

# WGICA 2017 REPORT

STEERING GROUP ON INTEGRATED ECOSYSTEM ASSESSMENTS

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REF ACOM AND SCICOM

## Interim Report of the ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean (WGICA)

19-21 April 2017

Seattle, USA



**ICES**

International Council for  
the Exploration of the Sea

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## Executive summary

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WGICA held its second meeting at the Alaska Fisheries Science Center/NOAA in Seattle, 19–21 April 2017. Twenty-three persons from four countries (Canada, Japan, Norway, United States of America) attended the meeting. WGICA has prepared overview descriptions of key ecosystem features, and agreed an approach for producing an Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean (CAO). The geographical focus for WGICA is the basins of the CAO including the surrounding slopes. Processes and features on the surrounding shelves will be included to the extent that they are relevant and essential to understand what goes on in the basins. The two gateways for inflow of Atlantic water through the Fram Strait and the Barents Sea and Pacific water through the Chukchi Sea are given special attention.

The outline of the IEA for the CAO includes a basic description of the CAO ecosystem and assessment of (potential) impacts and vulnerabilities with regards to shipping, fisheries, and climate change. The ecosystem description will include topics such as climate and oceanography, sea ice biota, fish, marine mammals, and birds for both central basin areas as well as the Atlantic and Pacific gateway zones. A 'Key features' section provides a current synopsis of the ecosystem description (included as Annex 2). Elements of the IEA will include:

- A review of the scientific literature on the level of primary production by phytoplankton and ice algae (initial draft included as annex 3).
- A summary of knowledge of fish and fish stocks in the CAO, including new information from acoustic records from research ice-breakers.
- An overview of marine mammal and seabird abundance, distribution, habitat use, and ecology.
- A climate impact assessment based on a review of knowledge of changes in the CAO ecosystem that have taken place during the period of the 'Great melt' in the recent decades after the 1980s.
- A vulnerability assessment to shipping with information on sensitivity and potential vulnerability of species and their ice habitats to oil spills, noise and visual disturbance from ships.

## 1 Administrative details

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**Working Group name:** ICES/PICES/PAME Working Group on Integrated Ecosystem Assessment for the Central Arctic Ocean (WGICA)

**Year of appointment within the current cycle:** 2015

**Reporting year within the current cycle:** 2

**Chairs:**

John L. Bengtson, United States of America

Hein Rune Skjoldal, Norway

**Meeting venue:** Alaska Fisheries Science Center/NOAA, Seattle, WA, US

**Meeting dates:** 19–21 April 2017

**Participants:** 23 persons from four countries (Canada, Japan, Norway, United States of America). See Annex 1 for a list of WGICA meeting participants.

## 2 Terms of Reference

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Term of Reference a – Consider approach and methodology (-ies) for doing an IEA for the Central Arctic Ocean (CAO) (based on the outcome of the 2015 Workshop for the Integrated Ecosystem Assessment of the Central Arctic Ocean).

Term of Reference b – Assemble data and information and carry out appropriate statistical and other types of analyses including mathematical modelling.

Term of Reference c – Prepare an IEA outline for the current status of the CAO ecosystem (CAO LME and adjacent slope waters including Atlantic and Pacific inflows and relevant shelf-basin exchanges) and effects, potential effects, and vulnerability in relation to climate variability and change and human activities such as Arctic shipping and potential future fisheries.

Term of Reference d – Consider requirements and design of monitoring of the CAO to meet the need for repeated IEA in the near future as well as other types of assessments (which can be modular components of IEAs).

Term of Reference e – Identify priority research issues which, when addressed, can improve the knowledge base for the future iterations of the IEA.

### 3 Summary of work plan

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<b>Year 1</b>	Consider approach and methodology for IEA, start assembling of data and information, and consider monitoring requirements
<b>Year 2</b>	Continue assembling of data and information and carry out analyses. Prepare an initial and incomplete draft of IEA
<b>Year 3</b>	Finalize IEA report and consider monitoring requirements and priority research issues

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#### **4 List of outcomes and achievements of the WG in this delivery period**

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WGICA's main outcomes so far were to: 1) prepare overview descriptions of key ecosystem features, 2) agree an approach for the IEA, and 3) convene the working group's second meeting. Summary overviews of the principal ecosystem components were prepared and presented at the working group's meeting. Agreement was reached on the general approach for developing an integrated ecosystem assessment of the CAO. This comprises two main parts: a description of the CAO ecosystem, and an assessment of vulnerabilities and potential impacts of human activities, including transpolar shipping and commercial fisheries. The CAO ecosystem is undergoing climate change, and evidence of climate change impacts will be reviewed.

## 5 Progress report on Terms of Reference and work plan

An Integrated Ecosystem Assessment (IEA) is a core element of the Ecosystem Approach to Management (EA). The principle of the EA was adopted by the Arctic Council in 2004, and ministers reaffirmed the need for EA in the Arctic in the Fairbanks Declaration in May 2017. A definition of EA was adopted by the Arctic Council in 2013:

*“the comprehensive integrated management of human activities based on the best available scientific and traditional knowledge of the ecosystem and its dynamics, in order to identify and take action on influences which are critical to the health of marine ecosystems, thereby achieving sustainable use of ecosystem goods and services and maintenance of ecosystem integrity.”*

The geographical focus for WGICA is the basins of the CAO including the surrounding slopes. Processes and features on the surrounding shelves will be included to the extent that they are relevant and essential to understand what goes on in the basins. The two gateways for Atlantic water through the Fram Strait and the Barents Sea and Pacific water through the Chukchi Sea will be given special attention for those aspects (e.g. water flow, transport of plankton, and migration of marine mammals) which affect the CAO ecosystem. See the report from WGICA 2016 for more details.

The geographical scope is broader than the CAO LME which does not include slope regions (above 1000 m depth) defined as parts of surrounding shelf LMEs (see LME report at PAME: <https://pame.is/index.php/projects/ecosystem-approach/arctic-large-marine-ecosystems-lme-s>). The scope is also broader than the High Seas areas of the CAO (Figure 5.1).

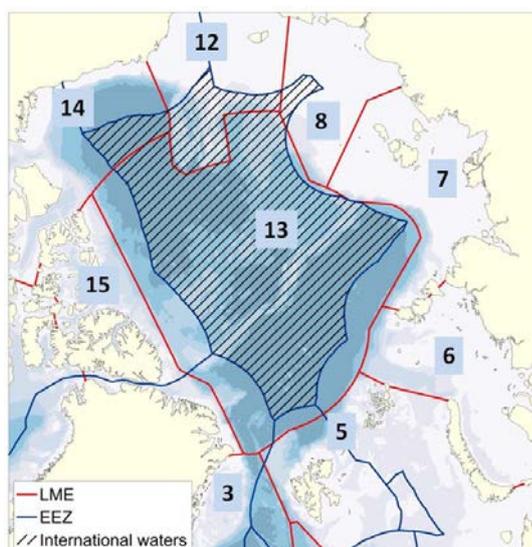


Figure 5.1. National boundaries (blue) and boundaries of the LMEs (red). The High Seas area (International waters) is hatched. Numbers refer to LMEs defined by red boundaries: 13 Central Arctic Ocean LME, 5 Barents Sea LME, 6 Kara Sea LME, 7 Laptev Sea LME, 8 East Siberian Sea LME, 12 Northern Bering-Chukchi Seas LME, 14 Beaufort Sea LME, 15 Canadian High Arctic – North Greenland LME, 3 Greenland Sea LME (northern portion only).

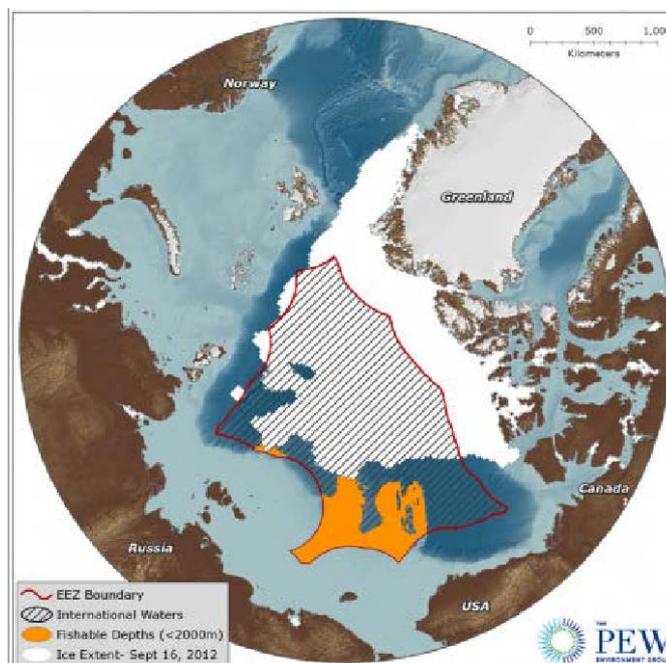
### 5.1 Approaches and methodologies to integrated ecosystem assessments (Term of Reference a)

Several groups have conducted integrated ecosystem assessments that may be relevant to WGICA's assessment of the CAO. The approaches and methodologies used by these groups were reviewed. A common feature of the approach of other ICES IEA groups (e.g. for the Baltic, North, Barents and Norwegian seas) is integrated trend analyses of large sets of time-series of physical, chemical and biological properties by multivariate techniques (ICES WKIDEA 2016 Report). Our approach for the work of WGICA will be different due to the general lack of time-series data for the CAO. Apart from oceanographic and sea ice conditions, which can be obtained by satellite remote sensing, biological time-series are scarce. Instead, we will attempt to put together composite 'pictures' (or descriptions) of conditions and events by compiling information from a large number of sources in the literature (including the 'grey' or unpublished literature).

### 5.2 Data, information and analyses (Term of Reference b)

Inflows to the CAO from both the Atlantic and Pacific have key roles for the circulation and ice conditions in the CAO and the conditions in the CAO influence the climate and climate variability of the northern North Atlantic and North Pacific. There are key environmental drivers that influence ecosystem dynamics and response of the CAO and shelf-basin interactions: decrease in sea ice extent and duration, seasonally warming seawater temperatures, change in prey concentrations, and northward movement of some lower to upper trophic level species. These changes have regional to global implications related to climate change, light penetration and availability for productivity, acidification events, the northward migration of biological organisms and biodiversity, and future development of commercial fisheries. Current and future impacts of climate variability and their impacts on sea ice flora and fauna, as well as the marine mammal and seabird populations in and surrounding the CAO, are core components in this synthesis effort. Implementing the ecosystem approach to management in the CAO requires sustained environmental observations coupled with the development of models that portray the underlying complexity of the ecosystems.

Coincident with ongoing environmental changes, the Pacific Arctic region is experiencing increased maritime traffic and offshore hydrocarbon exploration and development while being an important area for indigenous users of marine resources. Thus, there are socio-ecological systems where expected increases of anthropogenic impacts as well as issues of coastal-state jurisdiction and international governance come to play. Discussions are ongoing for developing an international agreement to monitor and regulate potential fisheries that could develop in the CAO beyond national boundaries, including identifying science needs to facilitate the development of an integrated ecosystem assessment of the Pacific sector influencing the CAO ecosystem. Twenty-two percent (614 000 square kilometres) of the CAO is made up of ridges and continental shelves at fishable depths of 2000 m or less (Figure 5.2; PEW Charitable Trust). Fishable depths shown in Figure 5.2 were derived from IBCAO v3 bathymetry ([www.ngdc.noaa.gov/mgg/bathymetry/arctic/](http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/)).



**Figure 5.2. International waters of the Central Arctic Ocean north of the 200 nm Exclusive Economic Zones (EEZs) (citation: PEW).**

### 5.2.1 Focal areas for the CAO Integrated Ecosystem Assessment

#### Amerasian Basin/Pacific Gateway (Grebmeier)

The WGICA’s Pacific Gateway subgroup will work with members of the Pacific Arctic Group (<http://pag.arcticportal.org/>) on a synthesis activity to evaluate the changing shelf-slope ecosystem through review of past research results and ongoing field activities. During the development of this ecosystem status report we will extend the assessment from the Pacific Arctic gateway as far into the CAO as feasible. We will also connect with the activities of the Arctic fish stocks and fisheries synthesis activities (e.g. Final Report of the Fourth Meeting of Scientific Experts on Fish Stocks in the Central Arctic Ocean, January 2017, 82 pp.). The status and trends influencing ecosystem structure and function will be evaluated. The northern regions of the Pacific Arctic shelf seas are becoming seasonal ice free earlier, allowing penetration of warmer Pacific waters and air-sea interactions to occur deeper into the Arctic Basin. There is increased accessibility for predators and prey to move northward during summer and fall months. The earlier opening of area can change primary production with increasing solar radiation and light penetration in surface waters, affecting both the algal species composition and primary production in marginal ice zone and into the deep basin. There are unknown consequences for carbon cycling and the biodiversity of zooplankton and benthic organisms as there are few studies on high Arctic foodwebs, plus uncertainties of the impacts and fate of export fluxes over Arctic shelves vs. over the deep Arctic Ocean. As such, we need a coordinated, multinational and interdisciplinary program to provide an interannual time-series suite of ecosystem and fisheries data from shelf-to-basin and in the CAO that allow for joint analysis and assessment via approved mechanisms and management goals.

#### Eurasian Basin/Atlantic Gateway (Ingvaldsen)

Since the last meeting, a draft document describing general oceanography, primary production, fish species and marine mammals have been developed. Some further

work including updates with recent papers should be conducted as several new review papers relevant to this topic has been published in 2016 and 2017. These include Haug *et al.* (2017) which have focus on future harvest of living resources in the Arctic Ocean north of the Norwegian and Barents Seas, with emphasis on possibilities and constraints. Another highly relevant review paper is Hunt *et al.* (2016) which focus on advection in polar and subpolar environments and which also give description of the different ecosystem parts in the Arctic. Several new publications on nutrient fluxes from Randelhoff in 2016 and 2017 are also relevant. Still another highly relevant publication is Polyakov *et al.* (2017) focusing on greater roles of Atlantic inflows on sea-ice loss in the Eurasian Basin. Observations from the 1990s and 2000s documented two warm, pulse-like AW temperature anomalies on the order of 1°C (relative to the 1970s), entering the Arctic through Fram Strait and occupying large areas of the Arctic Ocean. The strength of the 2000s warming peaked in 2007–2008, with no analogy since the 1950s. This AW warming has slowed slightly since 2008. However, after that there has been “atlantification” of the eastern Eurasian Basin accomplished by large reductions in sea ice cover and thickness, large increases in ocean temperatures, weaker stratification, shoaling of the Atlantic Water layer and disappearance of the cold halocline. They argue that the eastern Eurasian Basin is currently in transition towards the conditions of the western Eurasian Basin.

### 5.3 IEA outline – review status of IEA components (Term of Reference c)

#### 5.3.1 Key features of the Central Arctic Ocean ecosystem (Skjoldal)

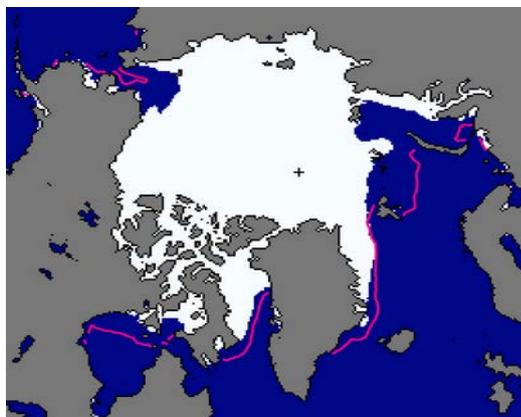
The Central Arctic Ocean (CAO) is a globally unique ecosystem due to its high latitude location at the ‘top of the world’, presence of sea ice, strong vertical stratification from freshwater input, and low primary production during a short summer season. It is a large geographical area, with the CAO LME being 3.3 million km<sup>2</sup>. The CAO consists of two deep basins (around 4000 m), the Eurasian and Amerasian (Canada) Basins, separated by the Lomonosov Ridge (about 1000 m deep) running from central Siberia across to northern Greenland. The basin slopes are generally steep, separating the basins from wide, shallow shelves on the Eurasian side and narrower shelves on the American side. See Annex 2 for a more detailed review of CAO key features.

#### 5.3.2 Climate, oceanography, and sea ice

##### The immediacy of Arctic change (Overland)

Observed Arctic trends and new analyses add increased certainty that the Arctic has moved outside the envelope of previous experience, and major changes are very likely to continue past mid-century. Observed and projected Arctic changes are large compared with those at mid-latitude and are driven by greenhouse gas (GHG) increase and Arctic feedback processes. While a major GHG mitigation effort may hold global temperatures to near +2°C, corresponding Arctic changes will be at least double the global average, with major climate, ecosystem, and societal impacts. Sea ice has undergone a regime shift from multiyear to first-year sea ice, and summer sea ice is very likely to be essentially gone within the next decade (Figure 5.3). Spring snow cover is decreasing and Arctic greening is increasing. There are potential emerging impacts of Arctic change on mid-latitude weather/climate and sea level rise. Climate changes in the last year highlight that changes are occurring faster than previously expected. Monthly average winter Arctic 2016 air temperatures reached +6°C above normal, almost twice as high as previous records. For the first time, sea ice extent did not fully recover in winter 2017. Substantial and immediate mitigation reductions in GHG emissions compliant

with Paris agreement should reduce the risk of extreme change for most Arctic components after mid-century, and reduce the likelihood of potential runaway loss of ice sheets and glaciers and their impact on sea level rise.



**Figure 5.3.** Sea ice coverage in November 2016. Note the late freeze up in Hudson Bay and the Kara and Chukchi Seas. The Red line indicates normal sea ice extents for November.

### 5.3.3 Primary production

The CAO is an oligotrophic sea area where presence of sea ice and strong vertical water stratification limit the level of primary production through availability of light and nutrients. There is considerable uncertainty as to how low the primary production by phytoplankton and ice algae is, and how reduced ice cover affects the level of primary production. We plan therefore to prepare a review of the scientific literature on primary production in the CAO. A first draft version has been prepared and was presented at the meeting. The draft is included as Annex 3 to this report.

Primary production in the CAO has been determined by a variety of approaches, including incubations with the classical C-14 method (or uptake of stable isotopes C-13 and N-15), changes in concentrations of oxygen, CO<sub>2</sub> or dissolved inorganic carbon, and inorganic nutrients, rates of sedimentation, and satellite remote sensing. While the estimates in the literature span two orders of magnitude in annual PP (from export production of around 0.1 g C m<sup>-2</sup> y<sup>-1</sup> to net community primary production of about 20 g C m<sup>-2</sup> y<sup>-1</sup> based on oxygen and nutrient data), they all agree in showing that the annual primary production is relatively low. The <sup>14</sup>C and <sup>13</sup>C data converge to give a fairly consistent picture of phytoplankton annual production (not including ice algae) of about 1–4 g C m<sup>-2</sup> y<sup>-1</sup> in ice covered waters and around 10 g C m<sup>-2</sup> y<sup>-1</sup> in open waters. Most of the estimates based on O<sub>2</sub>, CO<sub>2</sub>/dissolved inorganic carbon and inorganic nutrients are in the range 1–10 g C m<sup>-2</sup> y<sup>-1</sup>. Taken together, the data suggest a level of about 10 g C m<sup>-2</sup> y<sup>-1</sup> for net primary production in the CAO. The production is probably lower in the central area with more heavy ice cover even when ice algae are included, and higher (10–20 g C m<sup>-2</sup> y<sup>-1</sup>) in the peripheral parts with seasonal ice cover and slope regions. Spatially there is also a pattern with higher production in the Nansen Basin (associated with the inflowing Atlantic water) and low production in the Canada Basin associated with the anticyclonic Beaufort Gyre.

### 5.3.4 Fish and fish stocks

See Annex 4 for reports on Arctic fish and fisheries: Arctic fish overview (Skjoldal), Occurrence of fish in the Arctic Ocean (Mundy), Acoustic records of fish under ice (Gjøsæter), and Canadian Beaufort Sea – Marine Ecosystem Assessment (Hedges and Reist).

### 5.3.5 Marine mammals and seabirds

See Annex 5 for overview reports on marine mammals (Bengtson and Frie) and seabirds (Kuletz).

### 5.3.6 Ecosystem vulnerability

Assessment of vulnerability of the CAO ecosystem will focus on the specific environmental conditions and species that use habitats in the CAO, as highlighted in the 'key features' section. Assessment needs to evaluate vulnerability to existing and projected effects of climate change, including associated changes in ocean chemistry, along with potential human activities such as fishing and shipping in an integrated fashion that considers trophic linkages and cumulative effects, and recognizes effects that may occur beyond the CAO.

#### Arctic marine shipping

The PAME working group has requested WGICA to address the issue of vulnerability to shipping, in support of the work by national shipping experts within PAME of considering the need for protective measures in relation to Arctic marine shipping in the High Seas portion of the CAO (follow-up of the AMSA IID recommendation; see AMSA report on PAME webpage; Arctic Marine Shipping Assessment, 2009). One of the conclusions in AMSA was that oil spills were the greatest threat from Arctic shipping. Sensitivity to oil spills, as well as sensitivity to disturbances from ships, especially ships moving through ice or ice-infested waters, will be in focus for the vulnerability assessment of shipping in the CAO (see AMSA IIC, for a discussion of terminology and distinction of sensitivity, vulnerability, and potential vulnerability).

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 foodwebs.

In evaluating potential risks and impacts in the CAO ecosystem, it may be useful to view threats and potential impacts on a matrix which relates pressures and impact factors with the key ecosystem components. This will help guide the assessment of interactions and cumulative impacts across pressures. For the shipping vulnerability assessment, it will be necessary to take impacts from climate change into account. Specifically, we need to address the changes in the ecosystem caused by the loss of sea ice (up

to now and in the future), and how these changes affect the sensitivity and vulnerability to additional pressure from shipping.

#### **Maritime vessel risk assessment in a changing Arctic (Stevenson)**

In 2016, the Ocean Conservancy commissioned a Bering Sea vessel traffic risk assessment with Nuka Research and Planning Group. The purpose of the assessment was to better understand risks to the marine environment from oil exposure from vessel traffic and explore mitigation options. Some key findings from the assessment were presented. First, vessel traffic patterns differ in northern vs. southern Bering Sea. In the southern Bering Sea, most oil exposure is associated with vessels transiting through the area following North Pacific Great Circle Route. These vessels are not calling to local ports or servicing communities in the southern Bering Sea. In the northern Bering Sea, most oil exposure was associated with calls to ports (or lightering) in the region. So far, most of the vessels using these waters have some connection to the region i.e. they are delivering fuel or supplies to communities, engaged in fishing, or carrying ore from Red Dog. This kind of vessel traffic—the traffic associated with activities in the area—is relatively stable. Second, in the northern Bering Sea, tankers and cargo vessels are responsible for most of the oil exposure. Tankers account for 90% of the non-persistent oil exposure for all vessels as a result of their cargo capacities, since “exposure” combines oil carried as fuel and oil cargo. Exposure to persistent (e.g. heavy fuel oil) was from bulk (38%) and other cargo (36%) carries. Potential oil exposure by activity type was dominated by vessel calling to port or lightering to barges (46%). Finally, as vessel traffic increases in the region, transit traffic through the Bering Strait is the most likely area of growth in oil spill exposure, as bulk carriers and other large vessels are expected to increase the greatest compared to other vessel types. Mitigation options that were presented included: developing routing measures (e.g. ATBAs); planning for disabled vessels; preparing to reduce consequences of an oil spill, particularly vessels in innocent passage; and strengthening community spill response. Future shipping vulnerability assessments should be mindful of the fact that all vessels are not equal in terms of their potential risk of oil exposure to the environment.

### **5.4 Existing and planned monitoring programs (Term of Reference d)**

#### **5.4.1 Country reports**

See Annex 6 for country reports from Canada (Hedges and Templeman), Norway (Ingvaldsen), and Japan (Nishino).

#### **5.4.2 Other updates on recent and planned activities**

##### **CBMP (Bengtson)**

The Circumpolar Biodiversity Monitoring Program (CBMP) of the Arctic Council’s working group for Conservation of Arctic Flora and Fauna has completed its “State of the Arctic Marine Biodiversity Report” (SAMBR). The report is scheduled for release to the public in May 2017. This Report identifies trends in key marine species and points to important gaps in biodiversity monitoring efforts across key ecosystem components in: sea ice biota, plankton, benthos, marine fish, seabirds and marine mammals. Changes in these species are likely to indicate changes in the overall marine environment. The report found that changing food availability, loss of ice habitat, increases in contagious diseases, and the impending invasion of southern species are taking their toll on Arctic marine animals, and pointing to an ecosystem on the verge of a major shift.

### **The development of a fisheries regime for the central Arctic Ocean (Hoel)**

The Arctic Climate Impact Assessment (2005) predicted that fish stocks would expand northwards into the central Arctic Ocean. This, and increased attention to the effects of climate change such as reduction of sea ice, brought concerns in the US in particular that fish stocks could move into the central Arctic Ocean in the future. A Joint Resolution in the US Congress in 2008 therefore mandated that the US government initiated a process towards an international agreement to prevent unregulated fishing in the high seas area beyond national jurisdiction in the central Arctic Ocean. The five coastal states - the US, Canada, Denmark/Greenland, Norway, and Russia, met for the first time in Oslo in 2010 to discuss this. Realising that little was known about fish and ecosystems in that region, the governments called on their marine science institutes to provide a status of knowledge. A first science meeting was held in 2011, and since then another three have been held, evolving into a joint programme of scientific research and monitoring which is now about to be operationalised. A science plan, setting out the main science priorities, was developed in 2016 and an implementation plan will be developed in 2017. The core mission on this is addressing the question of whether there at some point in the future will be commercial quantities of fish in the high seas of the central Arctic Ocean which is now ice covered for most of the year. Meanwhile, the five coastal states negotiated an agreement to prevent unregulated fishing in the high seas area in the central Arctic Ocean, signed in 2015. In addition to establishing a commitment not to let their own vessels fish in this area until a regulatory regime is in place, the agreement (the 2015 Oslo Declaration) also establish a joint science and monitoring program and calls for further talks on the issue to include more parties. Such an expanded set of talks was initiated by the US late in 2015, and since then several rounds of talks have been held involving also Japan, the Republic of Korea, China, Iceland and the EU. The aim of these talks is to produce a legally binding agreement to prevent unregulated fishing in the central Arctic Ocean.

### **FisCAO -- Overview of 4<sup>th</sup> meeting of Scientific Experts of Fish Stocks in the Central Arctic Ocean (Mundy)**

Scientific Experts on Fish Stocks in the Central Arctic Ocean (FiSCAO) met in September 2016 to develop information supporting diplomatic negotiations on controlling commercial fishing on the High Seas of the CAO. The scientific mandates established in 2015 are to continue the scientific process, address specific questions, and to form a joint program of scientific research and monitoring for the CAO. To advance the development of a draft Joint Scientific Research and Monitoring Plan four questions were posed:

- What are the distributions and abundances of species with a potential for future commercial harvests in the CAO?
- What other information is needed to provide advice necessary for future sustainable harvests of commercial fish stocks and maintenance of dependent ecosystem components?
- What are the likely key ecological linkages between potentially harvestable fish stocks of the CAO and adjacent shelf ecosystems?
- Over the next 10–30 years, what changes in fish populations, dependent species, and the supporting ecosystems may occur in the CAO and the adjacent shelf ecosystems?

To answer these questions three terms of reference (ToRs) were adopted for the 2016 meeting: 1) complete a synthesis of knowledge, 2) develop a draft joint scientific research and monitoring plan, and 3) provide a framework for an implementation plan.

Prior to the meeting, a draft synthesis report on occurrence, distribution, abundance and phenology of selected fish species in the CAO was distributed for review. In addition, a monitoring plan was drafted and has been translated into a framework for an implementation plan. The draft framework contains a great deal of geophysical information but little is known about the higher trophic levels in CAO. The ToRs for the fifth FiSCAO meeting in October 2017 focus on the development of a synoptic mapping survey covering as much of the CAO High Seas as possible using available research platforms to characterize fish and invertebrate communities and their spatial variability to help establish if there is fishable biomass present in the CAO. To support this initiative, it is important that all countries involved in the coordinated research and monitoring program also participate in the development of the scientific research. Furthermore, the WGICA should continue to coordinate and link efforts with FiSCAO and other similar arctic-based science working groups to share data and avoid duplication of effort.

#### **DBO and PACEO (Grebmeier)**

The Distributed Biological Observatory (DBO) sites are a series of regional “hot spot” transect lines and stations located along a latitudinal gradient (<https://www.pmel.noaa.gov/dbo/>). The DBO sites are considered to exhibit high productivity, biodiversity, and overall rates of change and serve as a change detection array for the identification and consistent monitoring of biophysical responses. The DBO sites are occupied by national and international entities with a shared data plan. A developing long-term monitoring activity in the high Pacific Arctic is the Pacific Arctic Climate Ecosystem Observatory (PACEO), coordinated by three Asian countries: Japan, Republic of Korea, and China. PACEO includes a set of climate lines extending from the Chukchi Borderlands into the Canada Basin. The Synoptic Arctic Survey (SAS) is a developing international initiative for a coordinated multi-ship operation in the Arctic Ocean in the course of one summer season in one year ([www.synopticarcticssurvey.info](http://www.synopticarcticssurvey.info)) that could include standard physical, biochemical and biological measurement as with the DBO, plus key fisheries measurements in a pan-Arctic mode that would be a valuable contribution to our understanding of the status of the boundary seas girdling the CAO and extending into the deeper portions of the CAO. The International Arctic Drift Expedition (MOSAiC) plans directed *in situ* observations of the climate processes that couple the atmosphere, ocean, sea ice, biogeochemistry and ecosystem, although the biological component is limited (<http://www.mosaicobservatory.org/>).

#### **The new agreement on international cooperation in Arctic science (Hoel)**

Under the auspices of the Arctic Council, an agreement on international cooperation in Arctic science has been negotiated since 2013, and was signed at the Arctic Council ministerial in Fairbanks 11 May. The agreement is among the eight members of the Arctic Council (USA, Canada, Denmark/Greenland, Iceland, Norway, Finland, Sweden, and Russia) and is basically about facilitating international science cooperation. Its key objective is to reduce barriers to cooperation so as to provide for more and better knowledge about the Arctic. The agreement is legally binding and contains provisions on access to areas, exchange of data, entry and exit from territories of personell and equipment, among other things. It applies in a wide area, where “Arctic” is defined by each country in an annex to the agreement. The agreement can be read here: <https://www.state.gov/e/oes/rls/other/2017/270809.htm>

## 6 Revisions to the work plan and justification

### 6.1 Products needed for CAO IEA components

#### Approach and outline of the Integrated Ecosystem Assessment (IEA)

The group agreed to a provisional outline and framework of the IEA for the CAO. It included a basic description of the CAO ecosystem including topics such as climate and oceanography, sea ice biota, fish, marine mammals, and birds for both central basin areas as well as the Atlantic and Pacific gateway zones (Figure 6.1). The 'Key features' section (Annex 2) provides a current synopsis of the ecosystem description. The ecosystem description with highlighted key features will form the basis for assessment of (potential) impacts and vulnerabilities with regards to shipping, fisheries, and climate change.

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#### Six topics are planned to be core elements of the IEA for the Central Arctic Ocean (CAO)

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Ecosystem description with emphasis on key characteristics of the CAO	Could include illustrations and a map showing circulation layers, plus maps showing bird and mammal distributions, and diagrams showing trophic linkages among the key species in the CAO.
Level of primary production	This is a review of the scientific literature on the level of primary production by phytoplankton and ice algae, including consideration of limiting factors (light, nutrients) and seasonal and spatial patterns.
Fish in the CAO	This is a summary of knowledge of fish and fish stocks in the CAO, building on information included in this year's report: overview of Arctic fish, records of fish in the CAO, acoustic records, and the Arctic fisheries process. Regarding acoustic records, there should be more effort to acquire existing acoustic data and collect acoustic data in future.
Marine mammals and seabirds	This will be an overview of marine mammal and seabird abundance, distribution, habitat use, and ecology.
Vulnerability assessment (shipping)	Assessment of sensitivity and potential vulnerability of species and their ice habitats to oil spills, noise and visual disturbance, including the disturbance of sea ice by ships.
Climate impact assessment	This is planned as a summary and review of knowledge of changes in the CAO ecosystem that have taken place during the period of the 'Great melt' in the recent decades after the 1980s. The review will emphasize changes to plankton, ice biota, birds, and marine mammals. The knowledge of what the ecological impacts have been of the major loss of sea ice up to now, will form an important basis for assessing the potential impacts and vulnerability of the CAO ecosystem to future climate change.

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The IEA will address the effects of changes that have occurred in CAO ecosystems over the past few decades including:

- phytoplankton and zooplankton;
- small ice biota (e.g. sea-ice amphipods);
- fish (range extension; can possibly be addressed through existing literature);
- marine mammals and birds – have there been documented changes due to less ice? What are the anticipated changes?

There are several examples of recent papers and synthesis reports that are relevant to the IEA. It would be desirable to compile a list of recent papers and synthesis reports. All of the items above should be considered when constructing further work and developing a timeline.

It was noted that the IEA could be strengthened considerably if clear questions were posed about the anticipated ecological changes and potential impacts to ecosystem components. The ecosystem description and key features section could start with an overview of the structure and function of the ecosystem, including drivers and linkages. Based on the descriptions of how things have changed in the last 20 or so years, the IEA will then move on to the potential ecosystem changes in future, focusing on ecological linkages to individual species and how those species may be affected.

The initial sections of the IEA to be drafted will be: 1) a description of the CAO ecosystem, and 2) an assessment of vulnerabilities and impacts as shown below (Figure 6.1).

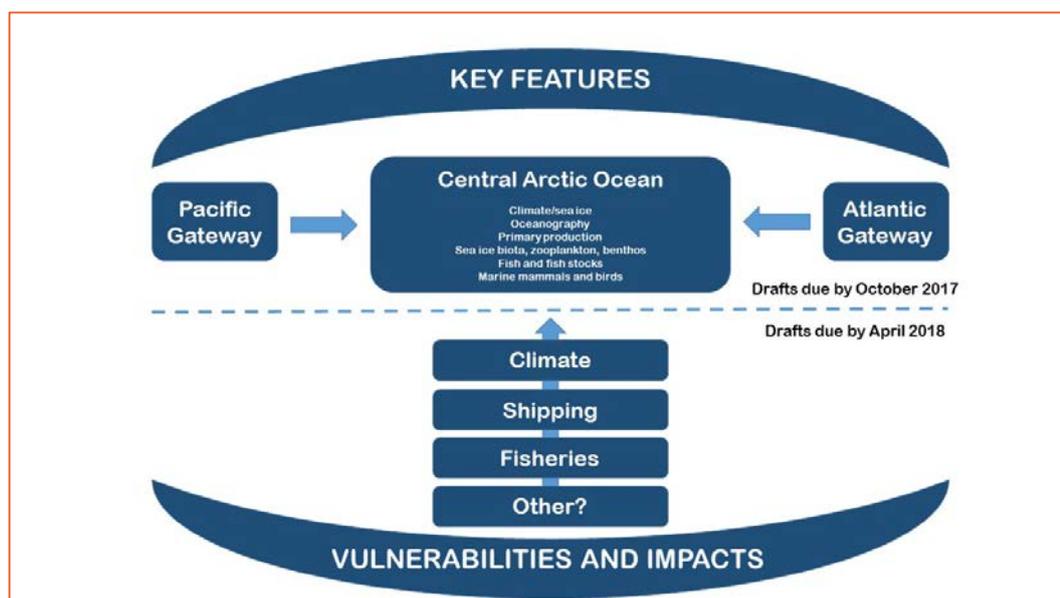


Figure 6.1. Provisional framework for Integrated Ecosystem Assessment of the Central Arctic Ocean.

Draft descriptions of the CAO ecosystem “key features” (due before the WGICA conference call in October 2017)

The basic features of the CAO ecosystem will be described, including complementary information from the Atlantic and Pacific Gateway areas as well as from adjacent slope and shelf habitats. These descriptions will outline habitat and connectivity among areas, trophic linkages, process functions, and ecological relevance, including conceptual models. The draft of the basic features section will be based on a draft report on the CAO LME prepared as part of updates of the Arctic LME descriptions for the ‘Oil and Gas Assessment’ by AMAP (lead author: Hein Rune Skjoldal). Suggested authors (to

provide new and additional information) for the various sections of the “key features” part of the IEA are listed below:

- Atlantic Gateway – Invaldsen and Atlantic gateway working group
- Central Arctic Ocean (CAO)
  - Climate/sea ice – Overland
  - Oceanography – Ingvaldsen, Ivanov
  - Primary production – Skjoldal, von Quillfeldt
  - Sea ice biota, zooplankton, benthos – Skjoldal, Blum, Melnikov, von Quillfeldt
  - Fish and fish stocks – Hedges, Lunsford, Gjørseter
  - Marine mammals and birds – Bengtson, Frie, Kuletz, Regehr
- Pacific Gateway – Grebmeier and the Pacific gateway working group

## 6.2 ICES and PICES

PICES has decided formally to join as a parent organization of WGICA along with ICES and PAME. Sei-ichi Saitoh from Japan has been appointed as a new chair of WGICA by PICES. The meeting welcomed the involvement of PICES and we look forward to working with Dr. Saitoh as a new chair.

## 6.3 Arctic Council working groups

Two Arctic Council working groups, Arctic Monitoring and Assessment Programme (AMAP) and Conservation of Arctic Flora and Fauna (CAFF), have expressed their continuing interest in the work being undertaken by WGICA. However, AMAP and CAFF have decided not to become formal sponsors of WGICA at this time.

## **7 Next meetings and conclusion**

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The group agreed to hold a virtual two-hour conference by phone mid-October 2017 (10-12 October most likely). Draft assessment sections will be due at that time, and topics for the next in-person meeting will be identified. Any gaps that are identified could also be brought up at the FiSCAO meeting in Ottawa on 24–26 October 2017.

An invitation from Canada to host the next in-person meeting of WGICA was gratefully accepted. That meeting is planned to be held in April or May 2018 in St. Johns, Newfoundland, Canada. The group confirmed that it would be best to meet for 3 days at that time. The main agenda items would be to work through the draft assessment sections.

In closing the meeting, chairs Bengtson and Skjoldal thanked the participants for their energy and contributions which had resulted in a very productive meeting. They also thanked the WGICA's host, NOAA's Alaska Fisheries Science Center for its support and hospitality for arranging and supporting the meeting.

## Annex 1: WGICA list of participants

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## Annex 2: Key features of the central Arctic Ocean ecosystem (Skjoldal)

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The Central Arctic Ocean (CAO) is a globally unique ecosystem due to its high latitude location at the 'top of the world', presence of sea ice, strong vertical stratification from freshwater input, and low primary production during a short summer season. It is a large geographical area, with the CAO LME being 3.3 million km<sup>2</sup>.

The CAO consists of two deep basins (around 4000 m), the Eurasian and Amerasian (Canada) Basins, separated by the Lomonosov Ridge (about 1000 m deep) running from central Siberia across to northern Greenland. The basin slopes are generally steep, separating the basins from wide, shallow shelves on the Eurasian side and narrower shelves on the American side.

### The physical realm – the 'stage'

Hydrographically, the water masses of the CAO consist of four vertical layers:

- A top layer of about 50 m thickness (varying from about 30 m to >100 m) shows large seasonal change with homogenization due to ice formation and brine excretion in winter, and stratification due to ice melt and stronger riverine input during summer.
- A gradient layer (including the so-called 'cold halocline') located from about 50 to 200 m depth. The cold halocline is a strong gradient in salinity without a corresponding gradient in temperature (near freezing), which is interpreted to reflect horizontal transport of water from adjacent shelves along density isolines. Pacific water of lower salinity than Atlantic water (by around 2 salinity units) is found in the upper part of the halocline in the Amerasian Basin with Pacific summer water layered above Pacific winter water.
- An Atlantic layer between about 200–1000 m depth of circulating Atlantic water from two main sources: the Barents Sea and Fram Strait branches.
- A deep layer below about 1000 m depth with water of Atlantic origin filling the deep basins.

Floating on top of the top layer is sea ice which forms a special habitat for a unique biota. The sea ice is broadly classified into annual ice formed during the preceding winter, and multi-annual ice which is thicker and may be several years old. The sea ice is a heterogenous environment with build-up of pressure ridges and opening of leads as it moves around as drifting pack ice.

The sea ice and the different layers of water move in different and partly opposing patterns. The sea ice and top layer move with two prominent features: the clockwise Beaufort Gyre in the Canada Basin, and the Trans-Polar Drift across the central ocean towards the Fram Strait. The Atlantic layer move with slope currents in counter-clockwise direction around the margins of the basins. The Lomonosov Ridge influences the circulation and contributes to setting up sluggish circulation cells in the main basins.

The Arctic Ocean is openly connected to the North Atlantic through the deep Fram Strait. About half of the Atlantic water (of order 5 Sv; 1 Sv = 10<sup>6</sup> m<sup>3</sup> s<sup>-1</sup>) that enters the Nordic Seas (north of the ridge between Scotland and Iceland) continues into the CAO through the Atlantic gateway. The residence time of the Atlantic water is of order 10–60 years depending on the route, and most of the water leaves through the Fram Strait. The Pacific water (of order 1 Sv) that enters through the Pacific gateway (which is about 1000 km of very shallow waters (around 50 m) from the northern Bering Sea up

through the Chukchi Sea), spreads out in the upper halocline layer in the Amerasin Basin and drains out mostly through the openings of the Canadian Arctic Archipelago and to lesser extent through the Fram Strait. The residence time of the halocline water is from one to a few decades, while that of the deep water is several hundred years.

#### The living part of the ecosystem – the ‘actors’

The CAO is geologically a relatively new ocean, ‘only’ about 50 million years old. Due to the open and deep connection through the Fram Strait, the CAO is biogeographically an extension of the North Atlantic (as part of the Arctic Mediterranean Sea) and most species are of Atlantic origin. The number of species that are adapted and capable to live under the harsh Arctic conditions is limited compared to other marine ecosystems, although a fair number of species is found among lower trophic level organisms. Thus, there are around 150 species of zooplankton recorded from the CAO, many of them deep-water species found in the deep basins. Only 12 species of fish have been recorded from the CAO, while 9 species of marine mammals are found more or less regularly in the CAO. Most higher animals are seasonal visitors to the CAO, and there is no clear evidence of any species populations that are resident and found only in the CAO (except perhaps for Arctic cod *Arctogadus glacialis* and a polar bear subpopulation).

The primary producers are tiny plants, unicellular algae, growing as phytoplankton in the upper lighted water layer, or as ice algae attached to the underside of sea ice. Small flagellates and diatoms make up most of the phytoplankton, which often is dominated by very small forms (so-called picoplankton, <2 µm). Diatoms of various types and species dominate the ice algae, where *Melosira arctica* is an important and characteristic species, forming meter long tufts suspended from ice floe margins.

Four species of copepods make up most of the mesozooplankton biomass: three species of *Calanus*, *C. hyperboreus*, *C. glacialis*, and *C. finmarchicus*, and *Metridia longa*. The *Calanus* species are predominantly herbivores and feed only during the short summer period, whereas *Metridia* is more an omnivore. Small copepods including *Oithona* and *Microcalanus* species are also important components of the CAO ecosystem. *Calanus hyperboreus* is a relatively large copepod (ca. 6 mm long) and has a multi-annual life cycle (up to 4 years or even more) which allows it to live in the CAO. It appears to reproduce successfully only in the southern and peripheral areas of the CAO with lighter sea ice conditions. The same is the case for *Calanus glacialis* which probably is a shelf species of less importance over the deep basins. *Calanus finmarchicus* is an expatriate (does not reproduce) transported with the Atlantic water (primarily the Fram Strait branch) into the Eurasian Basin. There is a similar transport of expatriate species with the inflowing Pacific water including *Neocalanus* and other copepod species.

Amphipods are an important group among the sea ice biota. *Apherusa glacialis*, *Onisimus nansenii* and *Gammarus wilkitzkii* are common species, of which *G. wilkitzkii* is the largest (up to 6 cm in length).

The majority of fish classified biogeographically as Arctic are demersal species living more or less closely associated with the seabed. Two dominant groups (in terms of number of species) are sculpins, which tend to dominate on Arctic shelves, and eelpouts, which are more common on Arctic slopes. Two small cod-fish are found in the CAO. Polar cod *Boreogadus saida* is found with presumably migratory populations on surrounding shelves (Barents, Laptev, Chukchi, and Beaufort seas). It is also found under the ice in the CAO but it is not clear to what extent this represents spillover of

larvae and juveniles from the surrounding shelf populations. Arctic cod *Arctogadus glacialis* has been found under sea ice primarily in the Amerasian Basin where it possibly forms a migratory population. Little is known about the species but it has been speculated (based on observations from previous ice-floe drift stations) that it may migrate to spawn in the Chukchi Borderland region. Greenland halibut is found in the slope region north of the Barents and Kara seas. They belong to the Barents Sea stock with spawning area on the western slope into the Norwegian Sea. This species is also found in the Amundsen Gulf region in the eastern Beaufort Sea.

Ringed seal is a true Arctic species distributed in low densities in the sea ice of the CAO. Satellite-tracking has shown that individuals from surrounding shelves (Barents, Chukchi, and Beaufort seas) make seasonal excursions in summer into the CAO, presumably to feed on sea ice amphipods and polar and Arctic cod. It is not known whether there is a component of ringed seals that live permanently and breed on pack ice in the CAO. As benthic feeders, bearded seals and walrus are mostly restricted to continental shelf and slope areas adjacent to the CAO basins.

Polar bear of several subpopulations can be found on sea ice in the CAO (Barents Sea, Kara Sea, Laptev Sea, Chukchi Sea, southern and northern Beaufort Sea subpopulations). A common pattern is that after spending winter with breeding in core areas of the respective shelf seas, large fractions of individuals from the various subpopulations migrate north with the seasonally retreating sea ice into the CAO. In addition, there is an Arctic Ocean subpopulation that possibly breeds mainly in the northernmost part of the Canadian Arctic Archipelago. Ringed seal is probably the main prey for polar bears in the CAO.

Bowhead whales of the critically endangered Spitsbergen population live in the waters north of Svalbard and use the marginal ice zone in the Nansen Basin as a foraging habitat in summer. Bowheads of the much larger Bering-Chukchi-Beaufort stock migrate seasonally to feed in the eastern and southern Beaufort Sea. *Calanus hyperboreus* is possibly the main prey item for bowheads of both stocks.

Beluga whales of the Karskaya stock complex (Barents-Kara-Laptev) and the Beaufort and Chukchi stocks may extend their seasonal feeding migrations into the CAO basins where they presumably seek polar cod and Arctic cod. Narwhal use the slope region north of the Barents and Kara seas and the marginal ice zone of the Nansen Basin as habitat, possibly feeding on Greenland halibut and the squid *Gonatus fabricii*. Harp seals from stocks in the Greenland and Barents seas may use the same area to feed in summer, as may some hooded seals from the Greenland Sea stock.

There is a limited number of seabirds that are found in the CAO, usually in small numbers, including black-legged kittiwakes, thick-billed murrelets and black guillemots. There are two gull species for which the marginal ice zone of the CAO constitutes important habitat for major parts of the populations. Ivory gulls breed on remote cliffs and nunataks in northern Greenland, on islands in the northern Kara Sea, and in smaller numbers in Arctic Canada. In late summer and autumn, the population uses ice habitat in the Nansen Basin before moving south with the advancing ice in winter. Ross's gulls breed on tundra in eastern Siberia. After breeding the population moves north and the gulls spread out in the marginal ice zone of the CAO.

#### **Spatial, seasonal and trophic dynamics – the 'play'**

The primary production by phytoplankton and ice algae in the CAO is generally low, reflecting strong limitation by light and nutrients. Sea ice and snow cover reduce the

light that reaches the water by factors of 10–1000 (light transmission of 10%–1‰). Nutrients are limited due to the cycle of ice freezing and thawing which leads to an impoverished upper layer with limited nutrient replenishment by vertical mixing. The growing season is short (2–4 months) and seasonally skewed towards the late summer period with minimum sea ice cover. The level of annual primary production is very low (1–5 g C m<sup>-2</sup> y<sup>-1</sup>) in areas with heavy pack ice, low (10–15 g C m<sup>-2</sup> y<sup>-1</sup>) in areas with lighter ice conditions, and somewhat higher (20–30 g C m<sup>-2</sup> y<sup>-1</sup>) in slope areas. Overall, the area-specific (per m<sup>2</sup>) primary production in the CAO is an order of magnitude lower than in adjacent Subarctic and boreal seas with open water (typically 100–200 g C m<sup>-2</sup> y<sup>-1</sup>). There are probably 4 hot spots of relatively high primary production: the southwestern Nansen Basin with inflow of Atlantic water, the Laptev sector with the ‘Great Siberian Polynya’, the Amundsen Gulf region with the Bathurst Polynya and associated leads, and the Chukchi Borderland region with inflow of nutrient-rich Pacific water. In contrast, the Beaufort Gyre is a region of very low primary production due to doming and downwelling in the clockwise gyre.

Phytoplankton and ice algae nourish the growth and reproduction of zooplankton and ice biota. The coupling from algae to grazers can be complex and involve micro-organisms and protozoans in the so-called ‘microbial loop’. *Calanus hyperboreus* is predominantly an herbivore which is restricted to feed on larger phytoplankton since it cannot filter the smallest forms (pico- and nanoplankton <5 µm). Some of the sea-ice amphipods can graze on layers of ice algae, while other species are mostly carnivorous. The trophic transfer efficiency from the primary producers to herbivores and further up in the foodweb is poorly known for the CAO. It could be low due to the apparent large role of small phytoplankton cells, which requires more steps in the microbial loop with associated metabolic loss before the production can be channelled to larger consumers. Some part of the foodweb can be effective, however, such as sea ice amphipods grazing on mats of ice algae, being in turn eaten by ringed seal.

The four regions indicated with relatively high primary production, are probably also core areas for reproduction by the large herbivorous or omnivorous copepods (e.g. *Calanus hyperboreus*). From these core areas, new cohorts of zooplankton can spread and be transported with currents into less productive parts of the CAO. Advective transport of zooplankton with the inflowing Atlantic water (notably *Calanus hyperboreus* and the expatriate *C. finmarchicus*) is a major process for sustained production and energy budget of the CAO. Transport of Pacific expatriates with inflowing Pacific water is probably also a significant contribution to the budget for the Pacific sector of the CAO.

There is limited knowledge of the distribution and amount of polar cod and Arctic cod in the CAO, but we know they are present with a wide distribution under the ice. Sea ice amphipods and large zooplankton (such as *Calanus hyperboreus* and *Themisto libellula*) are presumably the main food items for these two small cod fish. They are in turn probably the main prey for ringed seal, which again is the principle food for polar bear while they are summering in the pack ice of the CAO. Sea ice amphipods and other small ice biota and zooplankton are also probably the main prey for ivory and Ross’s gulls when they forage in the marginal ice zone of the CAO in late summer. The gulls also feed on faeces and remnants of polar bear kills (e.g. ringed seal).

Bowhead whales have fine-meshed baleen and can feed on large copepods including *Calanus glacialis*. It is likely that *Calanus hyperboreus* is the main prey for bowheads when they are feeding offshore in the Beaufort Sea and (for the Spitsbergen stock) in the Nansen Basin. Narwhals are deep divers and may feed on Greenland halibut and *Gonatus fabricii* in the Nansen Basin north of the Barents and Kara seas.

## Annex 3: Primary production in the central Arctic Ocean – a review

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Summary for WGICA, based on AMAP OGA LME description

Hein Rune Skjoldal, IMR, Norway – 17 September 2016/21 August 2017

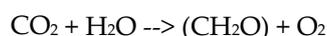
Some basics

### Concepts and terminology

Primary production is the production and growth of plants at the base of the trophic ladder being the basis for energy flow and material cycling in an ecosystem. While this is clear in principle, primary production is defined, expressed and measured in different ways, making it a complex issue. The primary producers in the central Arctic Ocean are microalgae in the forms of phytoplankton and ice algae.

- **Gross primary production** (GPP) is the total amount of organic material produced by algae through photosynthetic carbon fixation.
- **Net primary production** (NPP) is the gross primary production minus algal respiration.
- **Net Community Production** (NCP) is the net primary production minus also heterotrophic respiration by micro-organisms and zooplankton.
- **Export production** (EP) is the part of the primary production that leaves the euphotic zone through sinking and sedimentation.
- **New production** (NP) is primary production based on new input of nutrients to the euphotic zone, technically defined as growth of algae based on nitrate.
- **Regenerated production** (RP) is primary production based on recycled nutrients in the euphotic zone, technically defined as growth of algae based on ammonium and in some cases also urea.
- **Harvestable production** is usually equated with new production, being the production that can be removed by harvest without impoverishing the system.

The basic equation for photosynthetic C fixation is:



The basic equation for respiration is the same in reversed form. The primary organic material formed by photosynthesis and used as the basic substrate in respiration is the carbohydrate glucose. The biochemistry in organisms is more complex, and inorganic nutrients (N and P) are used to form amino acids, proteins and other biochemical constituents such as nucleotides and nucleic acids. In stoichiometric versions the equations for photosynthesis and respiration form the basis for the Redfield ratios (Redfield, Ketchum, Richards):

106 C: 150 O<sub>2</sub> : 16 N : 1 P (check oxygen; see Redfield *et al.*, 1963).

These ratios are relatively robust and can be used to convert results obtained with different methods, such as C fixation, uptake of N (nitrate, ammonium), and evolution of O<sub>2</sub>.

In a steady state and non-advective regime (basically an isolated and vertically connected water column), export production is equal to new production (input of nutrients by mixing from below equals the loss from the upper euphotic layer by sedimentation

over the annual cycle). NPP in the euphotic layer in the forms of C fixation, O<sub>2</sub> evolution and N uptake by algae balances the respiratory remineralization of the produced organic material taking part both in the euphotic zone and in the deeper part of the water column below. The seasonal draw-down of nitrate in the euphotic zone from maximum values in winter to minimum values sometime in summer is an expression of new production, where any input of nitrate into the euphotic zone by mixing across the deeper boundary during the vegetative period also needs to be counted. Through export production, a similar amount of nitrate is produced through remineralization of sedimenting material in the water column below the euphotic zone. For C (CO<sub>2</sub>) and O<sub>2</sub> the gaseous exchange with the atmosphere needs to be taken into account when considering equilibrium budgets over the water column.

The concept of Net Community Production (NCP) is much used in the literature although it is ill-defined and difficult in practice. It represents the difference between gross primary production by algae and the respiration by all organisms including algae, heterotrophic micro-organisms and zooplankton. Averaged over the water column and an annual cycle, NCP is zero in a steady-state system. That is, all material produced by algae are being recycled and remineralized. If NCP is calculated for the euphotic zone, it may be taken to represent new production since regenerated production is based on respiratory remineralization and recycling of nutrients. A practical aspect with incubation methods (see below) is to what extent larger organisms, e.g. zooplankton, are excluded from the measurement, and to what extent NCP estimates from bottle incubations are underestimating the real NCP in the euphotic zone.

Williams (1993b) reviewed concepts and definitions of the various types of primary production, and Codispoti *et al.* (2013) provided a recent summary of the topic. They concluded that despite the complexities, “there is a rough consensus that *total production estimated from <sup>15</sup>N incubations (roughly equals) PP estimated from <sup>14</sup>C incubations and that new production (roughly equals) NCP*”.

### **Role of advection**

The steady state situation with a vertically connected water column does not apply to the strongly stratified central Arctic Ocean. There are basically four main water layers: 1) polar upper mixed layer (ca. 0–50 m), 2) cold halocline gradient layer (ca. 50–200 m), 3) Atlantic layer (ca. 200–1000 m), and 4) deep water (ca. 1000–4000 m). The top layer moves more or less independent from the Atlantic layer deeper down; e.g. in the Canada Basin the top layer circulates clockwise as part of the Beaufort Gyre whereas the Atlantic layer below circulates anticlockwise.

The halocline layer receives the sedimenting material falling out of the euphotic zone as export production. This layer is then moved around in the central Arctic Ocean with pathways at least partly different from those of the top layer. The halocline layer carries with it productivity signals from upstream source regions on the Atlantic and Pacific sides. This may be in the form of organic material (both particulate and dissolved) which represents a biological oxygen demand (BOD) leading to decrease in O<sub>2</sub> concentration and increase in concentrations of nitrate and DIC. The signal may also be in the form of a nitrate deficit (relative to preformed winter concentrations) as demonstrated by the study of Olsson *et al.* (1999). They showed a fairly high nitrate deficit in the Atlantic halocline layer stemming from production in upstream areas in the Barents and Norwegian seas. This is an example of an advective signal that, if it was taken to represent processes in a vertically connected water column, would lead to a strong overestimate of the production in the upper layer of the water column above.

The above example demonstrates the complexity in interpreting measurements through the water column in the central Arctic Ocean. There may be signals from at least three different processes embedded in the observed concentrations in the halocline layer: 1) a productivity signal from upstream regions with reduced nitrate and increased O<sub>2</sub> and DIC, 2) a productivity signal also from upstream regions in the form of BOD leading to reduced O<sub>2</sub> and increased nitrate and DIC, and 3) a similar signal resulting from export production in the water column above. These three and opposing processes may be difficult to disentangle and the two first (advected signals with opposing signs) may lead to overestimates of *in situ* production if they are not carefully corrected for.

#### Limitation by light and nutrients

Light and nutrients are considered the two main limiting factors for primary production in the central Arctic Ocean. The high latitude location and the extensive sea ice cover limit the incoming solar radiation to the sea or ice surface and into the water column below. Low sun angle is associated with high reflection, and sea ice reduces the light penetration by one to several orders of magnitude (light transmission is typically from about 0.1% for thick and snow-covered ice to 10% for more transparent melting sea ice with no snow cover. Clouds and fog associated with open water in the cold climate is another factor that reduces the incoming light.

The strongly stratified conditions in the central Arctic Ocean limits the upward transport of nutrients by vertical mixing from below. This leads to a nutrient impoverished upper mixed layer (corresponding broadly to the euphotic zone) separated by a strong halocline from nutrient richer water in the Atlantic and Pacific water layers below.

The primary production in the central Arctic Ocean is driven ultimately by the input of nutrients from the Atlantic inflow with the Barents Sea and Fram Strait branches, and from the Pacific inflow through the Bering Strait and Chukchi Sea. Most of the nutrients in the Atlantic water do not become available for production since they are in the bulk Atlantic layer between about 200 and 1000 m depth. Nutrients from the Atlantic water are provided to the top layer in the western Nansen Basin where the heat of the inflowing water melts sea ice and creates a two-layered system (Rudels). Nutrients are also provided by Atlantic water that forms the cold halocline in the eastern Nansen Basin, some of which may be mixed into the upper layer by winter convection and processes such as upwelling alongshelf edges. The nutrient-rich Pacific water is separated into summer and winter waters that form layers at about 50–70 and 100–150 m depth in the upper halocline. Some nutrients particularly from the Pacific summer water are mixed up into the top layer by winter convection and other processes.

The annual inputs and reservoirs of nutrients supplied by Atlantic and Pacific waters set the upper limit of the total annual new production in the central Arctic Ocean. Anderson *et al.* (1998a) calculated the total annual input of nitrate by Atlantic and Pacific waters in the upper 200 m or so to correspond to an annual new production of 12 g C m<sup>-2</sup> when converted to units of C. This assumes that all the nitrate is utilized which is likely not to be the case. However, the calculation illustrates an upper maximum for the overall production in the central Arctic Ocean.

In broad terms the production in the Amerasian Basin appears to be more strongly nutrient limited while the production in the Eurasian Basin is more light-limited. This is reflected in very low nutrient concentrations, e.g. nitrate <1 μM, even in winter in

the Beaufort Gyre in the Canada Basin, whereas nutrients are somewhat higher (2–4  $\mu\text{M}$  nitrate) and may not be seasonally depleted in the Amerasian Basin.

### Methods

There is a wide range of methods in use for determining rates of primary production. They can be broadly grouped in five categories:

- Incubations
  - $^{14}\text{C}$
  - $^{13}\text{C}$
  - $^{15}\text{N}$  (nitrate, ammonium, urea)
  - Oxygen
- Chemical properties in water column
  - Carbonate system
  - Oxygen
  - Inorganic nutrients
  - $^{234}\text{Th}$
- Sediment traps
- Remote sensing
- Mathematical modelling

The C-14 method is the classical method for measuring primary production since its first was used by Steemann Nielsen in 1952. It is perhaps surprising that it is still not clear what the  $^{14}\text{C}$  method is measuring although there is consensus that it lies somewhere between GPP and NPP. It has more recently been supplemented by using the stable isotope  $^{13}\text{C}$ , often in combination with measurements of uptake of  $^{15}\text{N}$  nitrate and ammonium (and occasionally urea).

Incubations for C uptake are done in basically three different ways:

- *In situ* incubations where bottles are incubated suspended at their respective light depths across the euphotic zone (commonly down to 1% light).
- Simulated *in situ* incubations where bottles are incubated in an incubator where screens are used to simulate light levels corresponding to light depths.

P vs. I incubations where bottles from selected depths are incubated at different light levels to determine the relationship between rate of C fixation and light level, so-called P-I curve. Rates of primary production are then calculated or modelled from light, biomass (chlorophyll *a*) and photosynthetic parameters from the P-I curve (where P is normalized per unit chlorophyll *a*).

New production is often estimated using the *f*-factor which is the ratio of uptake of nitrate to uptake of the sum of nitrogen nutrients (nitrate plus ammonium and also sometimes urea) determined from uptake of  $^{15}\text{N}$  labelled nutrients. The *f*-factor can be used along with estimated primary production from uptake of  $^{14}\text{C}$  or  $^{13}\text{C}$ , and uptake of N from  $^{15}\text{N}$  labelled substrata can also be converted to units of C using Redfield ratio or study-specific empirical ratios.

Incubations measuring oxygen evolution from the photosynthetic C fixation was more commonly used earlier. In principle, rates of C uptake and fixation and  $\text{O}_2$  evolution should correspond since they are stoichiometrically related in the basic equation for photosynthesis and respiration. However, they have been found to correlate but not correspond, which may reflect differences in processes in the dark bottles which are used to correct the measurements in light bottles. (There is a dark uptake of  $^{14}\text{C}$ , which

is not well understood but is subtracted from the light value, while the dark respiration is subtracted to obtain the net production as the difference between incubation in light and dark.)

Methods based on changes in chemical properties in the water column include measurements of O<sub>2</sub> concentration and concentrations of CO<sub>2</sub> and dissolved inorganic carbon (DIC, including bicarbonate and carbonate ions). Increase in O<sub>2</sub> concentration and decrease in DIC in the euphotic zone can be used to estimate NCP, using appropriate corrections for gaseous exchange with the atmosphere across the sea surface. The opposite trends, decrease in O<sub>2</sub> and increase in DIC, in the water column below the euphotic layer can be used to estimate respiratory remineralization of organic material reflecting export production.

Seasonal drawdown of DIC in the euphotic zone between winter maximum and summer minimum is used as a measure of annual (or seasonal) new production. The same is the case for integrated contents of inorganic nutrients, notably nitrate and phosphate.

Sediment traps deployed below the euphotic zone are used to measure the vertical flux of particulate organic carbon (POC) and other variables such as PON and chlorophyll *a* and phaeopigments. This can provide a direct measurement of export production.

Satellite remote sensing of ocean colour is used to estimate primary production. This is done with algorithms for two conversions: ocean colour recorded by sensors is converted to estimate of chlorophyll *a*, which is then converted to estimate of net primary production (NPP) based on empirical relationships. This method has limitation in the central Arctic Ocean since it can “see” chlorophyll only in nearly ice-free waters (up to 10% ice cover), which excludes most of the area.

Coupled physical-biological models including nutrients and biochemistry are used to estimate primary production. With three-dimensional physics included, the models take horizontal advection into account, but a challenge is how well the vertical mixing processes are represented for the strongly stratified and seasonably variable Arctic Ocean.

## Results

### 14C and 13C incubations

Rates of daily and annual primary production from incubation with <sup>14</sup>C or <sup>13</sup>C from studies in the central Arctic Ocean are shown in Figure 1. Daily rates are commonly 10-100 mg C m<sup>-2</sup> d<sup>-1</sup>. They are extrapolated to annual rates in most studies by multiplying with a length of the vegetative season of 120 days, which translates them into estimates of annual primary production of roughly 1-10 g C m<sup>-2</sup> y<sup>-1</sup>.

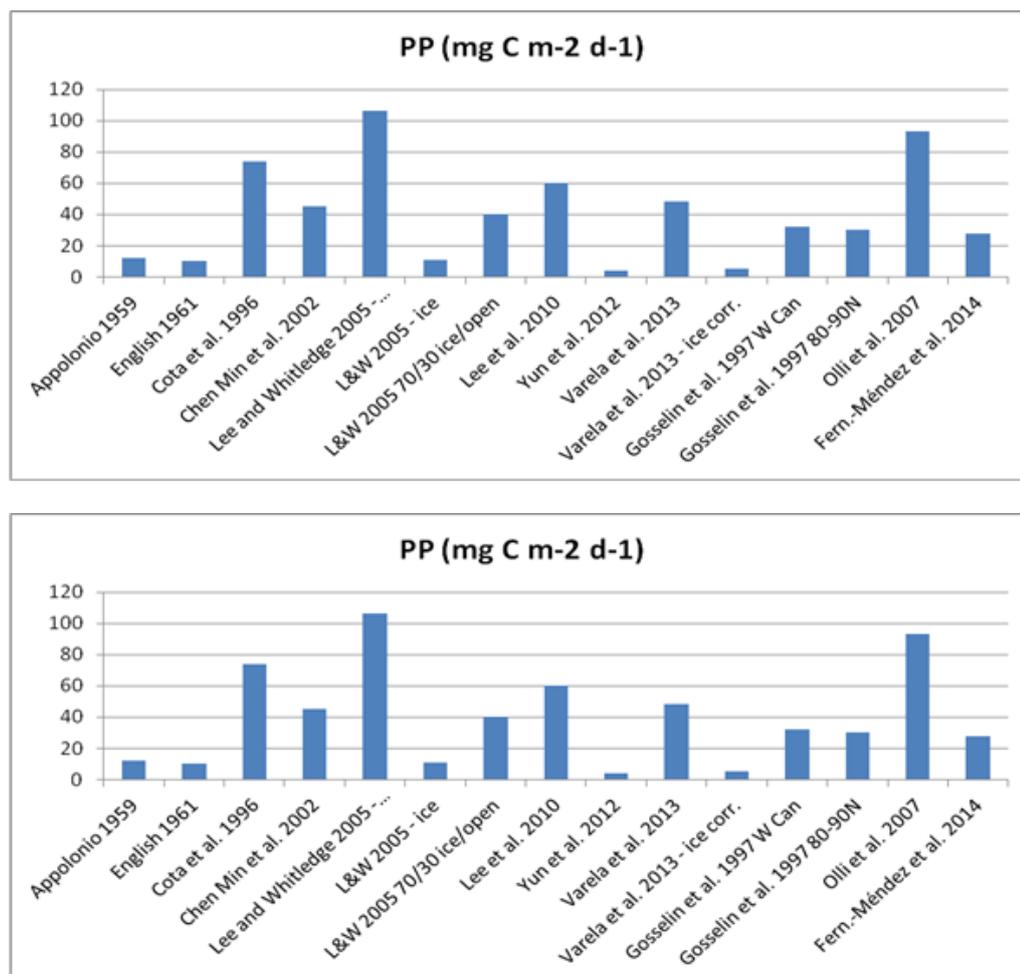


Figure 1. Daily (upper panel) and annual (lower panel) estimates of primary production from carbon fixation determined with C-14 or C-13 incubations.

There are two factors that have clear effects on the results; these are sea ice conditions and time within the vegetative season.

Lee and Whittledge (2005), working in the Canada Basin, found mean rates of about 100 mg C m<sup>-2</sup> d<sup>-1</sup> in open waters with a factor of 10 lower rates (about 10 mg C m<sup>-2</sup> d<sup>-1</sup>) in ice covered waters. Translated to annual rates (120 days) gave values of 13 and 1.4 g C m<sup>-2</sup> y<sup>-1</sup> for open and ice covered waters. An estimate of 5 g C m<sup>-2</sup> y<sup>-1</sup> was obtained for a representative situation with 30% open and 70% ice covered waters. Other estimates from the Canada Basin, mostly in open water, have been 5–9 g C m<sup>-2</sup> y<sup>-1</sup> (Cota *et al.*, 1996, Min *et al.*, 2002, Lee *et al.*, 2010).

Yun *et al.* (2012), working late in the season (September–October) in the Canada Basin, obtained much lower rates, with a mean of 4 mg C m<sup>-2</sup> d<sup>-1</sup> corresponding to 0.5 g C m<sup>-2</sup> y<sup>-1</sup> if extrapolated to 120 days. They pointed out the pronounced seasonal pattern with lower rates late in the vegetative season. By combining data that spanned the productive season they obtained an annual estimate of 3.3 g C m<sup>-2</sup> y<sup>-1</sup> (based on the studies of Gosselin *et al.*, 1997; Lee and Whittledge 2005; Lee *et al.* 2010; Yun *et al.*, 2012).

Early studies from ice drift stations obtained low rates, around 10 mg C m<sup>-2</sup> d<sup>-1</sup> corresponding to about 1 g C m<sup>-2</sup> y<sup>-1</sup> (Appolonio 1959; English, 1961). These low rates have been questioned due to less awareness for clean methodology at the time (e.g. Pomeroy, 1997) but the results are in broad agreement with later results. Pautzke (1979; PhD thesis at University of Washington, Seattle) did a comprehensive study over 4 seasons

from late winter to autumn at ice drift stations in the Amerasian Basin in the period 1971–1975 (Station T-3 in the northern part over the Alpha Ridge 1971–1973, and AIDJEX in the Canada Basin 1975). Pautzke did frequent P-I experiments to determine photosynthetic parameters (initial slope and maximum rate) and used these to calculate (model) annual primary production using light and chlorophyll *a* as input parameters. He obtained a mean annual production over the 4 years of  $3.2 \text{ g C m}^{-2} \text{ y}^{-1}$  (values for single years were 5.8 (1971), 2.2 (1972), 2.5 (1973), and 2.1  $\text{g C m}^{-2} \text{ y}^{-1}$  (1975)).

During the ‘Arctic Ocean Section’ cruise in 1994 from the Chukchi Sea to the Fram Strait via the North Pole, Gosselin *et al.* (1997) obtained mean daily rates of about  $30 \text{ mg C m}^{-2} \text{ d}^{-1}$  for stations in the Canada Basin and the Makarov and Amundsen Basins. This translates into annual primary production of about  $4 \text{ g C m}^{-2} \text{ y}^{-1}$  assuming a 120 d growth period. Gosselin *et al.* (1997) also measured the dissolved fraction (DOC) of  $^{14}\text{C}$  uptake which gave a total annual production of about  $6.5 \text{ g C m}^{-2} \text{ y}^{-1}$  for phytoplankton. They also measured rates of production by ice algae of similar magnitude as that of phytoplankton, giving a total annual primary production of  $15 \text{ g C m}^{-2} \text{ y}^{-1}$  for the ice covered part of the central Arctic Ocean; this included release of DOC which constituted about 1/3 of the total production (Gosselin *et al.*, 1997). Gosselin *et al.* (1997) obtained a much higher rate (about  $500 \text{ mg C m}^{-2} \text{ d}^{-1}$  at one station in the northern Nansen Basin (not included in Figure 1).

Fernández-Méndez *et al.* (2014) recorded similar rates ( $25\text{--}30 \text{ mg C m}^{-2} \text{ d}^{-1}$ ) in the Nansen and Amundsen Basins as the rates obtained by Gosselin *et al.* (1997) for phytoplankton (particulate), while Olli *et al.* (2007) found somewhat higher rates of particulate production ( $50\text{--}140 \text{ mg C m}^{-2} \text{ d}^{-1}$ ) in the North Pole region in Amundsen and Makarov Basins. The mean rate in the study of Olli *et al.* (2007) gave an annual rate of about  $11 \text{ g C m}^{-2} \text{ y}^{-1}$  for a productive period of 120 days. This could easily be an overestimate of a factor of 2 or more since the effective vegetative season is probably shorter (60–90 days) than 120 days (English, 1961 and Pautzke, 1979), and the high rates are probably not representative for the whole season (Yun *et al.*, 2012).

The annual rate of about  $12 \text{ g C m}^{-2} \text{ y}^{-1}$  reported by Apollonio (1985) was for a coastal bay (Dumbell Bay) at the north coast of Ellesmere Island where most of the production took place in a short ice-free period in late summer.

#### Estimates based on chemical properties in the water column

Estimates of annual primary production based on other methods than incubations are shown in Figure 2. The estimates are grouped into four categories: 1) based on changes in concentrations or inventories of  $\text{O}_2$  or DIC/ $\text{CO}_2$ , 2) based on changes in nutrients, 3) based on sediment traps, and 4) based on the  $^{234}\text{Th}/^{238}\text{U}$  method. The last two categories reflect export production, while estimates based on inorganic nutrients generally reflect new production. The estimates based on  $\text{O}_2$  or DIC are related to NCP.

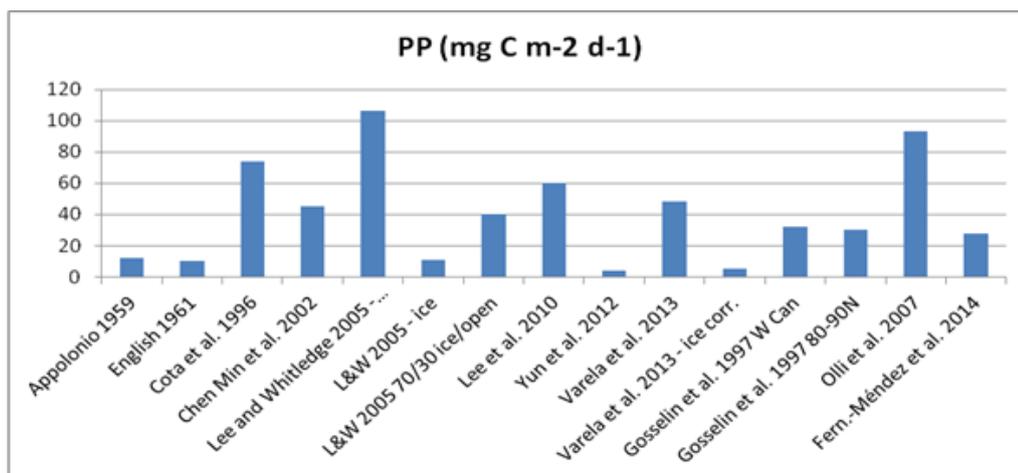


Figure 2. Estimated annual primary production ( $\text{g C m}^{-2} \text{y}^{-1}$ ) in the central Arctic Ocean. The first set of studies (from Wallace *et al.*, 1987 to Ulfsbo *et al.*, 2014 MB) are based on changes in  $\text{O}_2$  or DIC/ $\text{CO}_2$ ; the next set (from Anderson *et al.*, 1998a to Ulfsbo *et al.*, 2014 WML MB) are based on changes in concentrations and inventories of inorganic nutrients; the next set (from Hargrave *et al.*, 1995 to Lalande *et al.*, 2009) are studies of sedimentation; the last two entries (Moran *et al.*, 1997 and Cai *et al.*, 2010) are studies of vertical flux based on  $^{234}\text{Th}/^{238}\text{U}$  ratio.

The estimates summarized in Figure 3 range from 0.1 to 19  $\text{g C m}^{-2} \text{y}^{-1}$  with most of them lying in the range 1–15  $\text{g C m}^{-2} \text{y}^{-1}$ . The estimates of export production based on sediment traps and  $^{234}\text{Th}$  are generally low (0.1–4  $\text{g C m}^{-2} \text{y}^{-1}$ ). Many of the estimates based on nutrient inventories are also low (1–6  $\text{g C m}^{-2} \text{y}^{-1}$ ). Some of the estimates based on  $\text{O}_2$  or DIC are relatively high (9–19  $\text{g C m}^{-2} \text{y}^{-1}$ ).

#### $\text{O}_2$ and $\text{CO}_2/\text{DIC}$

Ulfsbo *et al.* (2014) reported results from a cruise with RV ‘Polarstern’ that crossed the Nansen, Amundsen, Canada and Makarov Basins in late summer (mid-August–September 2011) using four different approaches to estimate net community production. Estimates based on  $\text{O}_2$  (supersaturation in the upper mixed layer) and DIC (underway  $\text{pCO}_2$  and DIC profiles) were given as ranges: 0–10  $\text{g C m}^{-2} \text{y}^{-1}$  for the Amundsen Basin, Canada Basin and Mendeleev Ridge), 0–5  $\text{g C m}^{-2} \text{y}^{-1}$  for the Makarov Basin, and 5–15  $\text{g C m}^{-2} \text{y}^{-1}$  for the Nansen Basin (these are shown as midpoint values for the ranges in Figure 3).

Pomeroy (1997) used seasonal increase in oxygen concentration under ice as recorded from ice drift stations (station Alpha; English 1961, and station NP-22; Melnikov and Pavlov, 1978) to estimate annual production at 13 and 15  $\text{g C m}^{-2} \text{y}^{-1}$  for the two sites respectively. Adding a correction for loss of  $\text{O}_2$  to the atmosphere (equivalent to 6  $\text{g C m}^{-2} \text{y}^{-1}$ ) gave an estimate of annual net community production (NCP) of about 20  $\text{g C m}^{-2} \text{y}^{-1}$  for station Alpha where English (1961) did his early  $^{14}\text{C}$  work.

Zheng *et al.* (1997) applied a method based on tritium/ $^3\text{He}$  aging and  $\text{O}_2$  concentrations to estimate oxygen utilization rates and primary production in the western Nansen Basin. Rates of apparent oxygen utilization below the euphotic zone, when vertically integrated and converted to units of carbon, gave estimates of export production of 19  $\text{g C m}^{-2} \text{y}^{-1}$  for the southern part (south of  $83^\circ\text{N}$ ) and 3  $\text{g C m}^{-2} \text{y}^{-1}$  for the northern part of a section across the Nansen Basin. These values were considered to represent estimates of local new production. However, it is likely that the oxygen consumption reflected advection from upstream production, particularly for the stations in the southwestern Nansen Basin.

Wallace *et al.* (1987) used a similar method (using CFC compounds for age determination) to estimate apparent oxygen utilization rate at the CESAR ice drift station over the Alpha Ridge in the Amerasian Basin. They derived estimates of export production of about 5–13 g C m<sup>-2</sup> y<sup>-1</sup> based on depth-integrated oxygen utilization down to 155 m in the halocline layer.

Packard and Codispoti (2007) used an enzymatic assay method (respiratory electron transport system, ETS) to determine oxygen utilization rates in the water column below an ice drift station in northern Fram Strait at 83°N in April 1981. Integrating respiration from 50 to about 500 m depth and converting to carbon using Redfield ratio gave an estimate of export production of about 11 g C m<sup>-2</sup> y<sup>-1</sup>.

An important issue with estimates of export production based on oxygen consumption in the central Arctic Ocean is the extent to which they reflect advective transport of production (organic matter and associated BOD) from upstream high productive areas. This could be particularly the case near the inflow region of Atlantic water in the southwestern Nansen Basin contributing to the high rates recorded by Zheng *et al.* (1997) and Packard and Codispoti (2007). It could also have affected the estimate of Ulfsbo *et al.* (2014) for the Nansen Basin where there was a discrepancy between estimates based on pCO<sub>2</sub>/DIC (10–15 g C m<sup>-2</sup> y<sup>-1</sup>) and estimates based on O<sub>2</sub> (0–5 g C m<sup>-2</sup> y<sup>-1</sup>, read from their Figure 5c).

### Nutrients

The role of advection of productivity signals was clearly demonstrated by Olsson *et al.* (1999) who estimated nitrate deficits (apparent nitrate utilization, difference between observed and preformed source water nitrate concentrations) converted into units of C using C/N Redfield ratio. There was a positive nitrate deficit (reflecting production) through the entire halocline layer, shifting to a negative deficit (more nitrate) reflecting remineralization below 300–400 m depth in the Eurasian Basin. Olsson *et al.* (1999) interpreted the positive nitrate deficit in the halocline layer as an advective signal stemming from export production on the shelves rather than local production. They estimated a mean shelf export production of 15 g C m<sup>-2</sup> y<sup>-1</sup> into the basins of the central Arctic Ocean. The nitrate deficit was weakened by remineralization as it was transported around in the Eurasian Basin and Olsson *et al.* (1999) used this to estimate an export production of 2 g C m<sup>-2</sup> y<sup>-1</sup> for the Amundsen Basin.

Anderson *et al.* (2003) used a similar approach based on phosphate deficit to estimate export and new production. The vertically integrated phosphate deficit in the upper 50 m, converted to units of C, represented from 2.9 to 8.4 g C m<sup>-2</sup> for the Eurasian, Makarov and Canada basins. These deficits were accumulated over several years. When taking estimates of the age of the surface water (5–15 years) into account, the phosphate deficit suggested annual export production of about 0.5 g C m<sup>-2</sup> y<sup>-1</sup>. Adding a term for vertical mixing of phosphate into the upper 50 m layer, Anderson *et al.* (2003) suggested a total export or new production of about 1 g C m<sup>-2</sup> y<sup>-1</sup> for the central Arctic Ocean.

Anderson *et al.* (1998a) estimated the total annual input of nitrate to the upper mixed and halocline layers from inflowing Atlantic water, Pacific water, and river run-off (0.7 10<sup>12</sup> mol y<sup>-1</sup>); about 70% and 30% of this came from Pacific and Atlantic waters and only about 1% from rivers. Converted to units of C and normalized to a total area of about 5 million km<sup>2</sup> for the central Arctic Ocean basins and slopes, this is equivalent to a mean production of 12 g C m<sup>-2</sup> y<sup>-1</sup>. This is interesting as a theoretical maximum production assuming all nutrients in the upper layers (down to about 200 m) are used. In reality, much of the nitrate is not used, perhaps of order one third to one half (Anderson *et al.*,

1998a). This would give an estimate of new production of about  $5 \text{ g C m}^{-2} \text{ y}^{-1}$  based on annual nitrate input to the central Arctic Ocean.

Another approach using nutrient data is to estimate the seasonal drawdown of inorganic nutrients (nitrate and phosphate) relative to observed or calculated winter concentrations. There are some practical difficulties with this for the central Arctic Ocean because winter data are scarce and the difference between winter and summer concentrations is relatively small. This leads to considerable uncertainties in such estimates.

Codispoti *et al.* (2013) used nutrient data to estimate Net Community Production (NCP) equivalent to new production for a wider Arctic area. Their estimate for the Eurasian Basin was  $10 \text{ g C m}^{-2} \text{ y}^{-1}$  based on a 'qualitative' analysis and  $13 \text{ g C m}^{-2} \text{ y}^{-1}$  based on average for a limited number of grid cells. They obtained an estimate of  $3 \text{ g C m}^{-2} \text{ y}^{-1}$  for the Amerasian Basin (north of about  $75^\circ\text{N}$ ) and a low value of about  $1 \text{ g C m}^{-2} \text{ y}^{-1}$  for the Beaufort Gyre region in the Canada Basin (their Beaufort Northern subregion). For the western part of the Amerasian Basin they gave a value of around  $10 \text{ g C m}^{-2} \text{ y}^{-1}$  (their Northern Chukchi and Northern East Siberian Sea subregions). Codispoti *et al.* (2013) suggested a mean value of  $8 \text{ g C m}^{-2} \text{ y}^{-1}$  for the whole central Arctic Ocean (Amerasian and Eurasian basins combined).

Ulfsbo *et al.* (2014) produced estimates of NCP based on seasonal drawdown of inorganic nutrients from the upper summer mixed and winter mixed layers, respectively. The summer mixed layer is formed by melting of sea ice and is separated from the lower part of the winter mixed layer by a seasonal halocline. Ulfsbo *et al.* (2014) used the nutrient concentrations at the temperature minimum below the seasonal halocline to represent the winter concentrations from which the observed concentrations during the cruise in late summer were subtracted. The seasonal drawdown of nutrients represented annual new production (NCP) of from 2 to  $6 \text{ g C m}^{-2} \text{ y}^{-1}$  (values were given as ranges: 2–5  $\text{g C m}^{-2} \text{ y}^{-1}$  for Nansen Basin, -5 – 8 for Amundsen Basin, 2–10 for Canada Basin, 5–10 for the Mendeleev Ridge area, and 0–10  $\text{g C m}^{-2} \text{ y}^{-1}$  for Makarov Basin; shown as midpoint values in Figure 2).

The nutrient drawdown was much higher for the winter mixed layer, with values up to 5–25  $\text{g C m}^{-2} \text{ y}^{-1}$  for the Nansen Basin and 10–30  $\text{g C m}^{-2} \text{ y}^{-1}$  for the Mendeleev Ridge region (Ulfsbo *et al.*, 2014). The mean (midpoint) values for the winter mixed layer is 2–4 times higher than those for the summer mixed layer. The average mixed layer depth in summer was 21.5 m while the winter mixed layer varied from 40 m as a mean for the northwestern Canada Basin to a mean of 63 m for the Nansen Basin. Nutrient profiles (nitrate) presented by Codispoti *et al.* (2013) for the late summer period (20 August – 29 September) in the Eurasian Basin (their Figure S2 in Supplementary material) show two things: 1) nitrate in the upper summer mixed layer is not depleted but occur with concentrations 2–6  $\mu\text{M}$ , and 2) nitrate concentrations increase more or less gradually below 20 m through the cold halocline layer down to about 200 m for the ensemble of profiles. This suggests that it may be difficult to estimate the correct winter concentration for the upper layer from concentrations in a gradient below. If the value is taken too deep and therefore is too high, this leads to an overestimate of the seasonal nutrient (nitrate) drawdown between winter and late summer. It is an open question whether so much nutrients are being vertically mixed into the upper summer mixed layer from the layer below as the difference between new production calculated for the summer and winter mixed layers by Ulfsbo *et al.* (2014) would suggest. (This might be examined by considering the effect of ice melt on salinity which also would be effected by the vertical mixing across the seasonal halocline.)

### Rates of sedimentation

Vertical C flux in the layer below the euphotic zone can be used as estimate of export production. Annual rates from studies with long-term deployment of sediment traps (commonly about one year) are summarized in Figure 2.

Very low rates at 0.1–0.5 g C m<sup>-2</sup> y<sup>-1</sup> have been recorded in the Canada Basin. Honjo *et al.* (2010) in a comprehensive study with drifting (ice-tethered) sediment traps in two long-term deployments obtained rates of about 0.1 g C m<sup>-2</sup> y<sup>-1</sup> (0.08 and 0.12 g C m<sup>-2</sup> y<sup>-1</sup> for the two deployments). Higher rate at 2.7 g C m<sup>-2</sup> y<sup>-1</sup> was recorded when one of the traps drifted across the Chukchi Rise area. Similar low rates of about 0.1 g C m<sup>-2</sup> y<sup>-1</sup> were recorded with drifting sediment traps over the Alpha Ridge (0.07 g C m<sup>-2</sup> y<sup>-1</sup>, Hargrave 2004) and on the shelf north of Ellesmere Island (0.13 g C m<sup>-2</sup> y<sup>-1</sup>, Hargrave *et al.*, 1995).

O'Brien *et al.* (2013) recorded slightly higher values of 0.2–0.7 g C m<sup>-2</sup> y<sup>-1</sup> for three annual cycles for moored sediment traps in the southern Canada Basin. Higher values of 1.1 and 3.8–4.9 g C m<sup>-2</sup> y<sup>-1</sup> were recorded over the lower and upper slope off the Mackenzie shelf (recorded with a trap at 400 m over a water depth of 2700 m, and traps at 300–500 m over water depth of 700 m). The POC content of the sedimenting material was low (3–6%) and most of the sedimenting material (75–85%) was considered to be of terrigenous origin (O'Brien, 2009).

Fahl and Nöthig (2007) recorded a vertical C flux of 1.0 g C m<sup>-2</sup> y<sup>-1</sup> with a mooring over the eastern (Siberian) end of the Lomonosov Ridge. This represented C from marine production; the total C flux was 1.5 g C m<sup>-2</sup> y<sup>-1</sup>, of which about 1/3 was estimated to be of terrigenous origin. At a nearby location on the Laptev slope (1350 m water depth), Lalande *et al.* (2009) measured annual rates of 4.1 and 9 g C m<sup>-2</sup> y<sup>-1</sup> for two consecutive annual periods. The fraction of terrigenous material was not quantified but terrigenous POC from the Lena River and resuspended sediments from the Laptev shelf probably contributed to the relatively high vertical fluxes on the Laptev slope (Lalande *et al.*, 2009).

Two studies have used the <sup>234</sup>Th/<sup>238</sup>U method to estimate vertical C flux. <sup>234</sup>Th (thorium) is a particle-reactive and short-lived radionuclide (half-life 24 days) produced *in situ* from <sup>238</sup>U which has a very long half-life (4.5 billion years) and is found dissolved as a conservative 'salt' in seawater (Coale and Bruland, 1985). The basis for the method is the scavenging of <sup>234</sup>Th by sedimenting particles that leave the euphotic zone. Moran *et al.* (1997) obtained a relatively high estimate of 4 g C m<sup>-2</sup> y<sup>-1</sup> based on mean daily values of 36 mg C m<sup>-2</sup> d<sup>-1</sup> for stations across the central Arctic Ocean (Arctic Ocean Section 1994) extrapolated to 120 days. Moran *et al.* (1997) considered their results an upper estimate of POC flux for several reasons (small vs. large particles, recycling of POC).

A much lower estimate of about 0.3 g C m<sup>-2</sup> y<sup>-1</sup> was obtained in a comprehensive study with improved methodology by Cai *et al.* (2010) for a 'Polarstern' cruise to the central Arctic Ocean in 2007. Mean daily rate was more than an order of magnitude lower than that obtained by Moran *et al.* (1997) (2.5 vs. 36 mg C m<sup>-2</sup> d<sup>-1</sup>). Methodological improvement may have contributed to the difference. According to Cai *et al.* (2010) they conducted a high-resolution study "which resulted in one of the most complete and theoretically accurate <sup>234</sup>Th date set ever collected".

### Satellite remote sensing

Satellite remote sensing has been used to quantify primary production in the Arctic Ocean. The method is based on two sets of algorithms which (1) converts the recorded

ocean color to units of chlorophyll *a* and (2) estimates rates of primary production (NPP) from chlorophyll *a* using also input data for temperature and light (Arrigo *et al.*, 2008; Pabi *et al.*, 2008). There are two limitations for using the remote sensing method in the Arctic. The first is that even low amounts of sea ice (down to 10% areal cover) mask the ocean colour signal seen by the satellite. This limits the method basically to open water (<10% ice cover), leaving most of the central Arctic Ocean blank (no records). The other is the influence of coloured dissolved organic matter (CDOM) and suspended solids from the many large rivers that discharge into the Arctic Ocean. While this is dealt with by removing pixels with obvious influence by rivers, resulting maps still show quite high values in the major river plumes which are possibly mainly artifacts (Arrigo *et al.*, 2008; Pabi *et al.*, 2008; Matrai *et al.*, 2013).

Arrigo and colleagues have provided estimates of primary production for longitudinal sectors of the Arctic Ocean (Arrigo *et al.*, 2008; Pabi *et al.*, 2008; Arrigo and van Dijken 2011). The obtained data are mainly from the surrounding shelves and the peripheral part of the central Arctic Ocean with seasonally open water. Trends of increasing production over the last two decades reflected more open water, due to both less sea ice cover in winter and longer open water season where there was winter ice (Arrigo *et al.*, 2008; Arrigo and van Dijken, 2011).

Detailed examinations of satellite-based estimates of chlorophyll *a* and primary production along with *in situ* data for the wider Arctic Ocean (south to 60–65°N) were carried out for the surface layer by Matrai *et al.* (2013) and for the integrated water column by Hill *et al.* (2013). Satellite-based and observed (<sup>14</sup>C) primary production for the surface layer were only weakly and not significantly correlated ( $r^2 = 0.11$ ; Matrai *et al.*, 2013). The estimated integrated production based on satellite data was low for the central Arctic Ocean basin, with a value given of 1.4 Tg C y<sup>-1</sup> (Hill *et al.*, 2013). This was two orders of magnitude lower than the net (new) production based on seasonal nutrient draw-down (119 Tg C y<sup>-1</sup>; Codispoti *et al.*, 2013). This discrepancy reflects that satellite lacks information from much of the central Arctic Ocean due to sea ice, and that the estimate based on seasonal drawdown of nitrate is uncertain and possibly overestimate.

### Modelling

Rates of primary production (daily to annual) of the Arctic Ocean have been estimated using mathematical coupled physical-biological models. Using a nested coupled model (SINMOD; Slagstad and McClimans, 2005; Wassmann *et al.*, 2006a), Slagstad *et al.* (2011) simulated mean annual rates of 10 and 3 g C m<sup>-2</sup> y<sup>-1</sup> for gross and net primary production, respectively, for the Arctic Basins. In the Eurasian Basin, modelled annual gross primary production was 17 and 7 g C m<sup>-2</sup> y<sup>-1</sup> at 86 and 90°N respectively (Slagstad *et al.*, 2011). Simulating a future summer ice-free Arctic Ocean gave a total gross primary production of about 35 g C m<sup>-2</sup> y<sup>-1</sup> for the central Arctic Ocean (Slagstad *et al.*, 2011).

Popova and colleagues simulated primary production in the Arctic Ocean using physical and ecological models (NEMO and MEDUSA). Popova *et al.* (2010, 2012, 2013) obtained annual primary production values of <10 g C m<sup>-2</sup> y<sup>-1</sup> for the central ice covered part and 10–20 g C m<sup>-2</sup> y<sup>-1</sup> for the peripheral part with more open ice conditions in summer. Popova *et al.* (2012) compared modelled primary production using five coupled physical and biological ocean models. The models differed in many respects (numerical representation, parameterization, grid resolution, initial and boundary conditions, and complexity), but despite this they gave broadly the same results for the central Arctic Ocean with indicated production values of <10 and 10–20 g C m<sup>-2</sup> y<sup>-1</sup> in broad

areas, although with some differences in the proportion of these categories among the models. Popova *et al.* (2013) used the NEMO-MEDUSA model to examine the role of advection of nutrients to sustain primary production in the central Arctic Ocean. The time-scale of supplying nutrients from Atlantic and Pacific source waters in the sub-surface layer of the central Arctic Ocean was about 5–15 years, while nutrient supply from the surrounding shelves occurred on a time-scale of about 5 years.

### Some (preliminary) conclusions

There is a span of two orders of magnitude in the annual production values summarized in Figures 1 and 2, from export production of around  $0.1 \text{ g C m}^{-2} \text{ y}^{-1}$  to new production or NCP of about  $20 \text{ g C m}^{-2} \text{ y}^{-1}$  based on oxygen and nutrient data. Nevertheless, they all agree in showing that the annual primary production is relatively low.

The  $^{14}\text{C}$  and  $^{13}\text{C}$  data converge to give a fairly consistent picture of phytoplankton annual production (not including ice algae) of about  $1\text{--}4 \text{ g C m}^{-2} \text{ y}^{-1}$  in ice covered waters and around  $10 \text{ g C m}^{-2} \text{ y}^{-1}$  in open waters. As an average over the still largely ice covered central Arctic Ocean, a value of  $5 \text{ g C m}^{-2} \text{ y}^{-1}$  seems appropriate as a first approximation for the phytoplankton component of the annual primary production.

The other methods shown in Figure 2 reflect production of ice algae in addition to phytoplankton, affecting  $\text{O}_2$ ,  $\text{CO}_2/\text{DIC}$ , nutrients, and vertical C flux. Export production as recorded by sediment traps and the  $^{234}\text{Th}$  method is generally low. Very low rates are recorded in the Canada Basin ( $0.1\text{--}0.5 \text{ g C m}^{-2} \text{ y}^{-1}$ ) with higher values found over the surrounding slopes in the Beaufort and Laptev Seas ( $1\text{--}5 \text{ g C m}^{-2} \text{ y}^{-1}$ ). This is in agreement with higher production over the shelves being exported out into the basins and contributing to increased vertical C flux along the slopes. However, a considerable fraction of the C flux here is of terrestrial origin.

Most of the estimates based on  $\text{O}_2$ ,  $\text{CO}_2/\text{DIC}$  and inorganic nutrients are in the range  $1\text{--}10 \text{ g C m}^{-2} \text{ y}^{-1}$ . Some of the higher values ( $>10 \text{ g C m}^{-2} \text{ y}^{-1}$ ) based on  $\text{O}_2$  are from the southern Nansen Basin and may be high due to advected signals from upstream production in the Barents and Norwegian Seas. Some of the estimates based on seasonal drawdown of inorganic nutrients (primarily nitrate) are also high, e.g. the value of Codispoti *et al.* (2013) for the Eurasian Basin and the values of Ulfsbo *et al.* (2014) for the winter mixed layer.

There is an apparent discrepancy between the relatively high values obtained from seasonal drawdown of nutrients, which represent new production, and the  $^{14}\text{C}\text{--}^{13}\text{C}$  results and estimates of export production measured with sediment traps and the  $^{234}\text{Th}$  method. This is possibly due to uncertainty in the winter value of nitrate in the upper mixed layer leading to overestimate of the seasonal drawdown. Model results (Popova *et al.*, 2013) indicate that the vertical winter mixing is limited, resulting in low maximum nitrate concentration in the surface layer (see their Figure 3c).

Taken together, the data reviewed here suggest a level of about  $10 \text{ g C m}^{-2} \text{ y}^{-1}$  for primary production (NPP) in the central Arctic Ocean. The production is probably lower in the central area with more heavy ice cover even when ice algae are included, and higher ( $10\text{--}20 \text{ g C m}^{-2} \text{ y}^{-1}$ ) in the peripheral parts with seasonal ice cover and slope regions. Spatially there is also a pattern with higher production in the Nansen Basin (associated with the inflowing Atlantic water) and low production in the Canada Basin associated with the anticyclonic Beaufort Gyre.

The uncertainty associated with the seasonal drawdown of nutrients should be addressed with more careful analysis of the seasonal vertical physics, rates of algae production, and available nutrient data.

The central Arctic Ocean is an extremely oligotrophic system implying low ecological transfer efficiency to higher trophic levels. The significant fraction of production released as DOC (about 1/3) is processed in the microbial loop with little left to be used by higher trophic consumers (due to the number of trophic steps required; e.g. bacteria-protozoans-crustaceans-fish or seal). Phytoplankton is also mostly small with a substantial fraction being picoplankton (<2 µm). These are also part of the microbial loop and need to pass through an extra step in the foodweb (compared to diatoms which can be grazed by large calanoid copepods directly).

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## Annex 4: Fish and fish stocks

### Arctic fish overview (Skjoldal)

A total number of nearly 750 species of fish has been recorded in the wider Arctic area, which includes the Bering Sea and the Aleutian Islands on the Pacific side, and the Nordic Seas south to the Faroe Isles on the Northeast Atlantic side. Most of these species are classified as boreal (375 species, 51%) with the majority in the Pacific area (286 species vs. 85 species in the Atlantic). A smaller number of species are classified biogeographically as Arctic (69 species) or Arctic-boreal (41 species); 110 species in total or about 15% of the total number of species in the wider Arctic area. These can be considered true Arctic species able to live in the cold Arctic waters with temperatures down to freezing (-1.8°C).

The group of Arctic species is dominated by two taxonomic orders, Scorpaeniformes (scorpionfish and flatheads) and Perciformes (perch-like fish), which together make up about 70% of the species (78 species; Figure 1). The most numerous fish families in terms of number of species in the Arctic are sculpins (Cottidae), snailfish (Liparidae), and eelpouts (Zoarchidae). The large majority of Arctic fish are benthic or demersal, associated with the seabed (Figure 2). Pelagic fish are few, including the two very important small cod-fish, polar cod *Boreogadus saida* and Arctic cod *Arctogadus glacialis* (Figure 2).

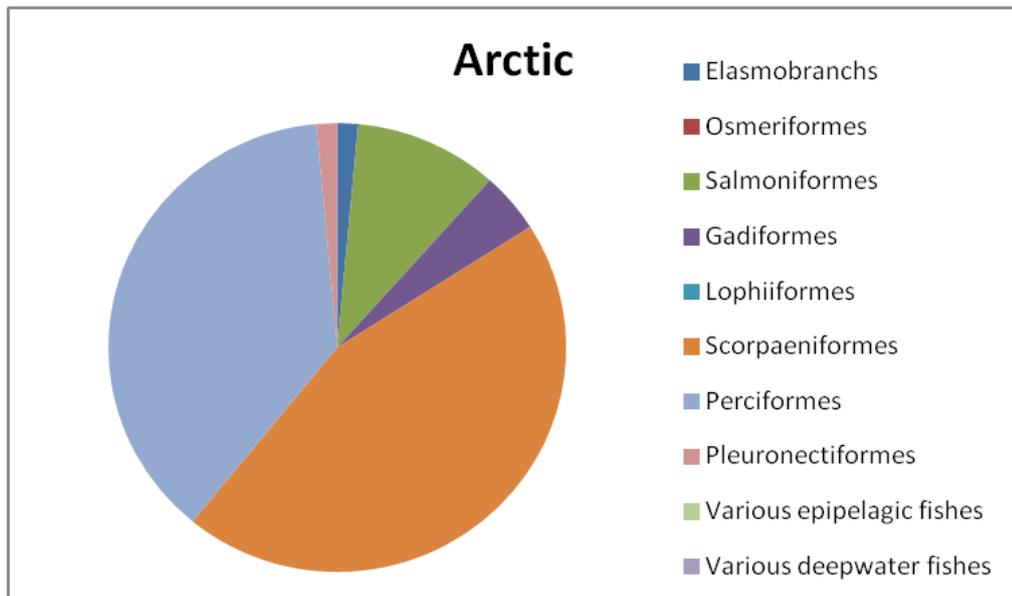
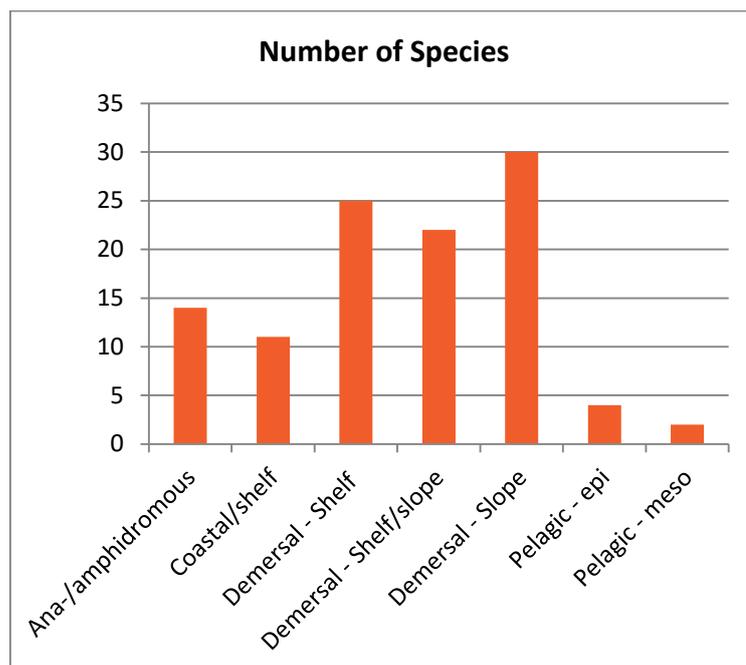


Figure 1. Taxonomic composition of 110 Arctic fish species (classified biogeographically as Arctic or Arctic-boreal).



**Figure 2.** Distribution of Arctic and Arctic-boreal fish species by habitat types, classified as ana- and amphidromous, demersal (or benthic) according to depth from mainly shallow coastal to deeper slope waters, and pelagic in two depth groups, epi- and mesopelagic (found mainly above and deeper than 200 m depth, respectively).

#### Occurrence of fish in the Arctic Ocean (Mundy)

A synthesis of knowledge for fish and shellfish fauna in the CAO was prepared for the Fourth Meeting of Scientific Experts on Fish Stocks in the Central Arctic Ocean (FiS-CAO). The synthesis examined 9405 records of fish and invertebrate species in the Arctic Large Marine Ecosystems (LMEs) assembled from the published literature. Included in the synthesis is detailed species catch records by the nine arctic LMEs when available along with their potential commercial importance. Highlights from the draft synthesis are: 1) 12 species of fish have been identified to occur in High Seas, 2) sampling on the shelf and shelf break areas of the CAO that are likely to contain fish is very limited, 3) more than 300 fish species are known to inhabit arctic waters nearby the High Seas, and 4) at present many of the scientific sampling efforts in the High Seas do not include fish collections.

Some caveats exist when describing fish occurrence in the CAO. The legal definition of the High Seas international waters is not the same as the bio-geophysical LME definitions that are more relevant to the corresponding zoogeographical distribution of fish species. The High Seas area is not restricted to the deep-water basin characteristics of the CAO; there is approximately 10 000 sq nm of the High Seas in depths of 38–84 m near the Pacific gateway and Siberian Sea which may be more biologically productive than the surrounding basin region. For future considerations, the trend of decreasing sea ice concentrations will likely influence the distribution of fish species in the CAO as ice extent changes. The shallow shelf regions near the Pacific gateway are in areas of accelerated loss of sea ice. With regards to fish occurrence in the CAO, these potentially productive ice-free shelf regions may represent important habitat in the CAO yet few data from these regions exist. Further research in these areas may be warranted.

### **Acoustic records of fish under ice (Gjørseter)**

Published information about the presence of fish under the ice in the CAO is sparse. The ice makes fishing operations difficult and acoustics is probably the most promising method to locate fish in the water column under the ice. So far, few examples exist where acoustic techniques have been applied to monitor fish resources in the ice covered area. Recently some acoustic data from the Swedish scientific icebreaker “Oden” were made available for analysis from surveys carried out in 2014 and 2016. These data, coming from an 18 KHz echosounder were sampled to locate gas seeps from the seabed in more shallow areas, and not for the purpose of monitoring fish. A first exploratory analysis of the data from the CAO shows that the echograms are extremely noisy, probably caused by mechanical noise from breaking ice or propeller cavitation etc., or possibly from electric noise from other instruments. Most of the data seem to be impossible to use for monitoring fish. However, during periods when the vessel was stationary, and after removing noise by running various filters built into the post-processing software, scattering from at least parts of the water column can be analysed. Preliminary analyses indicate that echoes from single targets, probably fish, can be recognized in some of these echograms. This work is in progress, and further analysis will reveal if this is widespread in this dataset. Further efforts should be made to investigate whether additional acoustic datasets are available from existing ice-going vessels, which could possibly be analysed and give further indications of whether pelagic fish is present in the CAO.

### **Canadian Beaufort Sea – Marine Ecosystem Assessment (Hedges and Reist)**

Fisheries and Oceans Canada is initiating a comprehensive vessel-based ecosystem assessment of the Canadian Beaufort Sea in 2017-2021. This will extend research conducted previously (2010-2015) under the Beaufort Regional Environmental Assessment-Marine Fishes Project. Research is planned to investigate marine ecosystem structure and function with a focus upon fish and their habitats, the physical and chemical environment, and lower trophic levels. Explicit linkages also exist to other projects investigating higher trophic levels (e.g. marine mammals) in the marine system and to coastal studies conducted in the area. Fieldwork will be conducted during the open-water seasons of 2017, 2018 and 2019; two years of analytical and synthesis activities will immediately follow in 2020 and 2021. Preliminary research themes for the CBS-MEA project include: 1) interannual variations in the fish communities and their supporting ecosystems; 2) extension of baseline knowledge; 3) development of better understanding of the nature and dynamics of key features relevant to the area; 4) linkages with coastal ecosystems and higher trophic-level organisms; and 5) understanding effects from stressors on the system.

## Annex 5: Marine mammals and seabirds

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### Marine mammal overview (Bengtson and Frie)

Pinnipeds, cetaceans, and bears are important components of Arctic marine ecosystems, as well as being valued nutritional and cultural resources for many coastal communities. The geographic distribution, habitat use, and seasonal movements of seals and walrus vary considerably. In the Arctic Pacific Gateway area, there are four species of ice-associated seals -- spotted (*Phoca largha*), ribbon (*Histiophoca fasciata*), ringed (*Phoca hispida*), and bearded seals (*Erignathus barbatus*); and one subspecies of walrus - Pacific walrus (*Odobenus rosmarus divergens*). Pinniped species found in the Atlantic Gateway area include ringed, bearded, hooded (*Cystophora cristata*), and harp (*Pagophilus groenlandicus*) seals as well as the Atlantic walrus (*Odobenus rosmarus rosmarus*). Ringed seals have a circumpolar distribution, with coastal fast ice areas providing important areas for reproductive activities. Ringed seals are also known to be distributed at relatively low densities offshore in the Eurasian and Amerasian Basins. In recent years ringed seals from western Svalbard have spent more energy during summer foraging excursions, partly because the summer ice edge has been more remote from their coastal wintering areas. Because walrus and bearded seals feed on benthic prey, they are mostly restricted to areas over the continental shelf. Ice-associated seals and walrus are highly dependent on suitable sea ice condition and distribution, and therefore may be particularly vulnerable to climatic change, offshore oil development, marine shipping, or other environmental impacts that could alter their habitat.

Cetacean species include bowhead whales (*Balaena mysticetus*), beluga whales (*Delphinapterus leucas*), and narwhal (*Monodon monoceros*). These species are highly migratory, with bowhead whales remaining closely associated with sea ice during most of the year. Bowheads show behavioral responses to anthropogenic noise, but effects on population growth are uncertain. Oil exposure may clog baleen and cause poisoning or respiratory disease. In the Pacific Gateway area, beluga whales are frequently found in continental shelf areas but are also known to range into deep water over the Canada Basin. On the Atlantic side, belugas are commonly observed in coastal waters of the Northern Barents Sea, but very rarely off-the-shelf. Narwhals react strongly to anthropogenic noise ranging from engine noise to seismic airgun activity. They are particularly sensitive to disturbance during the main feeding period in winter, which is generally spent in ice covered deep-sea areas. Northwest Atlantic data suggest a diet dominated by Greenland halibut, polar cod and squid. Decreasing ice cover may reduce this prey base and increase competition from less ice-dependent species, risk of predation, and disturbance. Narwhals have high levels of contaminants, but population effects have not been documented. Oil exposure may cause severe respiratory disease.

There has been no formal assessment of the specific size or trend of the polar bear (*Ursus maritimus*) subpopulation throughout the Arctic Basin. This area is thought to support relatively low densities of polar bears year-round, although animals from the subpopulations around the polar basin use the Arctic Basin area seasonally (e.g. during the summer minimum sea-ice extent). Polar bears may breed in the CAO, but good denning areas far offshore are likely very few. Continued retraction of sea ice is likely to reduce polar bear denning habitat and availability of ringed seals.

### Seabirds (Kuletz)

Marine birds (hereafter, seabirds) are good indicators of marine ecosystem conditions because they largely rely on the marine environment for food, and they can be readily

observed at sea and at their coastal breeding colonies. Being highly mobile, birds can respond quickly to changes in prey distribution, with the exception of those tied to colony sites when incubating and raising chicks. 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 birds in the Arctic, with few species recorded in the CAO. In the Pacific sector of the CAO, murre, kittiwake, and jaeger are most frequently encountered while Ross's gull and ivory gull predominate in the Atlantic sector; throughout the CAO, numbers of birds are extremely low, largely limited by lack of open water. In contrast, the adjacent continental shelves, and in particular the gateways linking the CAO with adjacent seas, have high seabird densities and high species richness. As the sole gateway in the Pacific sector, the relatively narrow Bering Strait region has among the highest seabird densities in the northern hemisphere, and as such presents a risk to seabirds from increased shipping. In the Atlantic sector, marine access regions for seabird movement are much broader, and include the Barents and Greenland seas and Baffin Bay.

There have been few at-sea surveys for seabirds in the CAO, although survey coverage has increased since mid-2000s in adjacent slope and gateway regions. In the pelagic waters of the Chukchi Sea, the seabird community has changed over the past 20 years from one dominated by piscivorous birds to one dominated by planktivorous species. The planktivorous seabirds do not nest along the Chukchi coast, rather they are among the migrants that now move into the Pacific Arctic during late summer and fall, concurrent with increasing open water, late summer plankton blooms, and a longer ice-free season. As open water increases in the CAO, birds might be expected to follow, depending on availability of food resources. In the Pacific sector, the Chukchi Borderlands may be a relatively shallow area that could experience increased seabird activity as ice cover decreases. In recent years with the opening of the Northwest Passage, at least a few individual birds have been recorded moving from the Atlantic to the Pacific and vice versa.

## **Annex 6: Country reports**

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Reports on national research and monitoring activities in or related to the CAO were provided from Canada (Hedges and Templeman), Norway (Ingvaldsen), and Japan (Nishino). Summaries of these presentations are included as Annex 6. WGICA will continue to collect information on national activities. We plan to consider this agenda item (ToR d) in more depth at the next (3<sup>rd</sup>) meeting in 2018.

### **Norway – Research updates (Ingvaldsen)**

The SI\_ARCTIC project has conducted annual surveys in the Atlantic gateway 2014-2016. The main aim of the surveys has evolved from baseline ecosystem investigations towards more detailed investigations. To understand the consequences of a warming Arctic Ocean, the first years of the project have had focus on comparative studies between the eastern Fram Strait and the region north of Svalbard. The results so far show pronounced differences between the regions. While the eastern Fram Strait is dominated by fish species and, to a lesser degree, marine mammals like seals and whales, the situation is opposite north of Svalbard. However, in both regions there is a mesopelagic layer, i.e. a layer of plankton and fish in 300-500 m depth. In Fram Strait Atlantic cod leave the shelf following the mesopelagic layer westwards into deeper water. The 2016 survey had focus on harp seals and prey investigation (in addition to ecosystem sampling), and so will the 2017 survey have.

### **Japan – Nutrient Dynamics Affecting Phytoplankton Distributions in the Pacific Arctic Region (Nishino *et al.*)**

The Chukchi Sea and Canada Basin are areas in the Pacific Arctic characterized by northward advection and spreading of Pacific-origin water that transports nutrients into the Arctic Ocean, and thus plays an important role in phytoplankton distributions. We have examined ship-based and mooring data to understand nutrient dynamics and its influence on phytoplankton distributions. In the southern Chukchi Sea, our data suggest that, in contrast to spring blooms that are caused by a nutrient supply with the advection of Pacific-origin water, autumn blooms there are maintained by regenerated nutrients from the bottom of the shallow sea where particulate organic matters are largely accumulated in autumn (Figure 1). On the other hand, large-scale ocean circulation controls nutrient distributions in the Canada Basin where sea ice reduction in recent years has changed the ocean circulation and thus impacts on the nutrient and phytoplankton dynamics (Figure 2). We found that oceanographic and biological responses to the sea ice loss are quite different between the Alaskan and Siberian sides of the region. On the Alaskan side, eddies also play an important role in the nutrient and phytoplankton distributions. However, on the Siberian side, data are still lacking and various biogeochemical processes should be clarified in future studies.

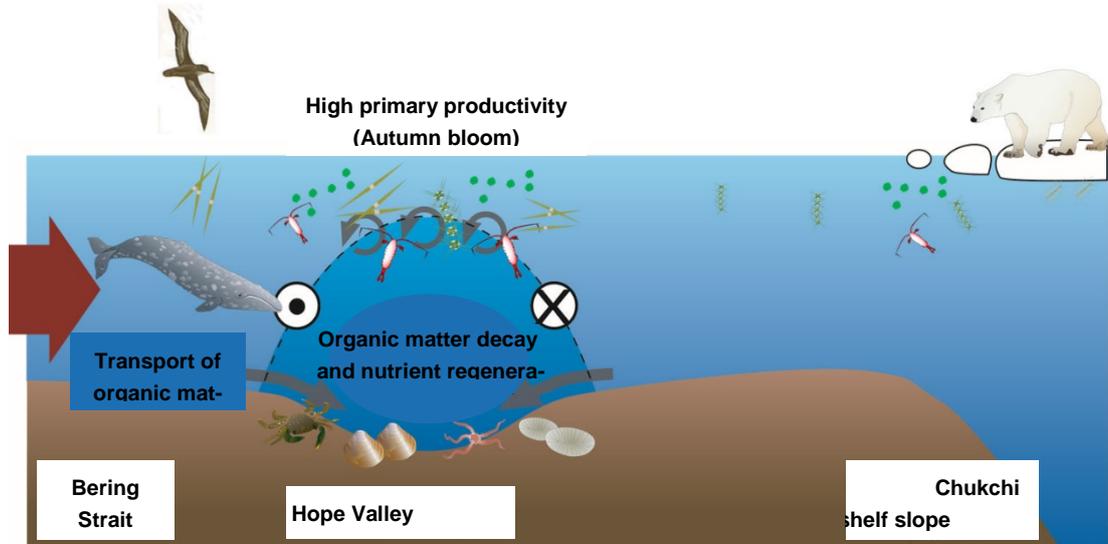


Figure 1: Schematic of autumn bloom in the southern Chukchi Sea. Over the Hope Valley, there is a dome-like structure of the bottom water, suggesting ocean circulation in a anticlockwise direction and converge of deep water there. The autumn blooms are, therefore, likely to be associated with particulate organic matters transported into the bottom of the valley, where nutrients such as ammonia are produced to increase phytoplankton with the organic matter decomposition.

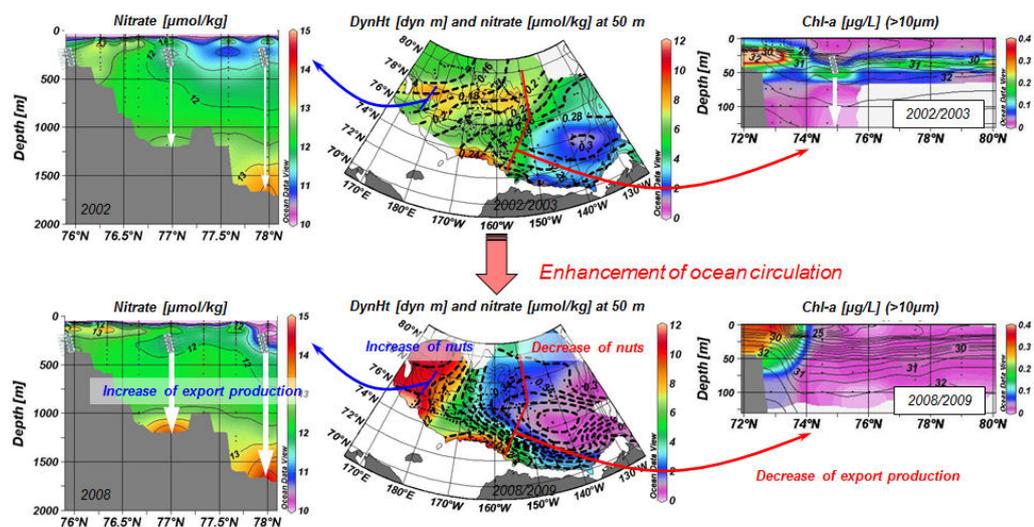


Figure 2: Schematic of an enhancement of the Arctic Ocean circulation and changes in nutrient distributions and biological activities due to the recent loss of sea ice. (Middle panels): Distributions of dynamic height (dyn. m; dotted lines) at a depth of 50 m relative to 250 m and nitrate ( $\mu\text{mol/kg}$ ; colors) at the 50 m depth in 2002/2003 (upper panel) and 2008/2009 (lower panel). (Right panels): Vertical sections of phytoplankton chlorophyll a ( $\mu\text{g/L}$ ) in large-sized cells of  $>10\mu\text{m}$  (colors) and salinity (contours) along red lines in 2002/2003 (upper panel) and 2008/2009 (lower panel). (Left panels): Vertical sections of nitrate ( $\mu\text{mol/kg}$ ; colors) along blue lines in 2002 (upper panel) and 2008 (lower panel).

**Canada – Research of Relevance to the WGICA (Hedges)**

Canada has several new research funds that are anticipated to generate research of relevance to the WGICA. Fisheries and Oceans Canada has a new Arctic Science Research Fund (included in the 2016 federal budget; ~\$800K/year) that represents part of Canada’s efforts to restore funding to support federal ocean science and monitoring programs, and to protect the health of fish stocks. The Government of Canada is also developing a second phase to its Aquatic Climate Change Adaptation Strategies Program.

Three focal areas in the Canadian Arctic were identified for this round of funding: the Beaufort Sea, the Northwest Passage (Lancaster Sound, northern archipelago) and Baffin Bay/Davis Strait, including the North Water polynya.

In 2017 Fisheries and Oceans Canada is expanding ongoing research in Eclipse Sound to develop an ecosystem level study. Building on existing narwhal and Greenland Shark studies in the area, the expanded program will now collect data on physical, chemical and biological oceanographic conditions, benthos composition, the benthic marine fish community, trophic linkages and individual movement and habitat use patterns in Polar Cod (*Boreogadus*), Greenland Halibut, Greenland Shark, narwhal and ringed seals. Data related to polar bears and birds will be incorporated through collaboration with Environment and Climate Change Canada researchers. Eclipse Sound is of particular interest because it will experience increasing vessel traffic over the next few years with the development of an iron ore mine south of the Sound. Fisheries and Oceans Canada is also discussing options for research and monitoring programs in the Last Ice Area north of Elsmere Island. Canada's ArcticNet program is ending in 2017 but discussions of a replacement program are ongoing.

In 2016 the Government of Canada announced its new Oceans Protection Plan (OPP). The OPP will aim to help Canada achieve a world-leading marine safety system that will increase Canada's capacity to prevent and improve response to marine pollution incidents. The plan will be implemented with a budget of CD \$1.5 billion over 5 years to achieve several goals, including (broadly): safer navigation and better information sharing of marine traffic; development of enhanced and proactive monitoring and response capacity through advancing knowledge and technology around spills; developing a coastal environmental baseline and cumulative effects program; preserving and restoring marine ecosystems (including establishing new whale protections); and negotiating meaningful Indigenous partnerships to support marine safety. It is expected that the science activities associated with these deliverables, including data collection, assessment and tools will also contribute to enhanced knowledge applicable to the Arctic marine environment, vulnerabilities and mitigations.