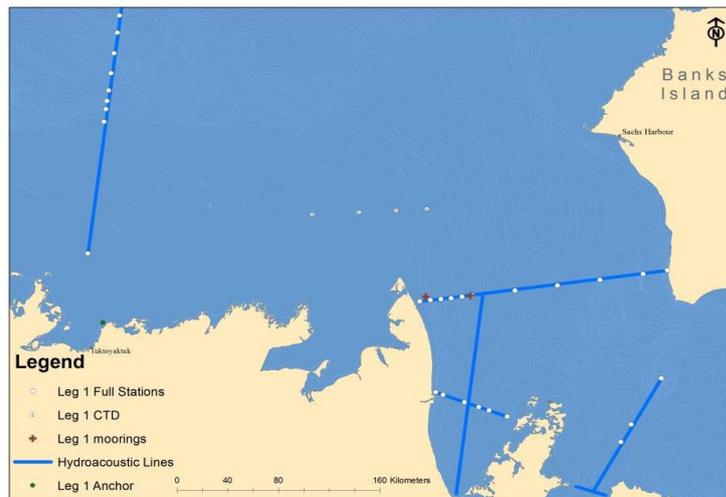
Figure 7.4. 2017 Canadian Beaufort Sea Marine Ecosystem Assessment sampling stations and transects.

7.2.5 Canadian Beaufort Sea Marine Mammal research

Community-based programs focused on marine fishes and mammals provide coastal data col-lections in the Canadian Beaufort Sea (Figure 7.5a and b). In particular, marine mammal research largely involves community-based programs supplemented with occasional aerial surveys. Community-based marine mammal programs annually collect data on animal health, species distributions/habitat use (through direct observations, moored hydrophones or deployment of pop-off archival satellite tags) and record any unusual occurrences with marine mammals or other ecosystem components. Aerial surveys support population assessments to support harvest management. In combination, these programs provide ongoing data on the presence, habitat use, movement patterns and health of marine mammals.
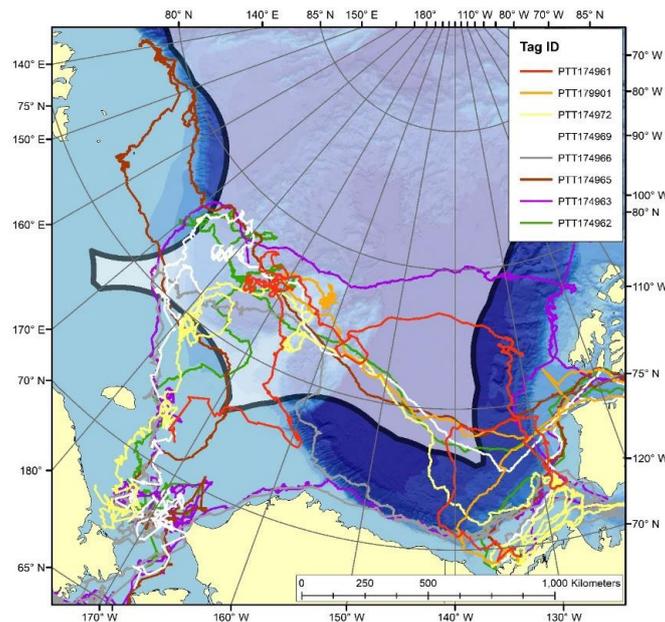
Figure 7.5a. Positions of eight whales recorded between mid-July to mid-November in 2018 and 2019; majority of records from late-August to mid-October.
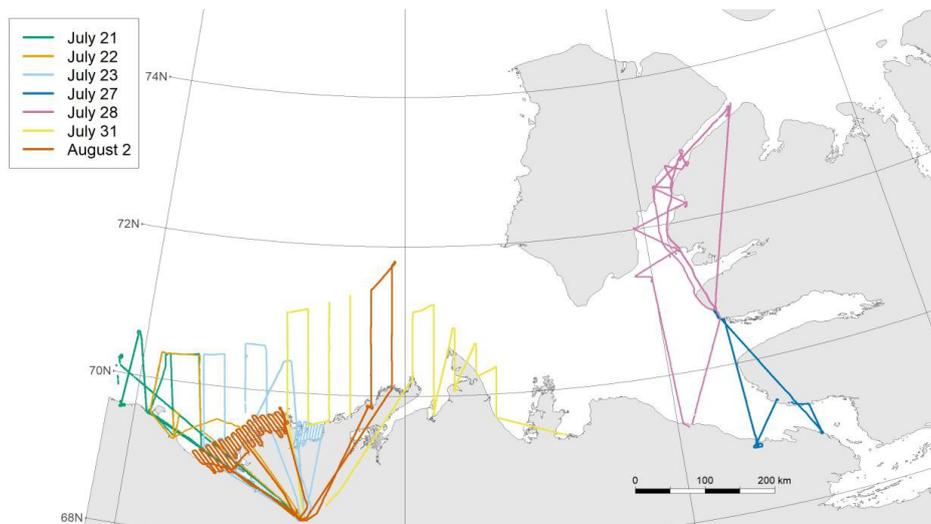
Figure 7.5b. Transects flown during an aerial survey on marine mammals in the Beaufort Sea in 2019. Field programs, both vessel (JOIS and CBS-MEA) and community-based (marine mammal health assessments and tagging), are planned for summer-fall 2020, but their status is currently uncertain because of the COVID-19 pandemic and resulting travel restrictions.

7.2.6   Nansen Legacy

The Norwegian research program Nansen Legacy is a 6-year project (2018-2023), mainly using the new Norwegian ice-going research vessel *Kronprins Haakon*. The core activities of the program include research expeditions into ice-covered waters of the northern Barents Sea and adjacent Arctic Basin. This is an integrated ecosystem research program spanning meteorology, ocean physics and chemistry, primary production and higher trophic levels, including marine mammals and birds. The first Nansen Legacy cruise was conducted in fall 2018, and some cruises were conducted in 2019, but not all planned cruises were completed due to required maintenance and improvements to the new vessel during the warranty period. By the end of 2023 the program is expected to complete 370 days at sea. Unfortunately, most cruises planned for the first half of

2020 have been postponed/cancelled due to the COVID-19 pandemic. Information about plans and cruises can be found at: https://arvenetternansen.com/.

7.2.7 Multidiciplinary Drifting Observatory for the Study of Arctic Change (MOSAiC) Expedition

The MOSAiC expedition started on 20 September 2019 using the German research icebreaker *Polarstern*. The goal of the expedition is to spend a full year drifting with the sea ice in the Arctic Ocean and conduct a continuous year-round multidisciplinary study of the coupled atmosphere-ice-ocean-biosphere system while following the Transpolar Drift (Figure 7.6). Throughout the expedition, scientists record data on sea ice and snow, oceanography, atmosphere, nutrient availability and fluxes, primary productivity, zooplankton, marine invertebrates, and fishes. In addition to observations of ambient conditions and biota, experiments are conducted on the vessel to understand ecosystem processes and linkages, in order to improve physical and ecosystem models. An accurate representation of these processes in models has been lacking so far but is essential for examining how climate change and anthropogenic stressors may affect the Arctic marine ecosystem and biota. Information about the background and progress of the MOSAiC Expedition can be found at: mosaic-expedition.org and https://follow.mosaic-expedition.org.
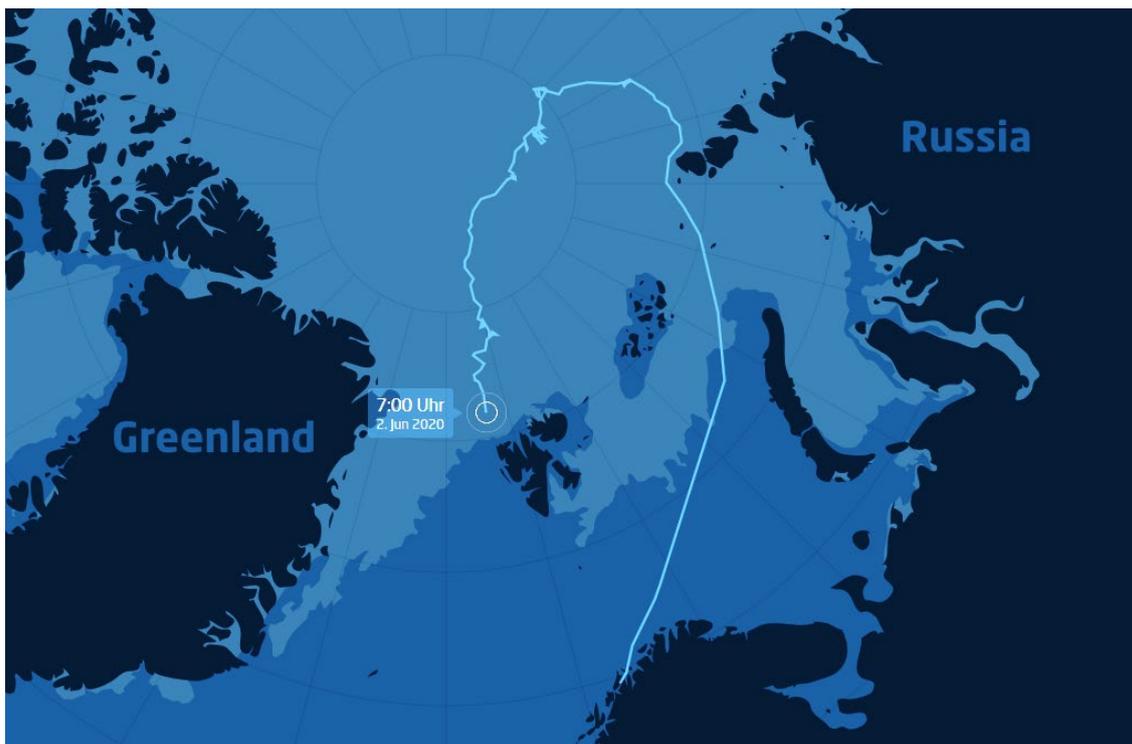
Figure 7.6. Cruise track of RV Polarstern during the MOSAiC Expedition from 20 September 2019 to 02 June 2020. In May 2020 Polarstern temporarily left the MOSAiC ice floe to exchange crew and cargo near Svalbard.

7.2.8 Ecosystem monitoring in the Atlantic gateway

Monitoring of the Atlantic gateway to the Arctic Ocean is undertaken through repeat section crossings of the shelf-break north of Svalbard (the Hinlopen section at about 20°E). The section is sampled annually in late summer/early autumn (since 2014). The current sampling routine includes physical and chemical oceanography, zooplankton (meso and macro) biomass and species composition, juvenile fish in the upper layers (trawling), pelagic fishes in the mesopelagic layer (trawling) and demersal fishes and benthos (trawling). Underway acoustic measurements

(EK80) and visual sightings of marine mammals and sea birds are also conducted. Year-round monitoring of physical, chemical and acoustic properties is conducted with moorings slightly further to the east (at about 30ºE as part of the ATWAIN-SIOS project). The repeated section and the moorings contribute to long-term monitoring detecting changes in physical, chemical and biological properties at the Atlantic gateway, and can be used to document changes in the deep scattering layer and the pelagic ecosystem at this entrance to the Arctic Ocean.

7.2.9 Synoptic Arctic Survey (SAS)

The CAO remains profoundly understudied, particularly carbon cycling, ecosystem alteration, and associated changes in atmosphere, ice and ocean physics that influence those biological and biogeochemical systems (Paasche et al. 2019). The region is expected to experience marked changes over the next decades, driven by ongoing climate warming, yet our understanding of key process is limited for this area. SAS seeks to quantify the present states of the physical, biological, and biogeochemical systems. Multiple countries have both confirmed and pending cruises as part of the 2020/2021 SAS networked activities, although many 2020 cruises have been postponed to 2021 due to the COVID-19 pandemic and some cruises are now planned for 2022. Key goals of the SAS are to establish the present state of the Arctic system, to document temporal changes where possible through comparison with historical data, and to quantify linkages between the adjacent shelves, slopes, and deep basins, objectives that are shared with the broader Pan-Arctic effort of the composite SAS. The SAS consists of regional shelf-to-basin ship-based surveys in 2020 and 2021 (and now into 2022) to obtain a Pan-Arctic understanding of essential ocean variables (EOVs) on a quasi-synoptic, spatially distributed basis in which no single nation bears the full burden of collecting the requisite data. The SAS will also provide an important legacy of field activities to future, quasi-decadal assessments of rapid and evolving Arctic Ocean system change.

7.2.10 North Pole 2020 expedition

Members of the Russian Academy of Sciences (RAS) plan a North Pole 2020 expedition involving 20 RAS institutions (https://arctic.ru/news/20200311/932193.html). The icebreaker *Kapitan Dranitsyn* will be frozen in the ice to become the base for the expedition which will also include satellite ice camps. It is expected to start drifting in the area of the New Siberian Islands (about 85°N), after which it will go to the Amundsen Basin, move along the Lomonosov Ridge and turn left, crossing the Gakkel Ridge. Major investigations involved in the expedition (with emphasis to climate change) include hydrometeorology, oceanology and ice studies, air pollution and aerosols, pollution (POPs, microplastic, trace metals and radionuclides), biodiversity (benthos, ice microbiota and plankton, pelagic plankton, marine mammals and seabirds), geology and seismology. *The status of the expedition is currently uncertain because of the COVID-19 pandemic and resulting travel restrictions.*

7.3 New tools, methods, and sampling gear for studies of the CAO

Sampling in the CAO is challenging due to the heavy sea ice conditions, in particular the impact on sampling for fish. Below we have given a brief overview of ongoing investigations and recent progress on this matter.

7.3.1 Sampling of fish in the ice-covered CAO (EU project EFICA)

Addressing the urgent need to assess fish stocks of the CAO in the framework of the Agreement to prevent unregulated high seas fisheries in the CAO, the EU-funded European Fish Inventory of the Central Arctic Ocean (EFICA) Consortium aims to map the fish stocks present in the CAO for the first time. Sampling fish with trawled nets is impossible as long as the CAO is covered by perennial sea ice. Therefore, new methods are being applied to maximize the information on fish without using trawled nets. To this end, EFICA is participating in the ongoing MOSAiC expedition on the RV *Polarstern* and planned to sample on the SAS expedition with RV *Oden* that was originally scheduled for August-September 2020 but which, due to the COVID-19 crisis, now will take place in 2021. On MOSAiC, EFICA uses a combination of hydroacoustics, an *in situ* deep-sea camera system, longlines, gillnets, fishing rods and eDNA sampling. These approaches will be extended with large ring nets that can sample the water column vertically during the SAS-*Oden* 2021 Expedition.

7.3.2 The SUIT in the Arctic Ocean – Recent sampling of polar cod under sea ice in the Chukchi-Beaufort region

The ice-water interface constitutes a unique habitat of the CAO, providing the only surface substrate in the euphotic zone. At this interface, sympagic and cryo-pelagic organisms interact, and carbon is transferred from internal sea-ice biota to the pelagic food web. This important habitat, however, is inaccessible with conventional sampling gear. Based on small-scale sampling with divers and dip nets it became evident that the ice-water interface can host significant abundances of under-ice fauna and constitutes an important nursery habitat for young polar cod *Boreogadus saida* (Hop et al. 2000, Gradinger and Bluhm 2004, Melnikov and Chernova 2013). During the past eight years, a novel sampling device was used to study the large-scale distribution of under-ice invertebrates and polar cod in the Eurasian Basin of the CAO, the Surface and Under-Ice Trawl (SUIT, van Franeker et al. 2009, Flores et al. 2012). Studies using SUITs equipped with environmental sensor arrays demonstrated that the under-ice community structure varies with changes in sea-ice properties and oceanographic conditions (David et al. 2015, Flores et al. 2019, Ehrlich et al. 2020), and investigated the spatial variability of physical properties, ice-algae biomass and primary production in ice-covered waters (Lange et al. 2016, 2017, Massicotte et al. 2019, Castellani et al. in press). In particular, SUIT sampling enabled the first basin-scale study of the distribution of polar cod in the ice-water interface layer and highlighted the potential of sea ice as a vector of trans-Arctic migrations in the Eurasian Basin (David et al. 2016). Further SUIT-based studies confirmed a high dependency of young polar cod and their prey on ice algae-produced carbon (Kohlbach et al. 2016, 2017) and investigated microplastic ingestion of under-ice polar cod (Kühn et al. 2018).

7.3.3 The SUIT in the Arctic Ocean – Results from the Go-West project

Based on their observations in the Eurasian part of the CAO, David et al. (2016) had proposed that young polar cod associate with sea ice on the Siberian shelf during autumn and then get advected across the CAO during their first and second year of life. Building on these investigations, the University of Alaska Fairbanks and AWI speer-headed a first field survey with SUIT in the American Arctic in November/December 2019. This survey was realized within the project "Go-West", using the US vessel RV Siquliak. The overall goal of Go-West was to test the hypothesis that entrainment of young polar cod into the under-ice habitat during autumn is significant also in the Chukchi and Beaufort Seas and adjacent CAO. The specific objectives of Go-West

were to: 1) Identify sea ice habitats favourable for polar cod in terms of physical properties, ice algal biomass and prey composition; 2) test for the presence of deep scattering layers in the underlying water column; 3) quantify the carbon flux between sea ice, plankton, and polar cod and assess the pre-winter condition of polar cod; and 4) study the connectivity between central Arctic under-ice populations and shelf-based spawning populations.

Go-West was in large parts funded by the Arctic Research Icebreaker Consortium (ARICE). The project represented 7 institutes from 5 nations, and the team consisted of 11 members from 6 countries. Go-West was conducted during RV Sikuliaq expedition SKQ201923S (06 November – 02 December 2019), together with the physical-oceanographic project Coastal Ocean Dynamics in the Arctic (CODA). The study region covered the continental slope between the shelf break and the Canada Basin between the Chukchi Sea and the Beaufort Sea off Alaska's North Slope (Figure 7.7). Go-West sampled Polar cod and its prey in the ice-water interface layer with a Surface and Under-Ice Trawl (SUIT), along with high resolution profiles of sea-ice and surface water properties. In addition, backscatter of fish and zooplankton in the water column was recorded with an EK80 echosounder, and pelagic communities were sampled with midwater trawls and vertical zooplankton nets. A CTD probe equipped with a rosette water sampler sampled vertical profiles of water column properties and was used to collect water samples for biogeochemical parameters. During four ice stations, sea ice was sampled for biogeochemical and optical properties.
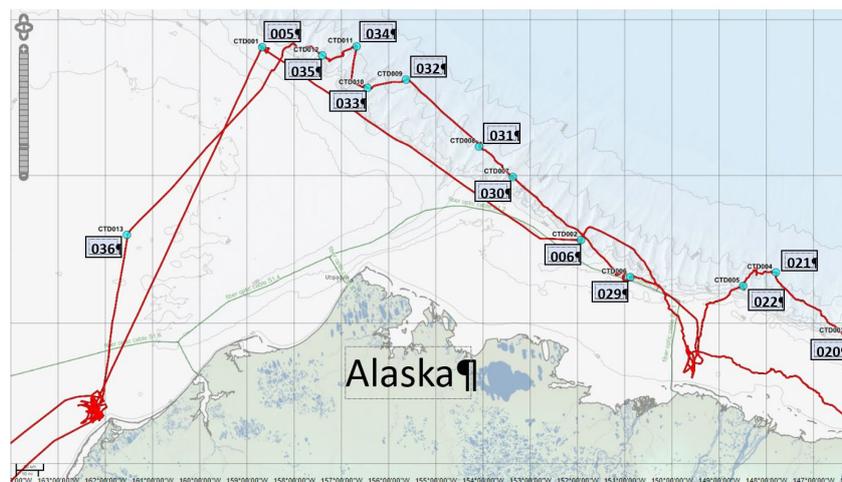
Figure 7.7. Working area and track chart of R/V Sikuliaq, Cruise SKQ201923S with fishing stations and ship CTD station numbers indicated (from: Flores, Mueter et al., 2020).

Altogether, Go-West completed 11 SUIT stations (1 in open water, 10 under ice), 4 ice stations and 3 midwater trawls. On the continental shelf, under-ice macrofauna abundance was low. The highest densities of under-ice macrofauna were found at the deep-water stations, including several neritic taxa. Polar cod were caught at all SUIT stations (Figure 7.7). Most fish appeared to be first-year juveniles between 6 and 8 cm in size, pending age determinations. The trophic relationships between ice algae, zooplankton and sea-ice fauna and Polar cod will be analyzed in detail based on diet and trophic biomarker samples. Investigations of otolith microchemistry and population genetics studies on each sampled fish will help elucidate their origins and migration patterns.

The preliminary results of this expedition support the hypothesis that juvenile Polar cod associate with sea ice in autumn and show that prey is available to sustain them at the onset of winter. In conclusion, SUIT can be a useful tool to study polar cod and ice-associated fauna at large spatial scales, and to link spatial distribution with sea-ice properties and life cycle studies.

7.3.4   A new, non-invasive tool, environmental DNA

More detailed information on fish communities in the CAO is in dire need for ecosystem assessment and to support management. Despite the number of current and planned campaigns in the CAO, usual field protocols do not always include typical fish sampling elements using large nets and trawls. Non-invasive techniques that can be employed without affecting the vessel's planned trajectory can offer a great deal of opportunities to collect information on the fish fauna. These would include hydroacoustics and environmental DNA.

Environmental DNA (eDNA) means DNA genetic substances contained in a state of free-floating DNA, fragments of cells, feces, saliva, urine and skin cells (Tsuji et al. 2019). The constant loss and shedding of genetic material from macrorganisms impart a molecular footprint in environmental samples that can be analyzed to determine either the presence of specific target species or to characterize biodiversity without the need for capture or visual surveys. Target organisms can also be detected at any life stage, including in the egg, larval, and juvenile forms from eDNA samples. Therefore, emerging eDNA technologies are non-invasive, sensitive, and cost-efficient compared to traditional survey approaches (Rees et al. 2014). Environmental DNA approaches are used to detect specific fish species and determine fish community diversity (Thomsen et al. 2012, Shu et al. 2020). Although the technique has become widely available only recently, there are now numerous accounts of its application. Further utility of eDNA for fisheries management is the potential ability of eDNA quantities to reflect fish biomass in the ocean. Positive relationships between eDNA quantities and fish biomass and abundance are now being reported, for example from Atlantic cod, Gadus morhua (Salter et al 201). Application in the very central Arctic has yet to be made but some related sub-Arctic water fauna has been subject to such attempts, especially on the identical species with some success. Thomsen et al (2016) reported eDNA metabarcoding of seawater samples from continental slope depths in Southwest Greenland and compared seawater eDNA to catch data from trawling. Environmental DNA sequence reads from the fish assemblages correlated with biomass and abundance data obtained from trawling. Environmental DNA reads can be used as a qualitative and quantitative proxy for marine fish assemblages and this relates to monitoring effects of ongoing climate change on marine biodiversity in Arctic waters.

It is encouraging for such application that there is a fair amount of information regarding the genetics of some key species, for example Arctogadus glacialis and Boreogadus saida. Breines et al. (2008) determined the complete mitochondrial genome sequences of both species. Nelson et al. (2013) reported sets of 19 and 16 microsatellite loci for the examination of the population genetics of B. saida and A. glacialis, respectively. Six of these loci were developed from a collection of 9,497 expressed sequences from B. saida while the remaining loci were found in the literature and optimized for use in B. saida and A. glacialis. Later on, Nelson et al. (2020) provided good knowledge of B. saida population genetic structure that can provide insight into how the species may respond to environmental change, and allow for establishment of meaningful management units by analysing nine microsatellite DNA loci in 2269 fish collected at 19 locations across the species' range. The population genetic structure detected is likely to be important for the response of B. saida to environmental change and should be considered in management of human activities that may impact this foundational species.

For future surveys in the CAO, two non-invasive tools could be used in combination, such as hydroacoustics and eDNA, to record the occurrence of fish species and to estimate their abundance. Hydroacoustics can discriminate the classification of echoes from fish, while eDNA might be used to validate the acoustics data and to improve species identification. Berger et al. (2020) used eDNA to groundtruth the hydroacoustics they employed to detect pelagic fish in a whale feeding area in Canadian waters. The eDNA analyses helped determine the dominant species and the variability in their abundance. This kind of study will contribute toward collection of the

badly wanted data for science-based conservation in the CAO and in particular, will provide extra capacity for the field programs with no direct fishing plan and enable full use of the vessels' path and ship time.

7.4 Priority research and monitoring needs per ToR

Priority research, monitoring needs and recommendations for each of the expert groups ToR b-d are given below.

7.4.1 (ToR b): On-going and recent changes and events in the CAO

- Priority research is needed in ice edge areas (marginal ice zones) because the ice edge is lacking data, but is expected to have unique conditions of atmosphere and ocean inter-action, resulting in potential biological hotspot locations.
- Long-term monitoring is needed to detect changes in ocean properties and sea ice in the Arctic gateways, as changes in the gateways could be used as initial conditions for as-sessment of changes in the CAO.
- Monitoring of the Arctic slopes is necessary as these are the regions that will experience the largest changes in the near future.
- Winter observations are of critical importance since the number of such observations is very small, while detailed understanding of winter processes is essential for correct in-terpretation of the entire pattern of ongoing changes.

7.4.2 (ToR c): Continue to examine effects of climate change on the ecosystem and assess projected future changes

7.4.2.1 Phytoplankton and algae

- For the CAO, there is a lack of regular monitoring of phytoplankton and algae (CAFF 2017).
- It is important to have comparable, supporting data regarding the physical and chemical environment for evaluating this system.
- There is a general lack of baseline data in the CAO, especially throughout the year, and it may therefore be challenging to distinguish between natural variations and changes of primary producer communities due to anthropogenic modification (von Quillfeldt and Smith 2016).
- Monitoring should be standardized regarding gear, collections, timing, sample preser-vation and processing, storage and data management.
- Available monitoring protocols need to be more widely available for standardized mon-itoring parameters.
- Species information is required for monitoring biotic community changes that are driven by climate. However, comparable data from different laboratories requires taxonomic expertise, which is becoming rare. An alternative or complement to microscopy identifi-cation is the use of marker genes to identify species, although this approach requires infrastructure and access to sequencing facilities.
- Understanding how nutrient limitation enhances heterotrophy in ecosystems and quan-tifying the potential impact this limitation has on ecosystem function is fundamental for the development of future scenarios of the changing Arctic ecosystems (Flores et al. 2019)

7.4.2.2 Sea-ice biota

- Monitoring should be conducted with consistent methodology after coordinated plans (gear, collections, timing, sample preservation and processing, storage, and data management) for sampling at set locations, with consistent sampling and analyses to ensure comparability (Gill et al. 2011).
- Available protocols need to be more widely implemented for monitoring.
- A central repository for data as well as long-term funding for monitoring should be considered.
- Data should be deposited in existing databases and made available to researchers and beyond.
- Proper monitoring requires seasonal and annual field campaigns as well as sufficient, long-term financial support.
- As minimum, the bottom 10 cm of ice cores (which can be split into the lowermost 3-4 cm bottom ice and the next 6-7 cm of the core) should be sampled, because the bottom 10 cm often includes the majority of the biomass and abundance of ice biota (~65 % of ice meiofauna, up to 95% for algae based on the here compiled data sets).
- It is recommended that the 10-30 cm section also to be included (separately) where feasible, as an average 12% of the meiofauna have been observed in this ice section.
- Sterile procedures should be used to avoid contaminating the ice cores (e.g., Collins et al. 2010).
- The need for sampling the entire ice column will depend on project goals, which may also include modelling aspects of biota in sea ice (Duarte et al. 2015).
- Ice biota has rarely been studied as a whole at a given location and time period. *Gammarus wilkitzkii* and *Eusirus holmi*, both amphipod species, should therefore be monitored, since changes in their relative abundance may reflect changes in sea ice conditions.
- The most quantitative samples appear to be based on SCUBA-operated sampling of squares with electrical suction pump (Hop et al. 2000) and the under-ice trawl net SUIT (van Franeker et al. 2009), as well as imagery with sufficient resolution.
- Variability in contemporary and historic methods of sampling as well as temporal variability of sampling obscure potential temporal trends. Thus, actual changes in ice biota diversity and community structure need to be substantial enough to rise beyond the existing variability in order to be detected.

7.4.2.3 Zooplankton

Ship-borne, ocean-going field programs in the CAO are growing, yet regular monitoring program are not well-established and still sporadic. Information toward the present status and potential future prospects is insufficient and scarce. Coordinated field efforts and standard protocols are essential and warranted. Below are examples of research needs:

- Consolidated information on the distribution and abundance of major zooplankton species in the Central Arctic Ocean proper in different years and in different seasons (non-summer seasons in particular) is needed.
- Community change governed by the exchange of water masses from the Atlantic and the Pacific, and the nature of the population interactions between sub-Arctic and the Central Arctic, as well as between shelf and basins need to be studied.
- Differential life history response of major copepod species with regards to changing primary and secondary productivity, which is determined by the magnitude of melt (the position of sea ice edge, and sea ice thickness) and the timing of ice break-up, need investigations in different sectors of the CAO.
- Modelling efforts are needed to predict the degree and nature of borealization aided by new observational data, especially for the key biological input parameters.

- Laboratory and field-based research to evaluate zooplankton adaptation to future human activity such as shipping, pollution and energy exploration, should be developed. Topics of plastic ingestion, oil spill impacts, and ocean acidification are important for future studies.
- Applications of new tools and methods in the CAO should include, but not be limited to, environmental DNA, automated image collection and processing.

7.4.2.4   Marine mammals

- *Continued and expanded monitoring of marine mammal occurrence in the CAO:* Monitoring of geographic and seasonal occurrence patterns is of fundamental importance for the understanding of highly mobile species in a changing environment. Historically, monitoring of marine mammals in the CAO has mainly relied on opportunistically collected data from ice breakers, aerial ice monitoring programs and various research and tourist expeditions (e.g. Belikov and Boltunov 2002). Collection, collation and analyses of this type of data is highly valuable and should continue and expand with the increase of human activities in the region. Efforts should be made to optimize the quality, synthesis and dissemination of opportunistic observations. In addition, passive acoustic monitoring stations within the CAO would valuable tools for the majority of the arctic marine mammals. Based on prior indications and judgement of ecological habitat suitabilities, reconnaissance surveys should be carried out in selected areas to evaluate the need and feasibility of specialized abundance surveys.
- *Continued and expanded dedicated abundance surveys in the CAO:* Continued and geographically expanded dedicated abundance surveys for ice dependent species like narwhals, polar bears, seals and bowheads around the CAO ice edge are needed for responsible management of human activities. In particular, a more complete survey of narwhals in the Nansen basin should be a near future priority as this population component has shown high affinity to conditions prevailing in the CAO. It is furthermore likely to constitute a significant proportion of the total abundance of a distinct grouping of narwhals to the East of Greenland.
- *Telemetry based studies of marine mammal movements in the CAO:* Satellite telemetry, preferably with oceanographic tags, provide highly valuable information on movement patterns, habitat selection, diving behavior, potential diets and population affiliation. Currently available telemetry data for marine mammals in the CAO are generally based on animals originally tagged outside the area, which may be biased towards short term visitors. Tagging animals already within the CAO would be more likely to reveal information on potential long-term residents of the CAO. Elucidating the population affiliation of Nansen basin narwhals is of particularly high importance as these animals are likely to represent a significant proportion of the total abundance of narwhals to the East of Greenland.
- *Genetic studies:* Genetic assignment of population affiliation of marine mammals observed in the CAO is a high priority for all species. In addition, genetic samples may provide information on sex and some physiological parameters through quantitative analyses of gene expression (Sigsgaard et al. 2019). High quality DNA from individual biopsies provide the most straightforward technical basis for these analyses, but faecal dna or environmental DNA from targeted areas may provide similar information with extended protocols (Sigsgaard et al. 2019). In addition, eDNA may provide community data on suites of species.
- *Studies of life history, health and ecology based on biological material:* For marine mammals observed in the CAO access to biological material from live animals for assessment of health, age and reproductive status are generally limited to biopsies, faeces, cells in exhaled air, and occasional live sampling of blood samples, epithelial cells, hair and

whiskers. These samples can provide useful data on reproductive status (sex hormones), health (stress hormones, contaminants, pathogens and antibodies), trophic information (stable isotope and fatty acid analyses). With the exception of data collected from live-captured animals for tagging, many of these techniques are, however, highly opportunistic and time consuming and unlikely to be widely operational for realistic levels of field time in the CAO. For abundant species like ringed seals, lethal sampling may be defendable for more detailed analyses of health and reproductive status, contaminant levels, age and diet. Similar data derived from indigenous and commercial hunting have previously proven highly useful for arctic populations (e.g. Nguyen et al. 2017, Beatty et al. 2019). The relevance of available hunted samples for CAO related studies, should be assessed.

- *Analyses of soundscapes relevant for marine mammals within the CAO:* In addition to data on occurrence patterns of vocal marine mammals, general analyses of CAO soundscapes are important for the overall understanding of marine mammal acoustic ecology in the area. This is because levels of both anthropogenic noise and sounds from natural sources like wind and wave action are likely to change in response to changes in ice cover (Stafford et al. 2018). Soundscape data can be obtained from passive acoustic monitoring devices. Baseline studies for the pacific and arctic gateways are available (Moore et al. 2012, Ahonen et al. 2017, Stafford et al. 2018).

- *Studies of arctic mammal sensitivity to low frequency anthropogenic noise:* Although several studies are available on the sensitivity of bowhead and beluga whales to seismic airguns and vessel noise, there are still considerable gaps in the knowledge base required for vulnerability assessments of marine mammals in the CAO. Very few studies of behavioural responses to noise exist for other arctic marine mammals and no studies appear to exist on effects of military sonars on arctic marine mammals (Gomez et al. 2016). With expected increases in industrial and military activity in the CAO and other parts of the Arctic, these gaps need to be filled.

- Since marine mammals in the CAO are most likely closely connected with larger populations outside the core area of the CAO, continued monitoring of these more central populations are important in order to put the information from the CAO into a population and species-wide context. Generally agreed circumpolar research and monitoring recommendations for arctic mammals are summarized in CAFF (2017).

7.4.2.5   Benthos

- There is a clear need for a better understanding of the quantity, phenology, and the regionality of carbon supply and demand in the deep Arctic basins, which will allow us to evaluate how the ecosystem may change in the future (Wiedmann et al. 2020).

- The high heterogeneity of the CAO sea-floor have implications for sampling, monitoring and potential response of use of the deep sea in the Arctic such as: (1) larger and more stratified sampling strategies are required to cover different benthic habitat types present than previously appreciated, (2) advanced autonomous technology would be required to capture short-term events and small-scale areas of high densities/biomass/flux, (3) recovery after disturbance of the seafloor is likely extremely slow, and (4) our poor understanding of biotic communities makes is challenging at best to distinguish any potential response to change from new findings filling an earlier knowledge gap.

- Further temperature monitoring is needed to evaluate the recent warming trend in the CAO and its impact on carbon export to the deep sea.

7.4.2.6 Fish

- Consolidated information is needed on the distribution and abundance of major fish species (*Boreogadus* and *Arctogadus* in particular) in the CAO in different years, and across different habitats (water column and sea ice associated areas).
- Evaluating the diversity of fish species across different habitats (upper water column, mid-water, demersal, sea ice associated) should occur.
- The life history response of by polar cod species with regards to changing biological productivity and abundance of prey organisms, which is determined by the nature of sea ice melt, should be studied, especially in a pan Arctic perspective.
- Evaluation of the pan-Arctic population structure of polar cod species and the nature of the interaction of populations between low latitude Arctic and the high latitude Arctic, as well as between shelf and basin, is needed.
- Studies of the degree of borealization of fish communities as determined by field data and specimens is needed, along with developing predictions by modelling efforts.
- Investigations into the damage to and adaptation of major fish populations (especially to the early life history stage) by future human activity through both laboratory and field-based research. Such topics as plastic ingestion, oil spill impacts, ocean acidification impacts, and disturbance to the sound scape need to be studied.
- Evaluating the interactions of human activities with apex predators and predicting the changing availability of prey to the top of the food web is needed.
- Applications of new tools and methods in the CAO to include, but not be limited to, more sophisticated hydroacoustics, environmental DNA, automated image collection and processing.

7.4.3 (ToR d): Assess the consequences of climatic and oceanographic changes on transport pathways and potential effects of contaminants

- There is a need to standardize and harmonize methods to quantify microplastics in abiotic and biotic matrices in order to establish monitoring data series in the CAO.
- There should be monitoring of contaminants (including litter and microplastics) in all parts of the CAO (Note: this was also identified as current Arctic research priorities in the '2020: State of the Arctic science' report of the International Arctic Science Committee).
- Monitoring long-distance pollution transport in the Arctic (metals, NOx, SOx, organic pollutants, etc.) is needed. (Note: this was also identified as current Arctic research priorities in the '2020: State of the Arctic science' report of the International Arctic Science Committee).
- Monitoring human activities, such as fisheries, shipping, cruise, scientific exploration (of which physical contact or operation is expected), both within and in the surrounding areas of the CAO, should be implemented.

7.4.4 (ToR e): Review and report on new studies on fish as well as other biological components

- The largest knowledge gap concerns the presence and size of fish stocks inside the CAO. New research programs are needed to remedy this gap, and they should include the development of methodologies to sample fish in an ice-covered sea. Data collected should focus on spatial and seasonal distributions of fish in the CAO, and potential migration

patterns of fish stocks in the CAO, and use advanced technologies, such as ice-moored autonomous hydroacoustic buoys and eDNA samplers.

- The significance of the under-ice habitat for the key forage fishes polar cod *Boreogadus saida* and ice cod *Arctogadus glacialis* is not fully understood. A detailed understanding of the role of sea ice for the survival and distribution of these species is urgently needed to predict the impact of climate change on these species and their ecosystems, and to develop sustainable management schemes.
- Assessments of the current and future carrying capacity of the CAO for fish populations must combine detailed knowledge on the changing habitats, distribution of potential prey stocks, predators, and competitors in relation to the physiological envelope in which Arctic fishes thrive.
- Potential range expansions of commercial fish stocks into the CAO must be assessed in combination with economic expansion potential of the fishing industry and emerging management schemes.
- New management tools mediating between local communities, industry and societies must be developed that can safeguard sustainable development of ecosystems and human stakeholders in the face of a rapidly changing environment.
- Model studies must be better constrained by the factors mentioned above.

7.5 Summary and Conclusions

Physics, contaminants, primary and secondary producers and sea ice biota dominated the identified key points for monitoring in the CAO. Important issues included standardization of protocols/sampling and obtaining data at times when data historically are rare (i.e. during winter).

For benthos and fishes, mapping and baseline studies were identified as priorities, including the development/use of new technology. Regarding fish and possible future fisheries in the region, priority research includes the development of new management tools mediating between local communities, industry and societies that can safeguard sustainable development of ecosystems and human stakeholders in the face of a rapidly changing environment.

Regarding marine mammals, monitoring and mapping of distribution and abundance were identified as key points, but also studies on life history, health and ecology were highlighted. In addition, studies directly related to increased human activity, like analyses of soundscapes relevant for marine mammals, and studies of arctic mammal sensitivity to low frequency anthropogenic noise, were identified as priority research.

A synthesis of the state of knowledge about biodiversity in Arctic marine ecosystems, detectable changes, and important gaps in our ability to assess state and trends in biodiversity across sea ice biota, plankton, benthos, marine fishes, seabirds and marine mammals were conducted in the SAMBR report (CAFF, 2017), and the key priority research, monitoring needs and recommendations identified in section 7.4 fit well with those. The monitoring needs and recommendations for fish (7.4) are consistent with the outcome from the FISCAO process (PSCG 2020), i.e. the highlighted concern about the current knowledge gap on the presence and size of fish stocks inside the CAO as well as the necessity of development of methodologies to sample fish in an ice-covered sea.

A coordinated array of regional transect lines are recommended to be developed with key parameters to evaluate the regional to pan-Arctic scales, something the international DBO network and SAS are working towards. With more coordinated observations, we can then identify focal areas for monitoring on an interannual and decadal basis, knowing the limitations of required funding and the need for international agreements. The 5th FISCAO report developed monitoring recommendations by leveraging ongoing observing activities, which is only as viable as long

as those time series of observations are maintained. There is also a need for an international, coordinated effort (involving among others CAFF and its Circumpolar Seabird Expert Group (Cbird); the IUCN Polar Bear Specialist Group, and other relevant working groups) for these investigations to eventually develop monitoring capacity at various trophic levels, with associated environmental drivers.

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Additional references can be found in the subchapters from ToR b-e.

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8 ToR g. Prepare an Ecosystem Overview for the CAO ecosystem

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Working group: all WGICA members

8.1 Introduction

An Ecosystem Overview (EO) provides a description of an ecosystem, identifies the main human pressures, and explains how these affect key ecosystem components. The audience for EOs includes client commissions and stakeholders as well as the ICES community and networks. The EO for the CAO will be completed by an advice drafting group and approved by the ICES Advisory Committee, ACOM.

The purpose of the EO is to:

a) describe the location, scale, and management and assessment boundaries of the ecoregion;
b) describe the distribution of human activities and resultant pressures (in space and time) on the environment and ecosystem;
c) describe the state of the ecosystem (in space and time) and comment on pressures accounting for changes in state.

The EO consists of the following parts:

1. **Ecoregion description** – Maps and text showing the boundaries of the ecosystem and depth contours, relevant management and assessment regions, human usage, catchment areas, and designated areas (i.e. Natura 2000 areas). Appropriate subregions should be described.
2. **Key signals within the environment and ecosystem** – This focuses on changes on time and space scales that have consequences for advice. Major trends and shifts that are required to provide advice should be described.
3. **Activities and pressures** – Identify regional priorities, listing the predominant pressures in the ecoregion, with an indicative list of activities. The goal is to assess cumulative pressures from multiple activities.
4. **State** – Short concise descriptions of the main state of the ecosystem components within each ecoregion, linking the selected pressures to the state of the ecosystem.

WGICA will be preparing an EO for the CAO in 2020-2021. The focus in 2020 will be on conducting the activities and pressures assessment and developing draft text for the EO. In 2020, the EO will focus on the current situation where ice-cover is largely restricting human activities that occur inside the CAO. Most "current" pressures are therefore of a "global nature" and involve long distance transport of contaminants, litter and new species.

In 2021 WGICA will explore methods to merge both current and future pressures into the conceptual model of the EO. This "future" aspect is added because rapid changes are occurring in the CAO and the "precautionary principal" could be applied by evaluating the consequences of pressures on the ecosystem as early as possible.

The CAO is defined as the High Seas ice-cover, water surface, and water column in addition to the seabed under national jurisdictions in the deep basins, including the slopes but excluding the bordering shelf seas.

8.2   Pressure assessment

The first step in the selection of the main pressures involved the assessment of all pressures currently affecting the CAO. This assessment was conducted according to the ICES guidelines.

The following 16 WGICA experts were involved in this assessment: Henry Huntington, Natsuhiko Otsuka, Kathy Kuletz, Thomas Van Pelt, Lis Lindal Jørgensen, Karen Edelvang, Bodil Bluhm, Jackie Grebmeier, Fujio Ohnishi, Harald Gjøsæter, Hauke Flores, Pauline Snoeijs-Leijonmalm, Barbara Niehoff, Hyoung Chul Shin, Martine van den Heuvel-Greve, Bjørn Einar Grøsvik.

The following five main pressures, for the current situation, were identified for the CAO (see also figure 8.1):

1. Sea ice loss;
2. Introduction of non-indigenous species;
3. Introduction of contaminating compounds;
4. Marine litter;
5. Noise.
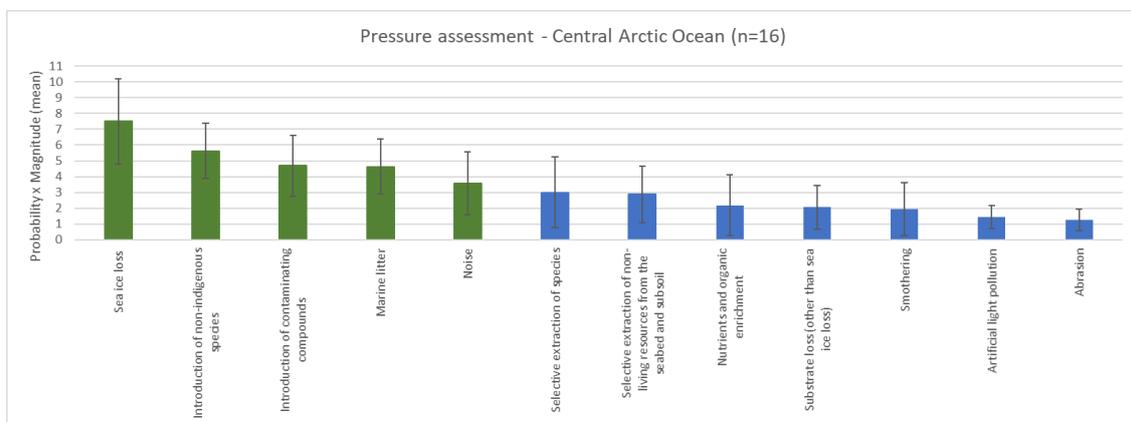
Figure 8-1. Results of the pressure assessment for the CAO for the current situation, based on scores from 16 WGICA experts. The higher the score the more important the pressure for the ecosystem. The five main pressures are presented in green, the other pressures in blue.

8.3   Linking main pressures with human activities and ecosystem components

Using the five main pressures for the CAO as a starting point, two further assessments were made to identify current human activities that contribute to these pressures and direct links that exist between these pressures and all ecosystem components. The ICES guidelines were followed for these assessments.

These assessments were conducted by the following 9 experts of WGICA: Kevin Hedges, Hauke Flores, Lis Jorgensen, Henry Huntington, Harald Gjøsæter, Martine van den Heuvel-Greve, Barbara Niehoff, Thomas van Pelt, Anders Mosbech.

8.3.1 Linking main pressures with human activities

The draft results for this assessment were just compiled. Further discussion on the outcome will follow later this year. The draft results identified a few main human activities that are linked to the current main pressures for the CAO (Table 8.1).

Table 8.1. Current human activities that are linked to the current main pressures in the CAO, based on scores of 9 WGICA experts. Scores ranged between 0-3; the higher the score the more important the link.

Pressure	Score ≥ 2.5	Score ≥ 2.0	Score ≥ 1.5
Sea-ice		Global sources	
Non-indigenous species*		Shipping	Tourism & recreation, research
Contaminating compounds		Shipping, global sources	Military, tourism & recreation
Marine litter			Tourism & recreation, shipping, global sources, military
Noise	Military, shipping		Tourism & recreation

Global sources may be added as a contributing human activity to this pressure

8.3.2 Linking main pressures with ecosystem components

For this assessment the draft results were just compiled. The outcomes will be discussed further later this year. The draft results identified the following links between ecosystem components and the five main pressures for the CAO (Table 8.2).

Table 8.2. Direct links between ecosystem components and the current main pressures in the CAO, based on scores of 9 WGICA experts. Scores ranged between 0-3; the higher the score the more important the link.

Ecosystem component	Score = 3.0	Score ≥ 2.5	Score ≥ 2.0	Score ≥ 1.5
Habitats	Sea-ice loss			
Food webs		Sea-ice loss	Non-indigenous species	Contaminating compounds
Productivity (algae)	Sea-ice loss			Non-indigenous species
Zooplankton		Sea-ice loss		Non-indigenous species, contaminating compounds
Benthos				Sea-ice loss, non-indigenous species
Fish			Sea-ice loss, non-indigenous species	Contaminating compounds
Sea birds		Sea-ice loss	Contaminating compounds	Marine litter
Marine mammals		Sea-ice loss	Contaminating compounds, noise	Non-indigenous species, marine litter

9   Outline of Report 2

Human activities, climate- and vulnerability assessment of the Central Arctic Ocean (CAO)

It was discussed that Report 2, as a natural continuation of Report 1, could describe:

<u>**Part 1**</u>

Human activities and related management bodies:

- ongoing, as well as future, human activities (global impact as well as local) and management bodies responsible for managing these Human activities.

- scenarios of a future where the ice cover is reduced, allowing a variety of different human activities, and how this will evolve under different management regimes.

<u>**Part 2**</u>

Climate assessment:

- the ongoing and future climate impact on the physical, chemical and biological CAO

Vulnerability assessment:

- the ongoing and future pressures/impacts from human activities and their effects on all the ecosystem components, including the fauna associated with the sea ice, the water column, and the seabed:
    - Sensitive and vulnerable areas
    - Fishable and harvestable concentrations of vertebrates and invertebrates and the potential production
    - Effects of pollution (including plastics), contaminants, noise and other
    - Risk of introduction and spread of invasive species
    - Future risk in case of exploration (seabed mining) and other activities

Originally the Report 2 (part 1 and 2) was given a deadline delivery of November 2021. The group considers that to be not enough time, since the report has not been started.

We suggest a revised timeline, as follows:

- Fall 2020: Finalize the Ecosystem Overview (EO) for the November 2020 delivery
- Spring – summer 2021: Write Part 1 (Human activities and management bodies) by following the structure of the EO
- Fall 2021: to have a physical meeting in ICES HQ to discuss the way forward to finalize Part 1, and to draft the ToRs for 2022-2024 that will support the writing of Report 2 - part 2.

2022-2024: write part 2 (Climate Assessment and Vulnerability Assessment).

Annex 1:   List of participants

[Text]

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Annex 2: Resolutions

WGICA - ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean

2018/MA2/IEASG06 A Joint **ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment of the Central Arctic Ocean (WGICA)**, chaired by John Bengtson, USA, Sei-Ichi Saitoh, Japan, and Lindal Jørgensen, Norway, will work on ToRs and generate deliverables as listed in the Table below.

	MEETING DATES	VENUE	REPORTING DETAILS	COMMENTS (CHANGE IN CHAIR, ETC.)
Year 2019	8-10 May 2019	Sapporo, Japan	ICES Scientific Report by 1 September 2019	
Year 2020	27-29 April	by correspondence	ICES Scientific Report by 1 September 2020	Hein Rune Skjoldal, Norway and John Bengtson, USA as outgoing Chairs. Lis Lindal Jørgensen, Norway as incoming Chair
Year 2021	To be decided	To be decided	Final ICES Scientific Report by 31 December 2021	Martine van den Heuvel-Greve, Netherlands, as incoming Chair

ToR descriptors

ToR	Description	Background	Science Plan codes	Duration	Expected Deliverables
a	Review and consider approaches and methodologies for conducting an IEA of the CAO ecosystem including Human Activities from the viewpoint of Climate and Vulnerability Assessments.	WGICA has produced a first version IEA report for the CAO. Before producing an updated and extended version, the basic approach and methodologies should again be considered.	2.2, 6.1, 6.5	Year 1	Report outcome in the 2019 interim report.
b	Review and report on ongoing and recent changes and events in the CAO associated with changes in sea ice, oceanographic circulation, and hydrographic properties	There is a need to follow developments in the CAO resulting from the predicted further loss of sea ice and other physical changes associated with global climate change.	1.1, 2.2, 6.5	Years 1-3	New information will be reported in interim reports in 2019 and 2020. A more full account will be given as part of a second version IEA report for the CAO in 2021.

c	Continue to examine effects of climate change on the CAO ecosystem by compiling and reviewing information on changes in response to the ongoing 'Great melt', and assess likely consequences to the CAO ecosystem of projected future changes associated with further loss of sea ice and other climate-related changes (i.e. a climate impact assessment).	This activity was started in the first 3-year period, and some information is included in the 2018 IEA report. There is a need to continue and carry out a more detailed assessment of the documented and/or inferred biological and ecological changes associated with the large physical changes that have already taken place (e.g. loss of half the area and ¾ of volume of summer sea ice).	1.1, 1.3, 6.1, 6.5	Years 1-3	Progress will be reported in interim reports in 2019 and 2020. A more full account will be given as part of the new version of the IEA report for the CAO in 2021.
d	Assess the potential effects on the CAO ecosystem of recent, ongoing and future climatic and oceanographic changes on Human activities (shipping, tourism, possible future fisheries, seabed exploitation of minerals and security) and recent on-going pollution (contaminant, garbage, and micro plastics)	This is a new activity which relates to assessment of pollution in the CAO. Pollution can be expected to be one of the more serious threat to the CAO ecosystem and should be included in an IEA.	2.1, 2.5, 6.1	Years 2, 3	Progress will be reported in interim report in 2020. Aspects of pollution wil be included in the new IEA report for the CAO in 2021.
e	Review and report on new studies on fish of the CAO ecosystem (the High Seas).	The information on many parts of the CAO ecosystem is still limited. New information is expected to come over the next few years as research ice-breakers pay more attention and use scientific ecchosounders and other observation techniques to record fish and other organisms in the water column and at the seafloor.	5.2, 6.1, 6.5, 6.6	Years 1-3	Progress will be reported in interim reports in 2019 and 2020. A more full account will be given as part of the new version of the IEA report for the CAO in 2021.

e	Continue to identify priority research needs and monitor how identified knowledge gaps (needed to improve IEA and management effectiveness) are being addressed and filled.	A by-product of doing the first version IEA of the CAO is a priority list of research needs. It is necessary to monitor how knowledge gaps are filled that will improve new versions of IEA.	1.3, 2.2, 3.1, 6.1, 6.5	Years 2, 3	Progress will be reported in the interim report in 2020 and outcome reported in 2021.
f	Prepare an Ecosystem Overview for the CAO ecosystem	This will be an addition to the series of Ecosystem Overviews prepared by ICES.	6.5, 6.6	Years 2, 3	Draft version will be reported in the interim report in 2020 and final version reported in 2021.

Summary of the Work Plan

Year 1	**Review IEA methodologies for IEA of the CAO. Review and report new information and changes in the CAO ecosystem.**
Year 2	Review and report new information and changes in the CAO ecosystem. Address pathways and effects of contaminants, make an initial list of research needs, and prepare draft Ecosystem Overview.
Year 3	Prepare a second version IEA eport for the CAO with information on status and trends, including impacts of climate change, pollution, and other relevant human pressures. Report on research needs and prepare final draft of Ecosystem Overview.

Supporting information

Priority	WGICA is one of several groups in ICES that do integrated ecosystem assessments, which is one of the priority action areas for ICES. Being a WG for the central Arctic Ocean, WGICA also contributes to the Arctic research action area. Jointly sponsored by PICES and the PAME working group of the Arctic Council, WGICA represents a collaborative effort that links ICES work in the wider Arctic Mediterranean Sea (the Nordic Seas and the central Arctic Ocean) with expertise on the Pacific Arctic through PICES.
	The work planned in WGICA will directly address ICES science priority area 6 Developing tools, knowledge and evidence of effective conservation and management and some elements of priority area 2 (Understanding ecosystems) and 3 (Impacts of human activities).
Scientific justification	ICES IEA EGs provide science based assessments of ecosystem status, trends and vulnerabilities to support implementation of the ecosystem approach to management.
	ToR a – The CAO is a data-deficient system where much of the data and knowledge comes from research activities, while monitoring is a more limited source of information. Based on the first version IEA report for the CAO, as well as experiences from the other IEA WGs in ICES, the approach and methods for IEA for the CAO will be considered prior to producing a second version IEA report in 2021.
	ToR b – The CAO is on a trajectory of reduction of sea ice with considerable inter-annual variablity. Trends and events will be reported to draw attention to the ongoing changes in the CAO.
	ToR c – The purpose and aim of this item is to provide a careful evaluation and summary of what we can say about the biological and ecological effects of climate change over the recent decades up to present. This can in turn be used for projections of likely effects of continued warming and loss of sea ice over next decades.

	ToR d – This item addresses pollution with focus on contaminant pathways (physical and biological) and potential effects in foodwebs of the CAO. The scale of activity will depend on the expertice available in the WG.
	ToR e – It is expected that new information will be forthcoming on occurrence of fish and other biota in the CAO from planned research activies. There is for instance increased awareness that scientific echosounders on research ice-breakers can provide valuable information. We will report on developments and include new information in the next IEA report.
	ToR d – This is an item meant to provide guidance to the research community at large on priority research issues to improve the knowledge base for continued IEA work.
	ToR e – This will add to the suit of Ecosystem Overviews prepared and published by ICES.
Resource requirements	No major resourcing.
Participants	Experts from ICES, PICES, and PAME
Secretariat facilities	Support for meetings at ICES HQ, when appropriate.
Financial	No financial implications for ICES.
Linkages to ACOM and groups under ACOM	Link to ACOM through the development of Ecosystem Overviews and advice.
Linkages to other committees or groups	Within ICES links across all ICES IEA working groups and to HAPISG EGs on human pressures on marine ecosystems, such as pollution.
Linkages to other organizations	This is a joint ICES, PICES, and PAME WG.