WGIBAR 2017 REPORT

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Report of the Working Group on the Integrated Assessments of the Barents Sea

16-18 March 2017

Murmansk, Russia

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

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Executive summary

The Working Group Report of the Working Group on the Integrated Assessments of the Barents Sea (WGIBAR), chaired by Elena Eriksen (Norway) and Anatoly Filin (Russia), met in Murmansk, Russia, 16–18 March 2017. The meeting was attended by 25 from 4 institutes and 2 countries.

Since the 1980s, the Barents Sea has gone from a situation with high fishing pressure, cold conditions and low demersal fish stock levels, to the current situation with high levels of demersal fish stocks, reduced fishing pressure and warm conditions (section 4). 2016 was a record warm year with the smallest area of Arctic and cold bottom waters (<0°C) and largest area of Atlantic waters (>3°C). The decrease in ice coverage provides improved conditions for phytoplankton production. Zooplankton biomasses in the Central Bank and Great Bank subareas have shown declining trends since the peak in 1995. The capelin stock biomass is well below the long-term mean while the cod stock is at a high level. Due to the low level of capelin, cod and other piscivores must compensate by feeding on other prey and therefore a predation pressure on other prey is potential large. So far, minor effects of low biomass of pelagic fish on growth of cod were observed. The levels of environmental and organic pollution in the Barents Sea are generally low and do not exceed threshold limits or global background levels. More detailed information can be found in the annual report "The state and trends of the Barents Sea ecosystem in 2016", which is available on the ICES WGIBAR page as separate document.

In 2017, WGIBAR has paid more attention to human impact on the ecosystem (state and changes in environmental and organic pollution, and effects of fisheries on the ecosystem. The group considered a stratification of the Barents Sea, focusing on primary production. Consequences of decreased biomass of pelagic fishes on feeding and growth and maturation of key species were also studied. An overview of multispecies and ecosystem models regarding perspective of their application for the integrated assessments of the Barents Sea ecosystem was presented and discussed.

1 Administrative details

Working Group name
The Working Group on the Integrated Assessments of the Barents Sea (WGIBAR)
Year of Appointment within the current three-year cycle
2016
Reporting year concluding the current three-year cycle
1
Chair(s)
Elena Eriksen (Norway)
Anatoliy Filin (Russia)
Meeting venue(s) and dates
16–18 March 2017, Murmansk, Russia (25 participants)

2 Terms of Reference a) – d)

ToR	Description	Background	Science Plan topics addressed	Duration	Expected Deliverables
a	Prepare relevant datasets that can be used to describe and analyze fluctuations and changes in the Barents Sea ecosystem	Science and advisory requirements		Year 1,2 and 3	Updated multivariate datasets (Year 1,2 and 3). Develop new spatially disaggregated time-series (Year 1 and 2)
b	Prepare an annual report on the status and trends of the Barents Sea ecosystem based on integrated analysis of multivariate datasets and other relevant information	Science and advisory requirements		Year 1, 2 and 3	Annual reports of the status, drivers, pressures, trophic interactions and expected changes
c	Identify knowledge gaps and priority research items that when addressed, can improve future integrated ecosystem assessments	Science and advisory requirement		Year 1, 2 and 3	Annual status reports
d	Explore the use of available ecosystem and multispecies models as an analytical tool in integrated ecosystem assessment for the Barents Sea	Science and advisory requirements		Year 1, 2	Annual meeting report
e	Provide recommendations to improve the monitoring of the Barents Sea ecosystem for integrated ecosystem assessments	Science and advisory requirements		Year 1	Annual meeting reports

3 Summary of Work plan

Year 1	Prepare relevant datasets and other relevant information, including pollution, that can be used to describe fluctuations and changes in the Barents Sea ecosystem and prepare an annual report on the status and trends of the Barents Sea ecosystem based on integrated analysis of multivariate datasets. Present and discuss available ecosystem and multispecies models as an analytical tool in integrated ecosystem assessment for the Barents Sea Identify knowledge gaps and priority research items that can improve future integrated ecosystem assessments and provide recommendations to improve the monitoring Map collaboration partners, their needs and advantage from the cooperation.
Year 2	Prepare relevant datasets and other relevant information that can be used to describe fluctuations and changes in the Barents Sea ecosystem and prepare an annual report on the status and trends of the Barents Sea eco-system based on integrated analysis of multivariate datasets. Identify knowledge gaps and priority research items that can improve future integrated ecosystem assessments Explore the use of the ecosystem/multispecies models as an analytical tool in integrated ecosystem assessment for the Barents Sea.
Year 3	Prepare relevant datasets and other relevant information that can be used to describe fluctuations and changes in the Barents Sea ecosystem and prepare an annual report on the status and trends of the Barents Sea ecosystem based on integrated analysis of multivariate datasets. Identify knowledge gaps and priority research items that when addressed, can improve future integrated ecosystem assessments.

4 List of Outcomes and Achievements of the WG in this delivery period

WGIBAR prepared relevant datasets and other relevant information, including pollution, to describe fluctuations and changes in the Barents Sea ecosystem and prepared an annual report "The state and trends of the Barents Sea ecosystem", which is available on the ICES WGIBAR page as separate document.

The Integrated multivariate (PCA, CCA, and NMDS) analyses were performed for different purposes. The time-series were standardized to zero mean and unit variance. Analyses of temporal development of abiotic variables (1979–2016) showed a shift from a cold to a warm regime and 2016 is an anomaly warm year. Further, abiotic time-series were combined with biomass of planktonic organisms (zooplankton and juveniles, organisms drifted with the currents into the Barents Sea) and analyses showed increasing of biomasses with the warming (1986–2016). Furthermore, selected abiotic and a wider range of biotic time-series were analysed for the period 1988–2016, which demonstrated that the increasing temperatures and area of warm water-masses were followed by increasing biomasses of krill and boreal fish stocks.

Several tasks relevant to WGIBAR have been prepared for the meeting, and were included in the report or as working document:

Subareas of the Barents Sea

The Barents Sea is a heterogeneous system changing from boreal conditions in southwest to Arctic conditions in the north. To better reflect the changing conditions and trends over the large shelf and slope regions of the Barents Sea Large Marine Ecosystem (LME), we have subdivided the Barents Sea into twelve subareas (The state and trends of the Barents Sea ecosystem in 2016, section 2.1).

Spatially integrated production (NPP)

Daily Net Primary Production (NPP) and open water area (OW) were calculated in collaboration with Kevin Arrigo and Gert van Dijken from the Stanford University, USA. NPP of the total polygon area show interannual variability and a significant increased trend over the years in the Barents Sea

Impact of snow crab on benthos community in the eastern Barents Sea

The snow crab is a new species in the Barents Sea. Since 2004, snow crab has been observed regularly during the ecosystem surveys. The crab has mainly been recorded west of Novaya Zemlya, and the working document (Report "The state and trends of the Barents Sea ecosystem in 2016) reports on structure and biomass of the benthos community to identify the impact of snow crab on benthos.

Available ecosystem and multispecies models for the Barents Sea

Development of multispecies models designed to improve fisheries management in the Barents Sea started in the mid-1980s. The working document n°1 (Annex 4) gives an overview of ecosystem and multispecies models: short description, classification and status of the models, as well as the main principles for choosing of models for ecosystem studies.

Most of the scientific work relevant to WGIBAR is done by other projects at IMR/PINRO or other institutions. Because of funding limitations there is little intersessional work done by WGIBAR as a group.

List of relevant publications

Arrigo K.R. and van Dijken G. 2015. Continued increases in Arctic Ocean primary production. Progress in Oceanography 136:60-70

Eriksen, E., Skjoldal, H.R. Gjøsæter, H. and Primicerio R. 2017. Spatial and temporal changes in the Barents Sea pelagic compartment during the recent warming. Progress in Oceanography 151: 206-226, http://dx.doi.org/10.1016/j.pocean.2016.12.009

Eriksen, E., Skjoldal, H.R., Dolgov, A.V., Dalpadado, D., Orlova, E.L., Prozorkevich, D.V. 2016. The Barents Sea euphausiids: methodological aspects of monitoring and estimation of abundance and biomass. ICES J. Mar. Sci. doi: 10.1093/icesjms/fsw022

Gjøsæter, H., Hallfredsson, E. H., Mikkelsen, N., Bogstad, B., and Pedersen, T. 2016. Predation on early life stages is decisive for year-class strength in the Barents Sea capelin (*Mallotus villosus*) stock. ICES J. Mar. Sci., 73: 182-195.

Johannesen E, Mørk H. L., Korsbrekke K., Wienerroither R., Eriksen E., Fossheim M., de Lange Weenck T., Dolgov A., Prokhorova T. and Prozorkevich D. 2017. Arctic fishes in the Barents Sea 2004-2015: Changes in abundance and distribution. Joint IMR/PINRO report series 1 2017. 46 pp.

Lien V.S., Schlichtholz P., Skagseth Ø., Vikebø F.B. 2017. Wind-driven Atlantic Water flow as a direct mode for reduced Barents Sea ice cover. J Climate, 30, 803-812

5 Progress report on ToRs a) –e)

5.1 Progress report on ToR a

We updated most of the time-series data compiled for the first meeting sets (ICES 2014a) prior to or during the meeting of this year. We have developed additional time--series for the macro benthos biomass and biomass of King crab and Snow crab (2005–2016), and are working with a new stratified time-series for the Barents Sea.

Progress report on ToR b

The following presentations focusing of status of different ecosystem components and pressures were given during the meeting:

Hydrography, Alexander Trofimov

The situation for 2016 was presented for the following parameters: temperature (water and air), salinity, sea ice coverage, NAO index, index for storm activity, Atlantic water inflow and areas of Atlantic, Arctic, and mixed waters.

Plankton, Andrey Dolgov

The most recent data on net primary productivity as estimated by using satellite data, biomass of mesozooplankton, occurrence of *Calanus glacialis* and *Calanus finmarchicus* in sections, abundance of euphasiids, abundance of amphipods and abundance of jellyfish.

0–group fish, Elena Eriksen

Strength of 0-group was presented for cod, haddock, NSS herring, capelin polar cod, and redfish. Anomalies for average 0-group body length was also presented for these species (except redfish).

Pelagic fish, Georg Skaret

Status and development of the stocks were presented for capelin and polar cod and the juvenile part of the NSS herring stock residing in the Barents Sea. Possible causes of the capelin stock collapse were discussed. Distribution of blue whiting (a stock that resides mostly in the Norwegian Sea) was also presented.

Demersal fish, Bjarte Bogstad

Status and development of the stocks was presented for cod, haddock, deep-sea (beaked) redfish, golden redfish, wolffish, long rough dab, and saithe. Data on diet were presented also for cod, capelin, and polar cod.

Benthos, Lis Lindal Jørgensen/Natalia Strelskova

Status and trends of the benthos biomass and snow crab and shrimp population abundances were presented. Two interaction drivers was discussed 1) Fisheries (temperature) and snowcrab impact on benthos, 2) temperature impact on the snow crab distribution of the Barents Sea.

Marine mammals, Roman Klepikovskiy

Status and trends of the marine mammal observation based on ecosystem survey in August-September 2016. The main groups of humpback and fin whales were feeding at concentrations of capelin, primarily in areas south of Spitsbergen and on the Great

Bank, other marine mammals in the Barents Sea were observed at concentrations of polar cod, capelin, herring, and cod fish.

Tatiana Prokhorova, non-commercial fish

Distribution of different zoogeographic groups of non-commercial fish species was presented for 2016 and 2006. Time-series of abundance indices for the same groups were also presented.

Pollution, Hilde Elise Heldal and Andrei Zhilin

Results from monitoring of pollution of radioactive substances, metals and persistent organic pollutants were presented. The data come from both sediment, water and fish samples.

WKIDEA, Hein Rune Skjoldal

Information about ICES Workshop on Integrated Ecosystem Assessment Methods (WKIDEA) have been provided. The presentation gave also several examples of use of multivariate analyses.

During the meeting a report "The state and trends of the Barents Sea in 2016" was made and will be presented.

The WGIBAR report "The state and trends of the Barents Sea in 2016" is used in the status report and in the Work Programme for the Norwegian - Russian environmental cooperation associated with the Joint Russian Norwegian Environmental Commission. In addition, several annual reports made separately in Norwegian and Russian by IMR and PINRO make use of the WGIBAR report on the state of the BS. Furthermore, the Arctic Fisheries Working Group (AFWG), the main stock assessment working group for the Barents Sea use information from the report in their report each year.

As of now, WGIBAR consists of researchers from IMR and PINRO, the institutions that do most of the monitoring of the BS ecosystem. In addition, Raul Primicerio, from the arctic University of Tromsø, held a presentation on multivariate analyses in ecosystem studies for WGIBAR participants and PINRO scientists and gave recommend further use of multispecies analyses.

5.2 Progress report on ToR c

During the WGIBAR meeting following research questions relevant to the state of the Barents Sea and ecosystem based management were identified:

The Barents Sea has been on a warming trend since 1980 with shorter oscillations between warm and colder years. 2016 is the warmest year on record exceeding 2006 and 2012 as the two most recent warm years. The warming has been associated with an expansion of Atlantic and mixed (0–3°C) water masses and a near disappearance of Arctic water (defined as water with subzero temperature), and strong reduction in winter sea ice.

The oceanographic changes that are taking place has implications for all life forms in the Barents Sea both in the water and on the seabed. There are many research questions related to distribution and population dynamics of single species and their interactions in foodwebs and communities. One particular question concerns the dominant herbivore copepod in the northern Barents Sea, *Calanus glacialis*, which has its habitat in the cold Arctic water. How will this copepod cope under warmer conditions with less sea

ice and extended period of predation by planktivorous fish? Some models predict that *Calanus glacialis* will not do well and lead to a decrease in production of large mesozooplankton in the northern Barents Sea (Slagstad *et al.*, 2011).

Associated with the decline in Arctic water, the transitional mixed water (0–3°C) has increased. An important question is whether this habitat is suboptimal for both *Calanus finmarchicus*, which thrives on the warm side, and *Calanus glacialis*, which is found in cold Arctic water. The declining trend in mesozooplankton biomass on the Central and Great Banks may be an indication that the mixed waters are less favourable for the *Calanus* species.

Russian and joint time-series reveal an increasing trend in krill (euphausids) over the last 10–15 years. This is likely related to warming and improved habitat conditions for advected krill, notably *Meganyctiphanes norvegica* and *Thysanoessa inermis* (Eriksen *et al.*, 2016, 2017). The increased amount of krill plays important roles in the ecosystem as food for a range of consumers, including fish, seabirds, and marine mammals. We need a better understanding of the spatial ecology and trophic role of the dominant krill species in the Barents Sea ecosystem. This includes to what extent the krill species reproduce in the Barents Sea, as opposed to advection from the adjacent Norwegian Sea.

Pelagic hyperiid amphipods, notably the large Arctic species *Parathemisto libellula*, have shown an opposite trend to that of krill, with a pronounced decrease in the Barents Sea over the most recent decades. Like for the krill species, we need better understanding of the biology and ecology of the dominant pelagic amphipods in the Barents Sea. They are to large extent omnivores and carnivores and play dual roles as prey for and food competitors with planktivorous fish such as capelin, juvenile herring, and polar cod.

The cod stock is now at a high level and capelin, which is a key prey item, is at a very low level. Increased overlap between cod and capelin in summer, where cod has been able to follow capelin on its seasonal feeding migration to the northern Barents Sea, has resulted in increased predation by cod which eventually lead to the collapse of the capelin stock in 2015. The estimated consumption of capelin by cod in 2016 was still fairly high although cod has been shifting to take more alternative prey composed of other fish species and benthos. One important research issue is to what extent the large cod stock will prevent the recovery of the capelin stock by continuing to exert strong predation pressure. Another issue is the predation pressure from cod on the alternative prey, including small Arctic fish (sculpins, snailfish, eelpouts, and others) which may not be so abundant. Will the large cod stock deplete these prey resources over the next few years, and will this in turn affect the feeding conditions and the overall status of the cod stock? May we witness a marked decrease in the condition and size of the cod stock in near future? These are questions that require our attention as we plan cruises and research activities.

5.3 Progress report on ToR d

An overview of the available ecosystem and multispecies models for the Barents Sea were presented (Annex 4, working document). The group agreed that the use of these models by WGIBAR would be useful, but this could be difficult to perform at this stage, since various modelling activities often are limited by the plans set up when funding was applied for. It is therefore important to get information about the work, which is ongoing in the different modelling groups, both to make it clear whether this work can be of interest for WGIBAR, and to identify whether there are questions of particular

interest for WGIBAR, which are not being addressed. The WGIBAR group will collaborate with the Working Group on Multispecies Assessment Methods (WGSAM) concerning methodological issues related to the ecosystem models.

5.4 Progress report on ToR e

The ecosystem survey is a cooperation between IMR and PINRO and has been run annually in August-October since 2004. The survey was established by combining several earlier surveys, including the acoustics survey for pelagic fish providing basis for the stock assessment of capelin. Indices based on ecosystem survey data are also used e.g. in the assessment of shrimp, cod, haddock, and Greenland halibut (*Reinhardtius hippoglossoides*) and cod stomach data sampled on the survey are used in haddock, cod, and capelin assessments. The ecosystem survey covers the whole Barents Sea shelf and samples all main ecosystem components allowing the study of spatial overlaps and interactions (see section 4 in the report "State and trends of the Barents Sea in 2016" for an example). The recent warming has led to ice-free conditions in August-September opening new areas to investigations, including the northern Arctic part of the Barents Sea.

During the relatively short period the ecosystem survey has been run many changes in the ecosystem has been documented. These include changes in production (Eriksen *et al.*, 2017), fish community structure (Fossheim *et al.*, 2015) and functional diversity of fish (Wiedmann *et al.*, 2014), influencing foodweb structure (Korstch *et al.*, 2015). The changes are mainly associated with the expansion of boreal fish into the northern, Arctic Barents Sea. This expansion has been particularly pronounced for cod for which warming together with reduced fishing pressure has led to stock level increase and more old and large individuals in the stock (Kjesbu *et al.*, 2014). The expansion of cod is much faster than predicted by niche-based and climate projection models (Ingvaldsen *et al.*, 2015). Other ecosystem components including shrimp have also shifted distribution towards the northeast during the survey period from 2004. This has led to a spatial shift in the shrimp fishery activity (ICES, 2016a). During the period the ecosystem survey has been run, a westwards expansion of the invasive snow crab (*Chionoecetes opilio*) has been documented (see Chapters 3.4 and 4.6 from the report "State and trends of the Barents Sea in 2016").

Parts of the text in this report are modified from the latest ecosystem survey report (which is available on http://www.imr.no/tokt/okosystemtokt_i_barentshavet/survey_reports/survey_report_2016/nb-no) and most of the maps shown are based on data from the ecosystem survey.

The timing and the survey design was not optimal, and coverage was not synoptic during the Joint Norwegian-Russian Barents Sea survey (BESS) in 2016. These factors in addition to incomplete area coverage impact the survey results and their interpretations. WGIBAR recommends that the annual monitoring of all ecosystem components should be kept at the same level as in the period up to 2016.

5.5 Cooperation

Cooperation with other WGs

- Stock assessment groups in particular the Arctic Fisheries Working Group (AFWG)
- Other IEA groups in particular the Working Group on the Integrated Assessments of the Norwegian Sea (WGINOR) and the ICES/PAME Working

Group on Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean (WGICA)
- Working Group on Multispecies Assessment Methods (WGSAM), Working Group on the Ecosystem Effects of Fishing Activities (WGECO)

Cooperation with Management structures

- The Joint Russian Norwegian Fisheries Commission, in charge of joint fisheries management in the Barents Sea
- The Joint Russian Norwegian Environmental Commission, in charge of joint environmental management in the Barents Sea.
- The Norwegian Ministry of Climate and Environment, in charge of Norwegian holistic ecosystem-based management plan for the Norwegian part of the Barents Sea.

Cooperation with other IGOs

Relevant groups within the Arctic Council. WGIBAR will continue to map collaboration partners, and their needs and advantage from the cooperation during 2017, and present the overview at next meeting.

6 Revisions to the work plan and justification

Relevant collaboration partners will be evaluated, their needs and advantage from the cooperation will be presented at next meeting. ToR e, collaboration part, will be prolonged to 2018.

7 Next meeting

Next WGIBAR meeting is planned to be held in Norway back to back with the Russian-Norwegian scientist meeting in March 2018.

Annex 1: List of participants

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Annex 2: Recommendations

The WGIBAR "The state and trends of the Barents Sea ecosystem in 2016" report will be useful for ICES assessment WG's (AFWG, WGWIDE, WGHARP and NIPAG) as background ecosystem information for the stock development.

Recommendation	Adressed to
1 "The state and trends of the Barents Sea ecosystem in 2016" report will be useful for ICES assessment WG's as background ecosystem information for the stock development	AFWG, WGWIDE, WGHARP, NIPAG
2.	
3.	
4.	
5.	

Annex 3: Agenda for WGIBAR 2017

March 15, Wednesday Arrival of the Norwegian delegation
March 16, Thursday (PINRO)

09:00–12.00 Plenary

09:00–09:10 Opening of WGIBAR meeting, adopting of the agenda and practical information

09:10–10:25 Ecosystem status and trends (15 minutes each):

- Oceanography (V. Lien /A. Trofimov)
- Plankton (E. Bagøien/A. Dolgov)
- Fish recruitment (E. Eriksen/T. Prokhorova)
- Pelagic fish (G. Skaret/D. Prozorkevich)
- Demersal fish (B. Bogstad/A. Russkikh)

10.25–10.45 Coffee and Tea break

10.45–12.00 Benthos (N. Strelkova/ L. Jørgensen)

- Sea mammals (R. Klepikovskiy)
- Fish trophic interactions (B. Bogstad/A. Dolgov/A. Benzik)
- Non-commercial fish (E. Eriksen/T. Prokhorova)
- Pollution (H. E. Heldal/ A. Zhilin)

12:00–13:00 Lunch

13:00–17:00

- Discussion of the current state and long-term dynamics of the Barents Sea ecosystem
- Practical work by groups
    - Perform the integrated analysis of multivariate datasets (E. Eriksen/ E. Bagøien/H.R. Skjoldal, R. Primicerio and other)
    - Based on discussion of observed changes identify research questions relevant to the Barents Sea integrated assessment and data needed
    - Identify knowledge gaps for improvement of future integrated ecosystem assessments (ToR c)
    - Produce recommendations to improve the monitoring of the Barents Sea ecosystem (ToR e)
    - Prepare the status description for ecosystem components to the report (ToR b)

March 17, Friday (PINRO)

09:00–12:00 Plenary

Methods and tools

09:00–09:30 Information about ICES Workshop on Integrated Ecosystem Assessment Methods (WKIDEA) (H. R. Skjoldal)

09:30–10:00 Present and discuss available ecosystem and multispecies models as an analytical tool in integrated ecosystem assessment for the Barents Sea (A. Filin)

10:00–10:30 Discussion of the WGIBAR database

10:30–10:50 Coffee and Tea break

11:00–12:00 Evaluation of functioning and vulnerability of ecosystem by multivariate analysis (R. Primicerio)

12:00–13:00 Lunch

13:00–16:00 Practical work by groups

- Prepare the status description for ecosystem components to the report
- Integrated analysis of multivariate datasets
- Describe research questions, analyse multivariate dataset and give current state of knowledge pertaining to these questions discuss

16:00-17:00 Summing up the results of the meeting

Future work, next meeting

March 18, Saturday (PINRO)

10:00–16:00 Practical work by groups

- Prepare the status description of the Barents Sea ecosystem to the report
- Updating the WGIBAR database
- Writing the chapters on ToR c. d, e.
- Complete the WGIBAR annual report and prepare the presentation at the March meeting (Annual Norwegian-Russian scientist meeting)

Annex 4: Available ecosystem and multispecies models for the Barents Sea (Working document 1)

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Introduction

Ecosystem models describe the structure and function of an ecosystem. These models deal with physical variables (currents, temperature, salinity), chemical variables (acidification, major nutrients) and biological variables (phytoplankton, plankton, benthos, fish and top predators). Ecosystem models can be used both to better understand the functioning of a marine ecosystem, and to provide indications of how an ecosystem is likely to change in response to climate change and to changes in human activities, including fisheries.

According to Plaganyi (2007) the following classes of models to modelling multispecies/ecosystem effects may be specified:

Whole ecosystem models: models that attempt to take into account all trophic levels in the ecosystem.

Dynamic Multispecies Models or Minimum Realistic Models: limited number of species most likely to have important interactions with fishable target species.

Dynamic System Models (Biophysical): represent both bottom–up (physical) and top–down (biological) forces interacting in an ecosystem.

Extensions of single-species assessment models: expand on current single-species assessment models taking only a few additional interspecies interactions into account.

Ecosystem models may be useful for looking at how change in one ecosystem component is affecting the whole or parts of an ecosystem, thereby identifying the most important interspecies/ functional group links and sensitivity of the ecosystem to changes. They are also useful for scenario testing (change in fishery management, climate change and pollution events). Benefits of multispecies models include improved estimates of natural mortality and recruitment; better understanding of stock–recruit relationships as well as variability of growth and maturation rates; testing of alternative harvesting strategies and different climate change scenarios.

Development of multispecies models designed to improve fisheries management in the Barents Sea started in the mid-1980s (Bogstad and Filin, 2011). It was initiated due to dramatic developments in some of the main exploited stocks in the region. In the middle of the 1980s a collapse in the capelin stock was observed. This situation had a drastic effect on higher trophic levels and was followed by a dramatic decline in cod catches. This demonstrated the necessity of adopting new management measures incorporating ecosystem effects and their consequences. To this end, the work on development of multispecies models for the Barents Sea at the first stage was focused on rather complex models that included interactions between several main species. At IMR, the models MULTSPEC (Bogstad *et al.*, 1997), AGGMULT (Tjelmeland and Bogstad, 1998) and Systmod (Hamre and Hatlebakk, 1998; Hamre, 2003) were developed. At PINRO, in cooperation with VNIRO, the MSVPA model was chosen (Korzhev and Dolgov, 1999). However, it was found that all these models were generally too complex for direct implementation in practical management.

Since the second part of the 1990s, priority has been given to less complex models with fewer biological processes included. IMR has developed the Bifrost model, which is now used in the management of capelin (Gjøsæter *et al*., 2002). Also, SeaStar, the assessment model used until 2008 for assessment of Norwegian spring-spawning herring (Tjelmeland and Lindstrøm, 2005), allows for including predation by minke whale on herring. PINRO has developed the STOCOBAR model that describes cod stock dynamics in the Barents Sea, taking trophic interactions, fisheries and environmental influence into accounts (Filin, 2005). Along with multispecies management models the Ecopath model was also adapted for the Barents Sea (Blanchard *et al*., 2002; Mackinson *et al*., 2003), but more in exploratory scenario approaches than for direct implementation in stock assessment and management.

From 2010 onwards, interest in ecosystem modelling in the Barents Sea has increased and several ecosystem models have been developed. The increased interest was triggered by both the global politically stated aim of introducing an ecosystem approach to fisheries management, which required the development of relevant analytical tools, and also the growing interest in quantitative evaluation of possible climate change impacts.

Recently has also been increased interest in the use of ecosystem/multispecies models for integrated ecosystem assessments in the ICES regions (ICES, 2016). Following this, one of the research topics of the ICES WG on Integrated Assessments of the Barents Sea (WGIBAR) for 2017–2019 was to explore the use of available ecosystem and multispecies models as analytical tools in the integrated ecosystem assessment for the Barents Sea.

The aim of this working document is to provide an overview of the available ecosystem and multispecies models and their potential application in the work of WGIBAR.

Model descriptions

The current information on the ecosystem and multispecies models that were developed for the Barents Sea can be found in the reports of the ICES Working Groups on Multispecies Assessment Methods (WGSAM) and Arctic Fisheries (AFWG). Classification of the available ecosystem and multispecies models for the Barents Sea are presented in Table 1. Their brief descriptions are given below.

Table 1. Classification of the ecosystem/multispecies models for the Barents Sea.

Model acronym	Full name
Whole Ecosystem Models (End to End Models)	
EwE	Ecopath with Ecosim
ATLANTIS. NoBa	Atlantis in the Nordic and Barents Seas
NDND	Non-Deterministic Network Dynamic
Minimum Realistic Models (Multispecies Models)	
Bifrost	Boreal Integrated Fish Resource Optimization and Simulation Tool
STOCOBAR	Stock of Cod in the Barents Sea
CODCAB	Cod and Capelin in the Barents Sea
Gadget	Globally Applicable Area Disaggregated General Ecosystem Toolbox
Dynamic System Models	
NORWECOM	Norwegian Ecological Model system

SYMBIOSES	System for Biology-based assessments
Extensions of Single-species Assessment Models	
EcoCod	Ecosystem and Cod
MSVPA with MSFOR	Multi-Species Virtual Population Analysis; Multi-Species Forecasting Model

Ecopath with Ecosim (EwE)

This a whole ecosystem mass balance model (Christensen and Pauly, 1992). EwE is considered the most widely deployed ecosystem model, and is freely accessible: http://www.ecopath.org/search/node/registered. EwE is typically used to characterize the trophic structure, ecosystem attributes and impacts of fishing and climate change in a specified region. This model has three main components: 1) Ecopath – a static, mass-balanced snapshot of the system; 2) Ecosim – a time dynamic simulation module for exploring past and future impacts of fishing and environmental disturbances; 3) Ecospace – a spatial and temporal dynamic module primarily designed for exploring impact and placement of protected areas (Christensen and Walters, 2004).

At the beginning of the 2000s Ecopath model was adapted at IMR for the combined Norwegian Sea and Barents Sea. Thirty functional groups were included, ranging from marine mammals to phytoplankton and detritus (Dommasnes *et al.*, 2001). Skaret and Pitcher (2016) expanded and developed the model for the Norwegian Sea and Barents Sea and used Ecosim to simulate the development of the ecosystems for the period 1950 to 2000. They included 58 functional groups, of which 12 were juvenile fish groups. Catch data on all targeted functional groups were used as forcing functions and the simulated abundance was fitted to 15 abundance time-series from VPA, acoustic abundance estimates or cpue-estimates. A primary production forcing function was added to investigate bottom–up effects in the ecosystem and significantly improved the model fit to the abundance time-series, in particular for the variable capelin abundance. The results suggested that bottom–up effects are important in this ecosystem.

Blanchard *et al*. (2002) developed an EwE model only for the Barents Sea. The model has been used to investigate the consequences of alternative functional response formulations on the predictions of responses by marine mammals (Mackinson *et al*., 2003). Falk-Petersen (2004) has also used the EwE approach to investigate the impacts of king-crab invasion in a Norwegian fjord.

EwE models have not been used at IMR in the past 10 years or so, but currently there is ongoing work initiated by Torstein Pedersen (UiTø) to use EwE-models to explore the combined effect on the Barents Sea of climate change, fisheries and new species invasions (especially the snow crab invasion).

ATLANTIS

This is an end-to-end ecosystem 3D box-model intended for use in management strategy evaluation (Fulton *et al*., 2004, de la Mare, 1996; Cochrane *et al*., 1998; Butterworth and Punt, 1999; Sainsbury *et al*., 2000). It has been applied to multiple marine systems (from single bays to millions of square kilometres) in Australia and the United States. Atlantis in the Nordic and Barents Seas (NoBa) includes 53 species and functional groups (Hansen *et al.*, 2016), where all large commercial stocks (e.g. Northeast arctic cod, haddock, capelin, saithe, mackerel) are represented by their own group, which is also the case for vulnerable stocks such as beaked and golden redfish. The fisheries are implemented as fishing mortalities, and there is ongoing work on including fishing

fleets for the Barents Sea. The model has been tested for several scenarios, including future climate, fisheries and sensitivity to key parameters (Hansen *et al.*, 2016).

NoBa is forced on a daily basis with temperature, salinity and volume fluxes from ROMS (Regional Ocean Modeling System), and will eventually also include sea ice (thickness and concentration) and snow thickness on top of the ice. The species groups are connected through a flexible diet matrix, where the amount of prey available for the predator is defined. The model is deterministic, and gives one trajectory for a given scenario.

The output from the model is biomass, age, number of individuals, predation, mortality and catches (if fisheries are included). These are spatial data, split between boxes and layers, except for predation, which is summed up over the whole area (including the Nordic seas).The model domain is made of 60 arbitrary polygons comprising $4x10^6$ km^2, which are defined based on information about the hydrography, depth and biology. These describe all foodweb levels from bacteria and phytoplankton to cod, polar bears, and whales.

NDND

NDND (previously DSF) is an ecosystem foodweb model based on Non-Deterministic Network Dynamic (Planque *et. al.,* 2014), and is under development at IMR (Tromsø). The modelling approach is based on stochastic trophic exchanges operating within an ensemble of constraints which include mass balance (i.e. the conservation of mass within the system), physiology (i.e. satiation: the maximum amount of food intake of a predator per year per unit biomass) and inertia (i.e. the maximum relative variation in biomass of a tropho-species per year). The current version of the model for the Barents Sea (Lindstrøm *et. al*, 2017) includes eight tropho-species groups and the trophic interactions between them (phytoplankton, herbivorous and omnivorous zooplankton, benthos, pelagic fish, demersal fish, marine mammals and seabirds). The model reproduces many of the properties of empirical time-series of species biomass in the Barents Sea. At the ecosystem level, the model also produces realistic fluctuations in trophic controls (top–down and bottom–up oscillations), or apparent regime shifts. The NDND model shows that many of the properties that are observed in real ecosystems could simply result from a very minimal set of constraints. The model is under development to include additional features such as age-structured populations, multiple geographical units, seasonality and climate forcing.

Bifrost

Bifrost is a multispecies model for the Barents Sea with main emphasis on the cod-capelin dynamics (Tjelmeland and Lindstrøm, 2005). The prey items for cod are younger cod, capelin and other food. The "other food" is a constant parameter. The parameters for consumption are estimated using a likelihood based on consumption per cod for ages 3–9 of capelin, cod and other food where the empirical consumption is calculated from stomach content samples and laboratory evacuation rate measurements. The capelin availability impacts on the cod cannibalism.

In prognostic mode, Bifrost is coupled to the assessment model for herring – SeaStar (Tjelmeland and Lindstrøm, 2005) – and the negative effect of herring juveniles on capelin recruitment is modelled through the recruitment function for capelin. For cod and capelin the weight at age and maturation at age during prognostic simulations are calculated using regressions for each age group on historic data using abundance and temperature as covariates. Also, weight-at-age and maturation-at-age can be drawn from historic values. The model time-step is one month.

Bifrost is used in management of the Barents Sea capelin. Using this model the parameters governing maturation of capelin and consumption of capelin by cod are estimated and transferred to field tool CapTool, in which quota calculations are performed. Bifrost serves two purposes: to be an assessment tool for capelin SSB and as a tool for evaluating harvest rules in the cod-capelin-herring system. In the Bifrost only the consumption of capelin by cod in quarter 1 is modelled.

STOCOBAR

This model describes stock dynamics of cod in the Barents Sea, taking multispecies interactions, water temperature changes and fishing mortality into account (Filin, 2005; Filin, 2012; Howell *et. al.*, 2013). STOCOBAR is an age-structured, single-area and single-fleet model with one-year time-steps. It includes cod as predator on up to eight prey items: capelin, shrimp, polar cod, herring, krill, haddock, own young (cannibalism), and "other food". The simplest version of the model that includes only cod and capelin is used operationally. The block schema of the model is shown in Figure 1.

The cod stock dynamics is described through imitation of cod growth, feeding, maturation, recruitment, cannibalism and fishing mortality. All these processes are influenced by temperature that is presented in the model as a temperature scenario. Capelin impacts on cod stock dynamics through the changes in cod growth, feeding, maturation and natural mortality induced by cannibalism. A Ricker recruitment equation is used to couple the cod spawning-stock biomass and cod abundance at age 1. Another option to simulate a cod number-at-age 1 is based on modelled indices of 0-group. In this case, along with spawning-stock biomass, effect of temperature is also considered. Cod recruitment-at-age 3 is modelled from its number-at-age 1 taking cannibalism into account.

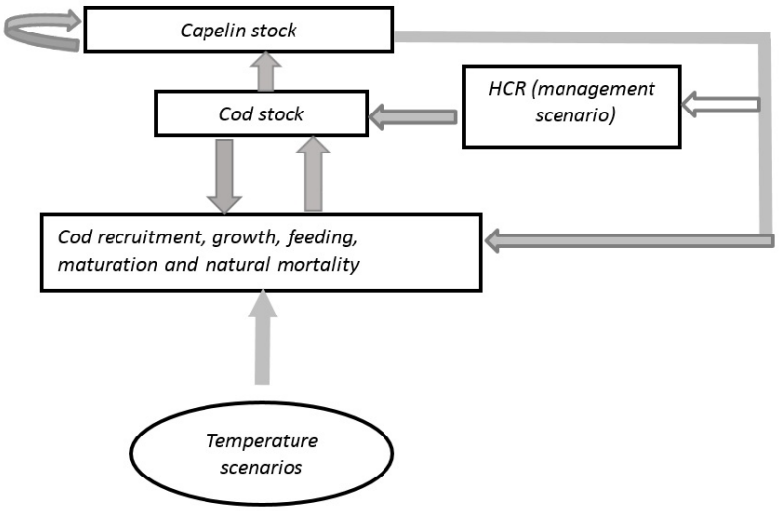

Figure 1. The block schema of the STOCOBAR model.

The imitation of capelin stock dynamics, unlike the process-oriented simulation of cod stock, is based on statistical links only. According to the observed data, the year-to-year variations in stock size of capelin depends concurrently on cod spawning-stock biomass and capelin stock size in previous year. To produce capelin stock projections historical replicates are drawn from the different datasets depending on modelled cod and capelin stocks in the previous year.

Temperature scenarios for the model runs may be produced both outside and inside of the model. The endogenous temperature scenarios reproduce cyclic dynamics of the

annual temperature on the Kola Section. It is based on a consecutive random selection from 3 sets of historical data corresponding to cold, moderate and warm periods. The long-term trends in the temperature scenarios may be implemented also.

STOCOBAR is a stochastic model. It is able to incorporate uncertainty (through bootstrapping simulations) in temperature scenarios, capelin stock dynamics, cod recruitment, fishing mortality rate and in growth rate of cod during the first year of life. Although the model does not explicitly include the concept of carrying capacity, this may be investigated by setting different constraints on cod consumption, its growth and natural mortality.

In order to parameterize the model, historical data on abundance of cod, its individual weight and length, fat content, maturity, fishing mortality rates, stomach contents, as well as data on the stock biomass of capelin and water temperature are used. In order to tune the model, the sum of square discrepancies between simulated and observed time-series is minimized using Solver in the Excel spreadsheets. Time-series are weighted differently when calculating sum of squares according to our judgement on data reliability and relevance.

STOCOBAR is designed as a tool for exploration of cod stock development under different climate change and management scenarios as well as for evaluating different harvest strategies and recovery plans. Results of the model studies are published in (Howell *et. al.*, 2013; Howell and Filin, 2014; Filin, 2015; Filin 2016*a,b,c*; Filin and Howell, 2016).

STOCOBAR was evaluated as an operational multispecies model for the Barents Sea at the ICES Working Group on Multispecies Assessment Methods in 2013 (appendix 1).

CODCAB

CODCAB is an extended variant of the STOCOBAR model, which includes age-structured capelin stock. Unlike the STOCOBAR in the CODCAB the recruitment function and fishing mortality are used for both cod and capelin. Survey data are used in estimations of the model parameters for capelin. The growth and natural mortality of capelin are not process-simulated in the model yet. CODCAB is designed as a tool for exploration of cod and capelin stocks development under different climate change scenarios and testing their harvest control rules on a multispecies basis.

GADGET

Gadget is a multispecies model (http://www.hafro.is/gadget; Begley and Howell, 2004; Howell and Bogstad 2010). It is age–length structured, with a monthly time-step and four spatial areas (the Barents Sea and three subsidiary regions). The Barents Sea Gadget implementation (structure shown in Figure 2) includes the major interacting species in the Barents Sea, including cod predation and cannibalism, predation from minke whales and harp seals, and herring predation on capelin larvae. Currently, cod and capelin are modelled as having a fully closed life cycle, while whales and herring have simpler recruitment functions. Predation by whales on cod, capelin and herring, and by cod on cod and capelin is included within the model, although the effects of prey availability on predator condition/growth are not currently modelled. Prey selection for each fish species is according to the length of the predator and prey, and conditioned to the stomach content data. Predation by harp seals act as an additional fishing fleet in the model. Gadget is a deterministic model; work is underway to include uncertainty in the forecast part of the model. The model does not include the effects of

temperature or bottom–up effects of food availability on predator growth and reproduction.

To parameterize the model are used survey and catch data on cod, capelin and herring as well as data on cod stomach content and minke whale abundance estimates. Principle of model parameter estimation is based on total objective function (Frøysa *et al.*, 2002), where weighting factors are set so that survey and catch data get about the same weight in the estimation.

This model was evaluated as operational multispecies model for the Barents Sea at the ICES Working Group on Multispecies Assessment Methods in 2013 (appendix 1).

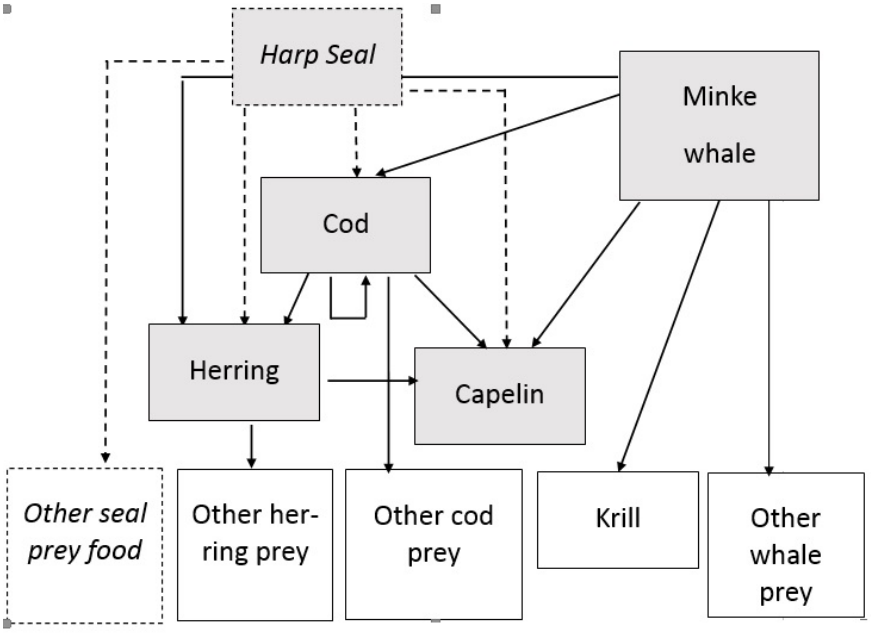

Figure 2. Gadget model structure. Only the stocks shown in grey are modelled dynamically.

SYMBIOSES

This model has been developed combining oceanography, ecotoxicology, plankton, larvae, and adult fish population models (Carroll *et al*., 2010) involving IMR, SINTEF, Akvaplan-Niva, STATOIL, IMARES and the universities of Nijmegen and Ghent, and others. The combined tool focuses on the impacts on egg- and larval-mortalities of a potential oil spill near the main fish spawning grounds. The model will include cod, capelin and herring, with initial focus on cod mortalities. By focusing on larval mortalities as the only link between the fish and lower levels of the ecosystem, it is hoped that the model will be able to avoid some of uncertainty issues surrounding "whole ecosystem models" and become an operational tool in risk management in the oil industry. The physical oceanography uses the ROMS model, the ecotoxicology section is a development of the OMEGA/DEBtox, the chemical fate model is MEMW, phyto- and zooplankton are modelled with SINMOD (Slagstad and McClimans, 2005; Wassmann *et al.*, 2006), the fish larvae and eggs use LARMOD (Vikebø *et al*., 2007), and the fish part of the model is the multispecies Gadget model described above. A first version of the model has been built, and is currently in the testing phase.

NORWECOM.E2E

Description of the NORWECOM model may be found in http://www.imr.no/temasider/modeller/norwecom.e2e/en. NORWECOM represents a model system, it is a merger of several models. This incorporates the models for the lower trophic levels and nutrient cycling (Skogen *et al*., 1995) and different individual based models (IBMs) developed initially for fish (Huse and Giske, 1998, Strand *et al*., 2002, Huse *et al*., 2004, Huse and Ellingsen, 2008, Utne *et al*., 2012) and zooplankton (Huse, 2005, Samuelsen *et al*., 2009, Hjøllo *et al*., 2012). Models include a fine scale representation of the physical features of the ecosystem as well as the biogeochemistry and the main components. For the Barents Sea a spatial resolution of 10 x 10 or 20 x 20 km are used typically with 1-hour time-step. In this case, producing 1-year projection takes approximately 12 hours simulation time.

At IMR the NORWECOM.E2E have been operational for a few years running phytoplankton, zoo-plankton and pelagic fish on top of numerical hydrodynamic models (e.g. with a resolution of 4 x 4 km and time-steps of 15 min). However, it is still under development to become a full end to end model (E2E) of the Norwegian Sea and Barents Sea ecosystems, and several projects are running to include more species.

At present, IBMs for adult pelagic fish (mackerel, herring, blue whiting), copepods *Calanus finmarchicus, C. hyperboreus* and krill (*Meganyctiphanes norvegica*) are running, while there is ongoing work to include IBMs for capelin, mesopelagic fish, and fishing vessels. The model system also has modules for ocean acidification (Skogen *et al.*, 2014) and contaminants (Green *et al.*, 2011). The model system has also been used to study climate effects through downscaling of global climate models (Skaret *et al.*, 2014).

For pelagic fish, the model cycle starts at the overwintering area, followed by spawning migrations, feeding migrations and migrations back to the overwintering area. The model includes the adult and juvenile stage of the life cycle, and there is ongoing work to extend these to full life cycle models by adding spawning and egg and larval stages. The pelagic fish module includes processes such as movement, feeding, growth and mortality. The pelagic fish feed on the modelled mesozooplankton. In a similar way, both copepod and krill individuals feed on the modelled phytoplankton and the local plankton abundance is updated continuously in the model. The krill, considered an omnivorous species, may also feed on the *Calanus* population. These modules are also 2-way coupled, thus the *Calanus* biomass removed by foraging krill is continuously added as mortality in the *Calanus* population so that mass balance is achieved.

The model can be used both for the Barents Sea and Norwegian Sea ecosystems. For the Barents Sea, the model can contribute with estimates on primary and secondary production, as well as phyto- and zoo-plankton biomass, both as annual estimates and time-series (daily/monthly). The model can also contribute on inter annual variability of this. For higher trophics the model has a module for capelin, but this module needs further development before it can be used in a realistic setting. Currently the model is tuned for the period 1995–2007. However, it is intended that the period 2006–2016 will be included into the model during 2017.

MSVPA with MSFOR

This model has been set up for the Barents Sea (Tretyak *et al.*, 1999; Korzhev and Dolgov, 1999), but this approach has now been abandoned. Up to 7 prey species were included (cod, haddock, capelin, shrimp, polar cod, herring, redfish), with cod and harp seal as the predators. A major problem when using MSVPA for the Barents Sea is that

capelin, which is a key species, has a short lifespan and almost total spawning mortality and thus is not suitable for use of VPA-type approaches.

EcoCod

This model is designed as an extension of the single-species CodSim model, which has been used to evaluate harvest strategies and investigate long-term yields (Kovalev and Bogstad, 2005). EcoCod was created to evaluate the long-term yield of NEA cod taking into account species interaction and influence of other important ecosystem drivers. The model simulates cod population dynamic using equations similar to VPA model. Most other relationships are linear regression models (multiple or single). The following processes are included for cod: recruitment, growth in weight, maturation, cannibalism and fishing. Initial population is taken from assessment made by AFWG. Capelin biomass and temperature are external datasets and taken from capelin acoustic survey and temperature data from Kola section. Recruitment function is Beverton and Holt for total egg production and age 0. Malformation of egg is included to take into account different quality of egg from cod at different ages. Cod at age 3 (recruitment to fishable stock) is modelled using age 0 and natural mortality-at-ages 0–2 as a function of capelin biomass and temperature. Growth (mean weight at age) is a function of capelin biomass, temperature and cod weight at previous age. Cod cannibalism at ages 3 and 4 is a liner regression with cod SSB taken with time-lag -3 year.

CHOICE OF MODEL

As shown above, many ecosystem and multispecies models have been developed for the Barents Sea. The choice of models that may be considered as appropriate exploratory tools for the WGIBAR, has to depend primarily on the research questions which are addressed. The capabilities of the available models for different investigations are summarized in Table 2.

Since we have a suite of relevant models, we could consider, as a perspective way, development of multi-model ensemble predictions of ecosystem responses to investigating changes. In this case, we seek to establish robust results from a suite of multispecies and ecosystem models. The major difficulties in applying this approach is that available models have different outputs and are on different temporal and spatial scales.

Another advantage of the use of a suite of relevant models is that multispecies and ecosystem models can combine their outputs. Multispecies models can use outputs from the ecosystem models through changes of the parameters that determine:

- the feeding and growth rate of the commercial species;
- the natural mortality of the commercial species;
- the distribution of the commercial species;
- the maximum stock size in relation to the carrying capacity.
- Ecosystem models can use outputs from the multispecies management models through corrections in:
- fishing mortality rate;
- fishing selectivity.

One of the main criteria for choice of the models is that the selected models have to represent adequately the system which is studied. In order to demonstrate this, a reality test has to be performed and results of this test must be available.

Table 2. The model investigations that can be conducted by the ecosystem/multispecies models for the Barents Sea.

Type of modelling	The addressed issues
Historical and current ecosystem assessments	Identify and quantify major energy flows in the ecosystem Describe the trophic interactions among species at different foodweb levels Estimate of integrated ecosystem parameters
Scenario modelling («what if» scenarios)	Climate change Ecosystem change Harvesting change
Hypotheses testing (alternative assumptions)	Primary/secondary productions Alternative prey ability Natural mortality rate Change in migration pattern Recruitment
Evaluation of human activity	Multispecies/ecosystem harvesting strategies Ecosystem effects of fisheries Pollution impact

We must also have confidence that model predictions are reliable and robust. Therefore uncertainties in the simulations have to be taken into account. The available models are characterized by different levels of complexity. The complex ecosystem models such as the ATLANTIS and NORWECOM require substantial data, including various environmental data, biological and foodweb information, data on interspecies interactions, fishery statistics and proposed management strategies. The amount and variety of data required to construct a fully detailed ecosystem model are virtually never available. If needed data are limited, the uncertainties associated with model predictions may be so high that the model is ineffective.

The data limitations are a major source of uncertainty associated with application of complex ecosystem models. However, the uncertainties may arise not only from data limitation, but also from model formulation, bias in data collection, misreporting of catches, deviations from the agreed HCRs and unpredictable environmental changes. Therefore, we need to be able to work with these uncertainties to produce meaningful results from the model analysis. Hence, a handling of uncertainties associated with model structure, parameter estimations and data should be one of the criteria for the choice of model. The assessment of confidence intervals in the model outputs is also desirable.

One should keep in mind that the complex ecosystem models are designed to provide more generality and realism, than precision. On the other hand, a more simple model which has a high hind cast accuracy will not necessarily give highly reliable forecasts, if ecosystem processes with little impact in the past and not explicitly modelled, start to have major ecosystem impacts.

Stochastic simulations should be used for the scenario testing. The evaluation of how often an event may occur and what the consequences would be of such an event needs to be completed through a risk analysis.

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Appendix 1

Multispecies model summary sheets adopted at the meeting of the Working Group on Multispecies Assessment Methods (WGSAM) (ICES, 2013)

Model Name	**STOCOBAR**
Contact details	PINRO, Anatoly Filin filin@pinro.ru
Category	Minimum realistic multispecies models
Generalized/custom	Custom application
Model Type	Age-structured, forward simulated, process-based, stochastic model. Describes stock dynamics of cod in the Barents Sea, taking into account trophic interactions and environmental influence. It includes cod as predator on up to eight prey items. The simplest version of the model species composition includes 3 categories of cod prey items: capelin, own young (cannibalism) and other food. Recruitment function is used for cod only. The model is able to produce stochastic temperature scenarios for future runs. It is designed as a tool for prediction and exploration of cod stock development as well as for evaluation of harvest strategies and recovery plans under different ecosystem scenarios. Impact assessment of ecosystem factors are based on «what if» scenarios.
Data used	Cod individual weight in stock, length, fatness (hepatosomatic index) and maturation from survey; weight in catch from fleet, initial abundance and fishing mortality by age from VPA assessment; cod stomachs content, Kola section annual temperature, F_{bar}, F_{pa}, B_{lim} for cod, natural mortality for cod at age 4 and older, total-stock biomass of capelin from Captool assessment.
Key model assumptions	The cod stock dynamics is described through modelling growth, feeding, maturation, recruitment, natural mortality (including cannibalism) and fishing mortality. The model can run with or without including temperature in cod recruitment equation. The capelin stock projections are based on statistical approach only. The following assumption are used: a proportion of prey species in a predator's ration reflects the proportion of these species in the sea; maximum consumption by fish depends on their body weight and environment temperature; a coefficient of proportionality between real and maximum consumption by a predator is the function of available food;

	growth of fish is a function of initial body weight and body length, water temperature and ration expressed as energy units; maturation rate of cod is determined first of all by their linear growth and fatness.
Time-step	One year
Spatial Structure	Single area is the Barents Sea
Estimated parameters	Parameters are estimated for modelling of cod consumption, growth and maturation rate, Ricker recruitment equation and annual deviation of cod recruitment-at-age 1.
Outputs	Cod stock numbers by age, individual weight, individual length, maturity ogive, fishable stock biomass, spawning-stock biomass, cannibalism mortality, catches, capelin consumption by cod, total capelin stock biomass.
Model tuning	Statistical fit to historical data
Uncertainties	Residues on cod recruitment-at-age 1 and stochastic temperature scenarios and capelin stock projection are used in multple model runs.
Model accessibility	Model is available on request from filin@pinro.ru
Documentation	Model structure described (see peer review reference), other documentation not currently available
Accepted WGSAM key run?	No
Main purposes	The model is suitable for long-term simulations aimed to evaluate of HCR for cod and consequences of climate change scenarios on cod stock dynamics and fishery.
Main restrictions	The model is less suitable for short time prognosis.
Examples	Theoretical studies on evaluation impact of capelin abundance in the Barents Sea on cod rebuilding strategy, impact of temperature on cod recruitment, estimation of relation between cod cannibalism and capelin stock size, evaluation consequences of climate change in the Barents Sea for cod-capelin relation, cod stock dynamics and its MSY.
Program language	Delfi. There is a GUI. The simple variant of the model (deterministic simulation) may be built without programming in Exceel sheet.
Peer review reference	Howell, D., Filin, A. A., Bogstad, B., and Stiansen, J.E. 2013. Unquantifiable uncertainty in projecting stock response to climate change: Example from NEA cod. J. Marine Science. DOI:10.1080/17451000.2013.775452
Model Name	Gadget (The Globally applicable Area Disaggregated General Ecosystem Toolbox)
Contact details	http://www.hafro.is/gadget, gadgethelp@hafro.is
Category	Minimum Realistic Model
Generalized/custom	Generalized toolbox
Model Type	Age–length structured, multi-area, multifleet forward simulation, process-based fisheries model. Species can be split into multiple "stocks", either actual stocks, or split by maturity or gender. Processes modelled are: growth, maturation, mortality, fishing level and selectivity, predation level and selectivity. Typically a choice of functions available for each process, with parameters estimated within the model.
Data used	Fleet total and survey data: by total catch, length, age, age and length; stomach contents, tagging data, cpue, and environmental data.

	Can potentially take parameters for consumption levels, prey preferences, fleet selection, growth and maturation from literature or external optimization if data unavailable. Can use variable levels of aggregation (e.g. wider length categories for the largest fish) in a dataset.
Key model assumptions	Assumes that all fish of a given ageand length are identical. Pure Markovian model, no "memory". Harvest Control Rule (HCR) assumes accurate up-to-date assessment of stock.
Time-step	User defined. Typically monthly or quarterly.
Spatial Structure	Single area or simple area structure. Models with low single digit numbers of areas are most tractable
Estimated parameters	All modelled processes (see "model type", above) can be estimated with one set of parameters for all years, annual factors, or blocks of parameters or trends through time
Outputs	Numbers and mean weight of fish in each age–length category in the population, in each "stock", in each fleet and in each survey. Predation by predator and prey age and length category. All outputs are for each time-step, and can be summarized with user-defined levels of aggregation.
Model tuning	Least likelihood fit to a weighted sum of datasets. Two optimization routines (wide area and local search) included.
Uncertainties	Model produces single run without uncertainty estimates. Multiple runs can be used to examine the parameter space around the optimum.
Model accessibility	Open source with online documentation, at http://www.hafro.is/gadget
Documentation	Available at http://www.hafro.is/gadget
Program language	Program in C++. Models are built in series of text files, no GUI
Accepted WGSAM key run?	No
Main purposes	Multispecies and/or mixed fisheries models where a small number of species and/or areas need modelling. Models where biological realism is desirable Models (single and multispecies) where age reading data are problematic.
Main limitations	Not well suited to detailed area structure or complex foodwebs. Complex modelling tool with a steep learning curve and high demands on model development time. For predation models a time-series of "other food" must be supplied to each predator. Can model fishing effort and HCRs, but assumes accurate and up to date knowledge of stock size.
Examples where the model has been applied	Theoretical multispecies in the Barents Sea(cod – capelin –herring - minke whale - harp seal), and Iceland. Bay of Biscay anchovy with climate drivers Assessment single species models: Barents Sea redfish, Southern Hake, Icelandic Tusk proposed Barents Sea Greenland Halibut Mixed fisheries assessment model, Mozambique Sofala Bank prawns
Peer review reference	Frøysa, K. G., Bogstad, B., and Skagen, D. W. 2002. Fleksibest - an age length structured fish stock assessment tool with application to Northeast Arctic cod (*Gadus morhua* L.). Fisheries Research vol 55: 87-101. Howell, D., and Bogstad, B. 2010. A combined Gadget/FLR model for management strategy evaluations of the Barents Sea fisheries. ICES Journal of Marine Science 67:1998-2004.

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Annex 5: The state and trends of the Barents Sea in 2016

Annex 5: The state and trends of the Barents Sea in 2016

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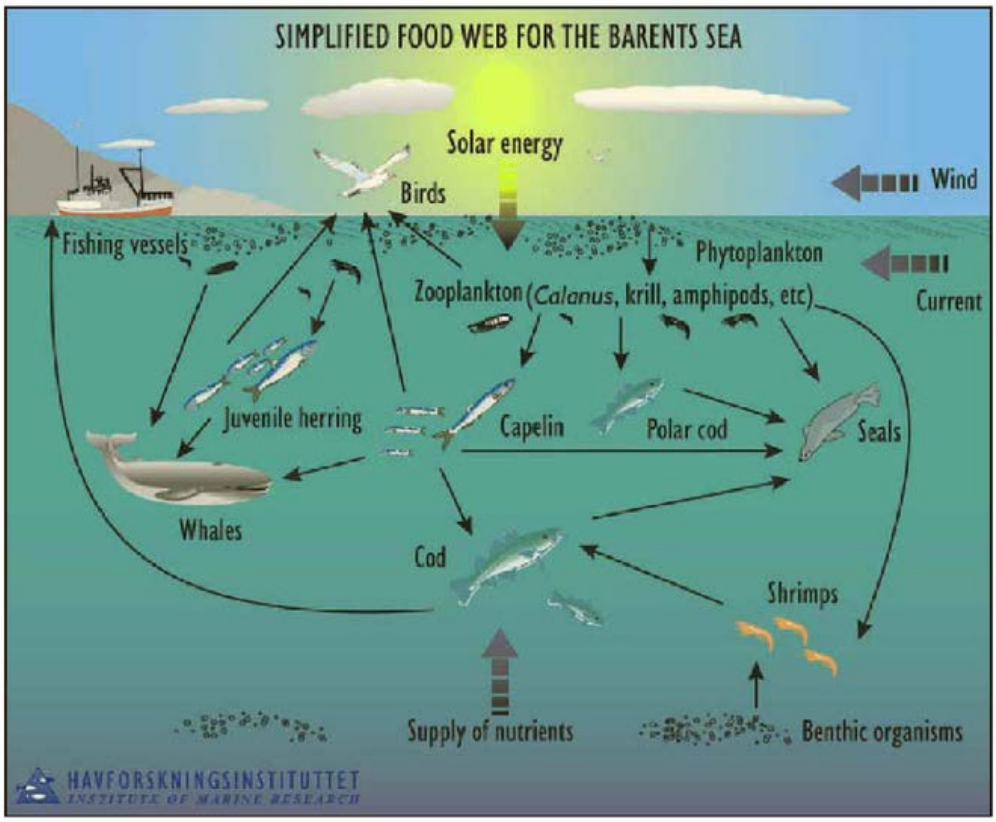


Contents

1 Summary

Since the 1980s the Barents Sea has gone from a situation with high fishing pressure, cold conditions and low demersal fish stock levels, to the current situation with high levels of demersal fish stocks, reduced fishing pressure and warm conditions. The current situation is unprecedented and the Barents Sea appears to be changing rapidly. The main points for 2016 are listed below:

- 2016 was a record warm year. The ice coverage of the Barents Sea in 2016 (annual mean and monthly means in March–July, November, December) was the lowest since 1951. The air and water temperature was warmer comparing to 2015 and the long-term average, and highest anomalies were observed in the east. In autumn 2016, the area of Atlantic waters (>3°C) was the largest, whereas the areas of Arctic and cold bottom waters (<0°C) were the smallest since 1965.
- The decrease in ice coverage provides improved conditions for phytoplankton production. Furthermore, the growing season (number of days with open water) has increased, and net primary production was the highest observed (based on satellite data 1998-2016, a noteworthy increase is observed in the Eastern regions.
- Mesozooplankton biomass for the entire Barents Sea during autumn 2016 was indicated to be somewhat lower than in 2015. The biomass was generally highest in the western regions, and comparatively low in the north-central and eastern areas. Zooplankton biomasses in the Central Bank and Great Bank subareas have shown declining trends since the peak in 1995. In the eastern areas, increases in abundances of small copepods, and decreases of large copepods have continued. An increasing trend in krill biomass has been observed during the last decades – and was above long-term average in 2016. Amphipods are still considered to be at a low level - although indicated to increase in 2015 and 2016. Jellyfish biomass was lower in 2016 than in 2015, and close to the long-term average.
- The Barents Sea fish stock biomass is dominated by demersal fish, notably cod, while pelagic fish is at a lower level due to the capelin collapse. The capelin biomass decreased from 2015 to 2016 by 40%, to about 0.33 million tonnes, which is well below the long-term mean. The causes of capelin decline are increased natural mortality (mainly for young age groups), and relatively low recruitment. In 2016, the highest biomass of 1-year-old polar cod ever was recorded, and it totally dominated in the stock which was estimated at 939 thousand tonnes. The 2016 polar cod estimate is the first above the long-term mean since 2010. Overlap with high concentrations of cod and increased predation pressure most likely influenced the polar cod stock decline up to 2015. The consumption of polar cod by cod increased from 2015 to 2016 and was in 2016 at the highest value since 2012.
- The cumulative biomass of demersal fish was highest in 2012–2013, and now tends to decrease. Numbers are going down faster than the biomass due to dominance of older individuals. Cod biomass stabilized at about 3 million tonnes, well above the long-term mean (1946–2016). Haddock abundance reached record levels in 2009–2012, declined from 2013, but is still at a high level. The biomass is about 1 million tonnes, twice the long-term mean (1950–2016). So far, minor effects of low biomass of pelagic fish on growth of large cod were observed. Due to the low level of capelin, cod and other piscivores

must compensate by feeding on other prey or survival, growth and reproduction will decrease. Increased predation pressure on alternative prey by the large cod stock has potential large, but unknown consequences for the Barents Sea.

- Overall there has been a decline in Arctic fish in the Barents Sea since 2004. Median catch of Arctic fish in the last three years was below the mean from 2004–2016 and the area where species from the Arctic-boreal, mainly Arctic and Arctic groups were found, decreased. The likely reason for this is the decrease in Arctic water masses in the Barents Sea.
- Benthos biomass show fluctuation, but are within the long-term mean in 2016. The distribution area of the invasive snow crab was smaller than in previous years, however the consequences and future development of this stock are un-known. The shrimp, *Pandalus borealis*, population was within the long-term mean and stable.
- In autumn 2016, the main groups of large whales were collocated with capelin and krill concentrations, primarily in areas south of the Spitsbergen and on the Great Bank.
- The levels of environmental pollution in the Barents Sea are generally low, and time-series recorded for the past decades show that the levels have been stable or decreasing. The levels of anthropogenic radionuclides, organic contaminants and metals in samples collected in 2015 and 2016 do not exceed threshold limits or global background levels. We do not expect adverse impact on marine organisms and stocks of commercial value in the Barents Sea from the present levels of environmental pollution.

2 Temporal development

2.1 Subareas of the Barents Sea

The Barents Sea is a heterogeneous system changing from boreal conditions in south-west to Arctic conditions in the north. To better reflect the changing conditions and trends over the large shelf and slope regions of the Barents Sea Large Marine Ecosystem (LME), we have subdivided the Barents Sea into twelve subareas shown in Figure 2.1.1 This division is a modified version of the system of subareas used in the analysis of spatial and temporal patterns of biomass of the pelagic compartment by Eriksen *et al.* (2017).

The Barents Sea opening with inflow of Atlantic water is divided into two subareas. The South-West subarea includes the system of banks along the north coast of Norway (Tromsøflaket and North Cape Bank) and the Norwegian Coastal Current. The Bear Island Trench is the deep area leading into the Barents Sea where most of the inflow of Atlantic water takes place. The Atlantic Current splits into two branches, one flowing east across the Thor Iversen Bank subarea located south of the Central Bank. This subarea consists of relatively deep banks that represents a shallowing between the deep areas of the Bear Island Trough and the South-East Basin. The Hopen Deep subarea is where the other branch of Atlantic water flows north. This is a deep area located between the shallower Central Bank in east and the Svalbard Bank in west.

The Central Bank subarea contains the Central Bank and the deeper areas between the Central Bank and Great Bank where Atlantic water from the Hopen Deep branch flows east on the way to the opening in northeast. The Central Bank has a clockwise circulation of water over it, and used to have Arctic conditions associated with ice freezing and formation of cold bottom water in winter. With warming this is now changing. The Great Bank subarea (or the Persey Elevation) to the north is another major bank in the northern Barents Sea which is traditionally an important summer feeding area for the Barents Sea capelin stock. The Svalbard subarea is heterogeneous with the Svalbard (or Spitsbergen) Bank and the Storfjord-system south of the archipelago along with the West Spitsbergen and North Svalbard shelf and slope areas. The Franz-Victoria Trough subarea lies between Svalbard and Franz Josef Land and includes the Franz-Victoria Trough leading into Olga Deep south of Kong Karls Land as well as the shelf region around Kvitøya and Victoria Island. The Franz Josef Land subarea is the waters around the archipelago bounded by St. Anna Trough in the Kara Sea in east and a line along approximately 78.5°N in south.

The Northeast subarea is the area east of the Great Bank and Central Bank and includes the Northeastern Basin, Novaya Zemlya Bank, the sill region between Novaya Zemlya and Franz Josef Land, and the head of the St. Anna Trough leading into the northern Kara Sea. The South-East Basin includes the deep basin and the surrounding slopes to the east of the Central Bank and Thor Iversen Bank. The South-East subarea is comprised of the general shallow waters of the southeastern Barents Sea with the Murmansk Rise, North Kanin Bank, and Goose Bank, and the Pechora Sea

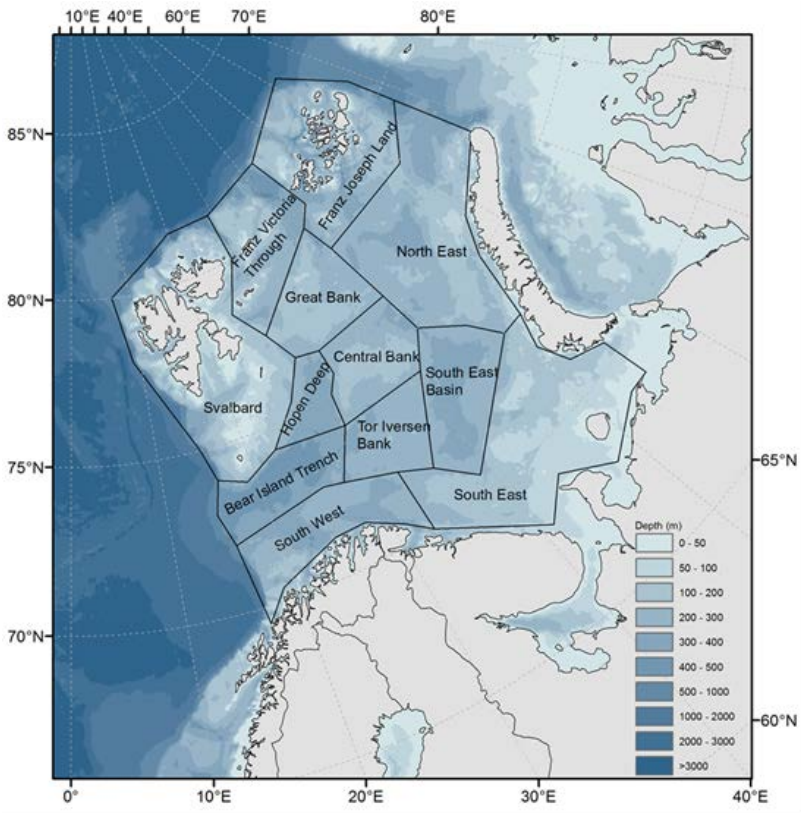


Figure 2.1.1. Map showing subdivision of the Barents Sea into 12 subareas (polygons) used to calculate mean values and time-trends for plankton and other data from Barents Sea surveys.

2.2 1980s to present: Integrated Trend Analysis

PCA – Abiotic variables

A Principal Component Analysis (PCA) for all abiotic variables, as listed in Table (Appendix 1), has been performed (Figure 2.2.1). Clearly, the analysis reveals that the two main drivers of variability of the Barents Sea climate system is the overall temperature (PC1; explaining 47% of the variability) and the through-flow of Atlantic Water (PC2; explaining 20% of the variability). The dynamic variability, i.e. changes in volume transports, are associated with changes in the North Atlantic Oscillation (NAO). The maximum sea ice cover (April) is strongly correlated with the temperature in the Kola Section, while the analysis shows that the changes in the maximum sea ice cover (September) is related to both the temperature and the volume transports in the Barents Sea. Notable years are easily distinguishable; both 2016 and 2015, as well as 2006, 2007, and 2012 were all anomalously warm and hence, are placed near the positive end of the x-axis (PC1). The years of the so-called "Great Salinity Anomaly" (1978, 1979, and 1980) are at the negative extreme of the x-axis. The areas of Atlantic Water and Arctic Water are positively and negatively correlated, respectively, with PC1.

Interestingly, 1979 and 2010 both belong to the negative extreme in the dynamical dimension, i.e. PC2, but they are far apart on the temperature scale (x-axis) as they belong to two different climatic regimes of the Barents Sea, namely the cold 1970s and the warm 2000s, respectively. 1989 stands out as the most extreme year in the dynamical dimension, marking the start of the current warm period.

The third axis (PC3; not shown) is related to the variability of the Atlantic Water inflow through the Barents Sea and is negatively correlated with the minimum sea-ice cover in September. We interpret this as the dynamic part of the summer sea-ice minimum,

which is often close to zero and therefore less dependent on the temperature and, according to the analysis, also dependent on the dynamic state of the Barents Sea. The summer sea-ice minimum is also negatively correlated with the exchanges through the openings in the northern Barents Sea.

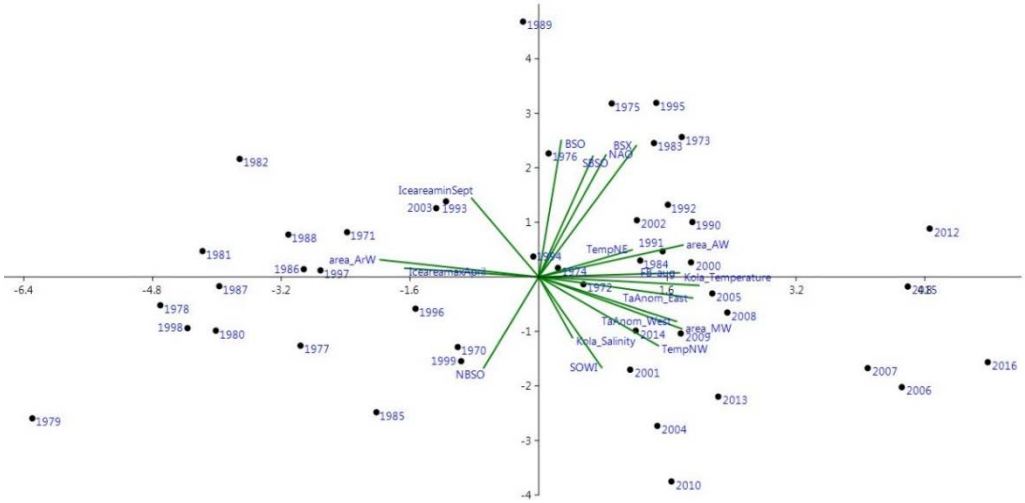


Figure 2.2.1 PCA of abiotic variables for the period 1979–2016.

Figure 2.2.2 clearly shows the «borealization» of the Barents Sea during the period 1979–2016. Temperature related variables, such as temperature itself, the area occupied by Atlantic Water (T >3°C), and the ice area at minimum and maximum sea-ice extent all show a clear trend towards warmer conditions. The variables connected to the dynamics, i.e. the flow of Atlantic Water (e.g. BSO – the inflow of Atlantic Water to the Barents Sea) does not show any clear trend, but rather some fluctuations partly in correspondence with the atmospheric forcing represented by the NAO. These results corroborate the findings that, while both the temperature and volume transport of the Atlantic Water into the Barents Sea contribute to the oceanic heat transport into the Barents Sea, they (temperature and volume transport) vary on different time-scales. While the volume transport fluctuates from year to year and even shorter time-scales, the temperature shows a clear signal of multidecadal variability, i.e. climate variability of addition to an underlying trend induced by climate change.

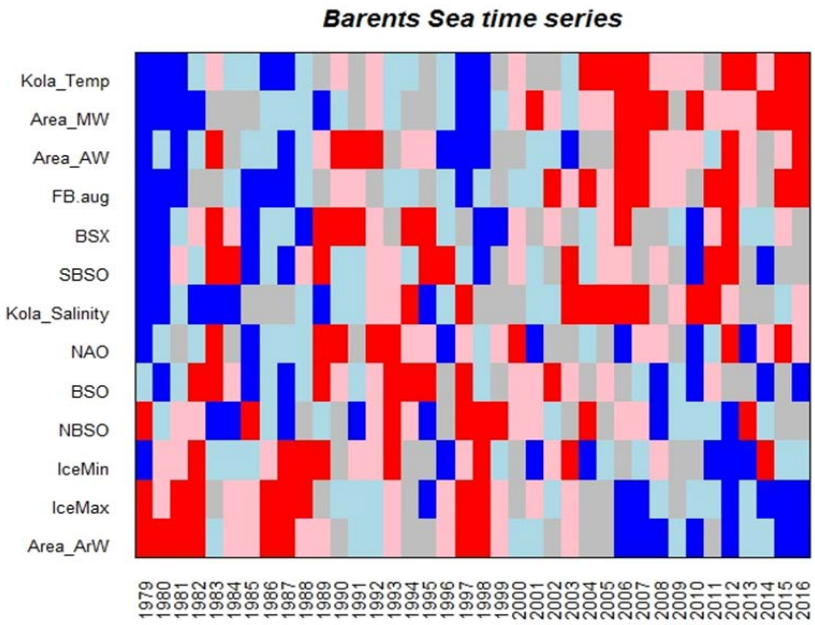


Figure 2.2.2. Time-series of annual means of abiotic variables in the Barents Sea sorted by trend. Blue means value below the 1979–2016 average and red means above the 1979–2016 average.

PCA – Zooplankton and 0-group fish

A PCA analysis was done on a set of variables including zooplankton biomass in three size fractions and sum total for the Barents Sea (Figure 2.2.3), 3 time-series of krill, and abundance of 0-group fish of 8 species (capelin, cod, haddock, herring, polar cod, Greenland halibut, long-rough dab, redfish, and saithe). These are all organisms that drift (or have drifted) with the currents into and inside the Barents Sea.

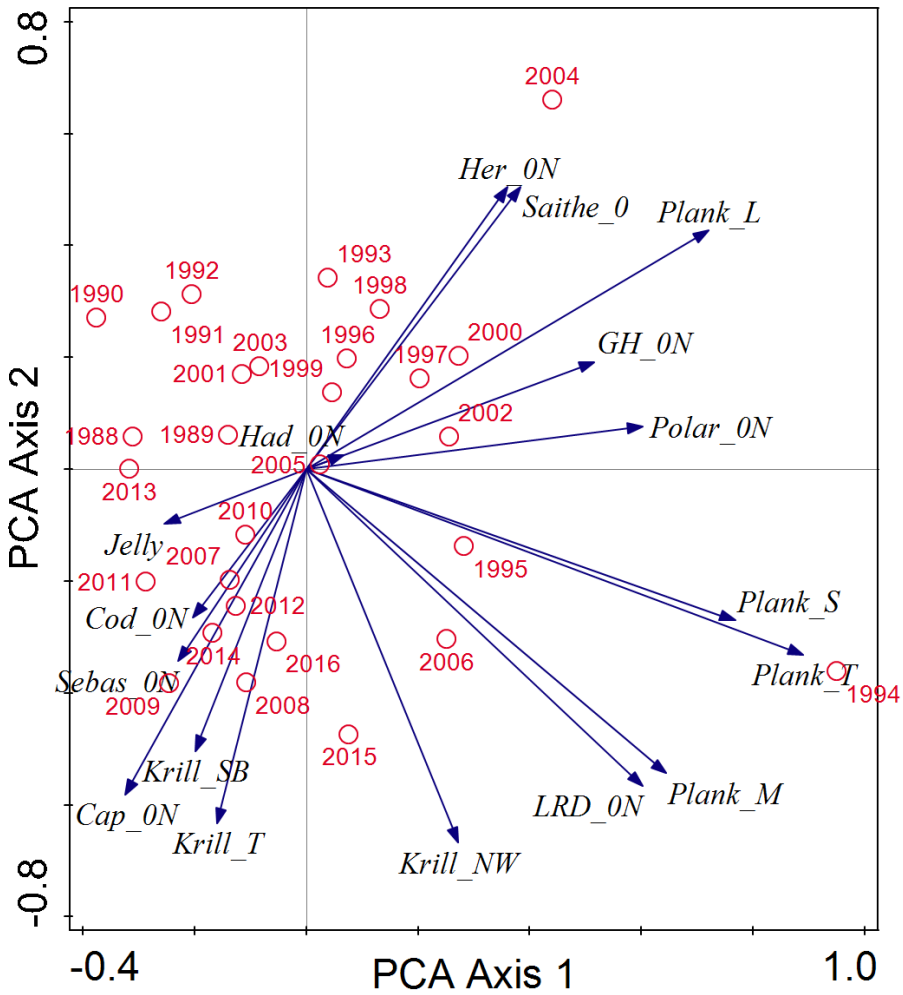


Figure 2.2.3. Results from PCA on 16 biotic variables: zooplankton biomass, abundance indices of krill, amount of jellyfish, and abundance of 0-group fish. Biplot of variables and years plotted on PC-1 and PC-2.

Three of the zooplankton biomass variables fell in the lower right-hand corner (total, small and medium size fractions), while the three krill variables pointed downwards associated with negative values along PC-2. Capelin, cod and redfish 0-group pointed in the same direction, whereas 0-group of herring and saithe pointed in the opposite direction. 0-group of Greenland halibut and polar cod were aligned with positive direction of PC-1, whereas 0-group of long rough dab fell in the 'southeast' sector aligned with the medium size fraction of zooplankton biomass.

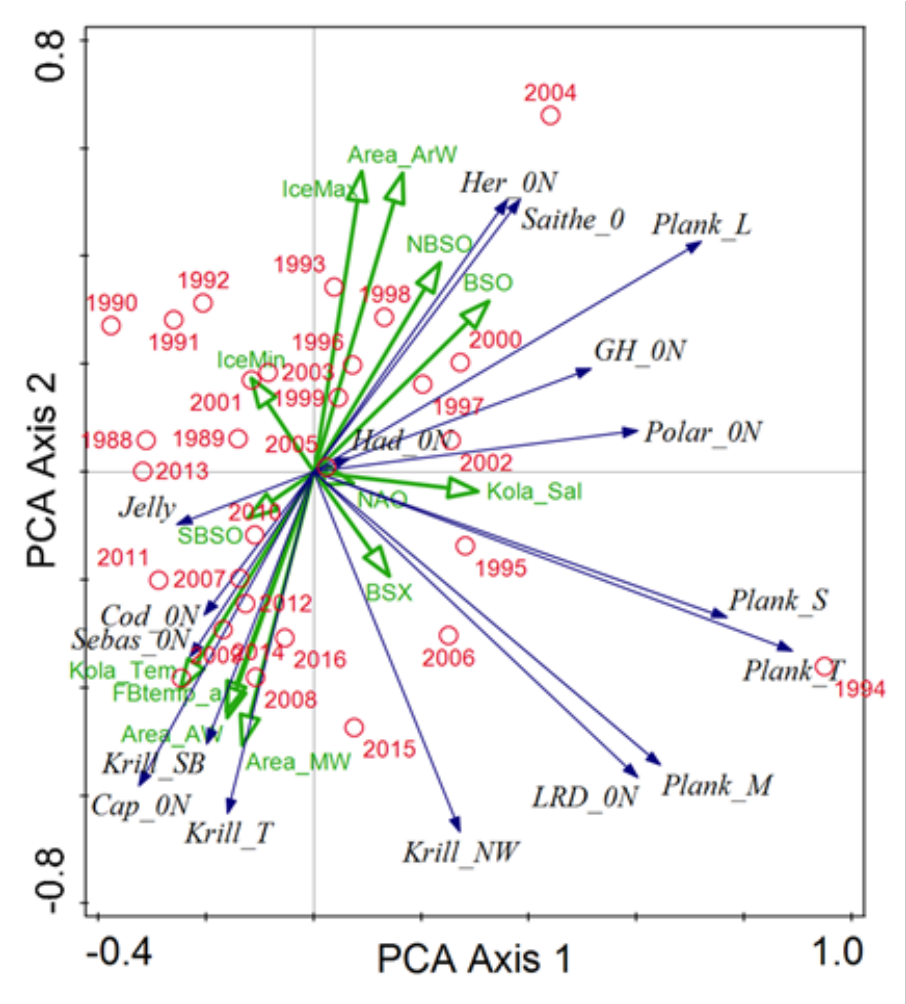


Figure 2.2.4. Same as Figure 1.2.3 but with environmental (abiotic) variables projected as passive variables onto the biplot.

When the set of abiotic variables were projected as passive explanatory variables onto the PCA biplot for the zooplankton, krill and 0-group fish, they aligned along an axis rotated about 30° to the right relative to the vertical PC-2 axis. The distinction between the warming and dynamic axes of the PCA for the abiotic variables (Figure 2.2.1) was less pronounced in this representation where the space was to some extent collapsed into a plane. The warming trend, revealed by the variables for areas of Atlantic and mixed waters and temperatures at the BSO and Kola sections, coincided with the variables for krill (total and southern Barents Sea) and 0-groups of capelin, cod, and redfish. In the opposite direction, associated with the cold side of the trend revealed by area of Arctic water and winter ice extent, were 0-group herring and saithe. These patterns reflected generally increasing trends with good recruitment of cod and capelin in the recent warm years, whereas recruitment of herring and saithe have been generally poor.

The projection of the years shows the low zooplankton biomass years in the early 1990s (1990–1992) in the upper left side, while the peak zooplankton biomass year 1994 is an extreme on the lower right (Figures 2.2.3 and 2.2.4). The recent warm years after 2006 are all located in the lower left part of the plot (except 2015 which is slightly on the right). 2004 is another extreme year on the opposite side in the upper-right corner.

PCA – Fish variables

A PCA analysis was run with 23 variables reflecting stock size, growth and maturation of cod (7 variables), haddock (6 variables), capelin (5 variables), polar cod (2 variables), and herring, long-rough dab and shrimp (1 variable each). A biplot with variables and years shown on PC-1 and PC-2 is given as Figure 2.2.5. In this case the environmental variables retained more of their configuration when projected onto the biplot, with the 'warming trend' variables oriented along PC-1 and the 'flux' variables oriented along PC-2 (Figure 2.2.6).

The fish variables formed several 'bundles' or clusters on the biplot. The capelin stock size grouped with weight-at-age of cod (3 and 5 years old) in upper right hand side of the plot where also some years with peak capelin stock (1990–1992) were projected. Another group of variables clustered around 4 o'clock in the diagram, consisting of the stock sizes of cod and haddock (3+, and haddock SSB). In the opposite direction were cod maturing at age 7 and cod weight-at-age as 8 years old, as well as shrimp mortality. The stock of juvenile herring (1–2 years old) was also oriented in this opposite direction. The recent years after 2007 grouped in the lower left portion of the diagram along with the variables for cod and haddock stocks.

Another group of variables that clustered in the lower left part of the biplot were related to growth of capelin as well as fishing mortality of cod and haddock. Years which projected in this part of the diagram were low capelin years associated with high growth rates of capelin (1988–1989, 1994–1998, 2004–2006).

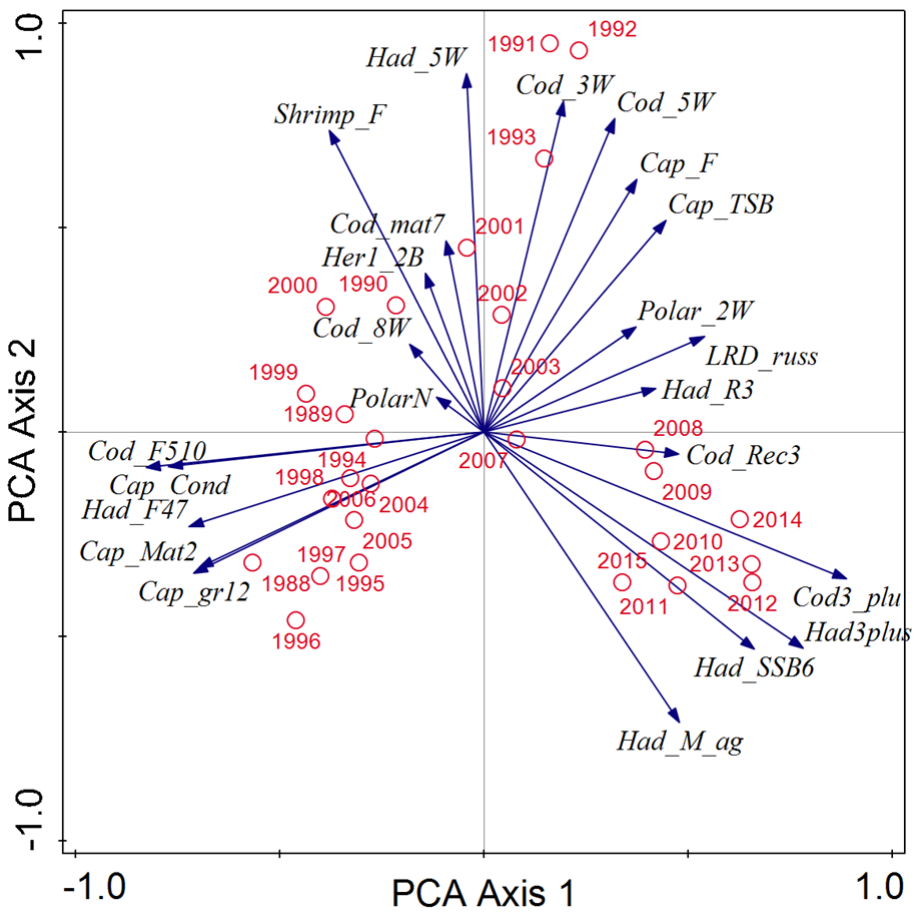


Figure 2.2.5. Results from PCA on 23 biotic variables for fish related to stock size, recruitment, maturation, growth, and mortality of different species fish (cod, haddock, capelin, herring, polar

cod, saithe, Greenland halibut, and long-rough dab). Biplot of variables and years plotted on PC-1 and PC-2.

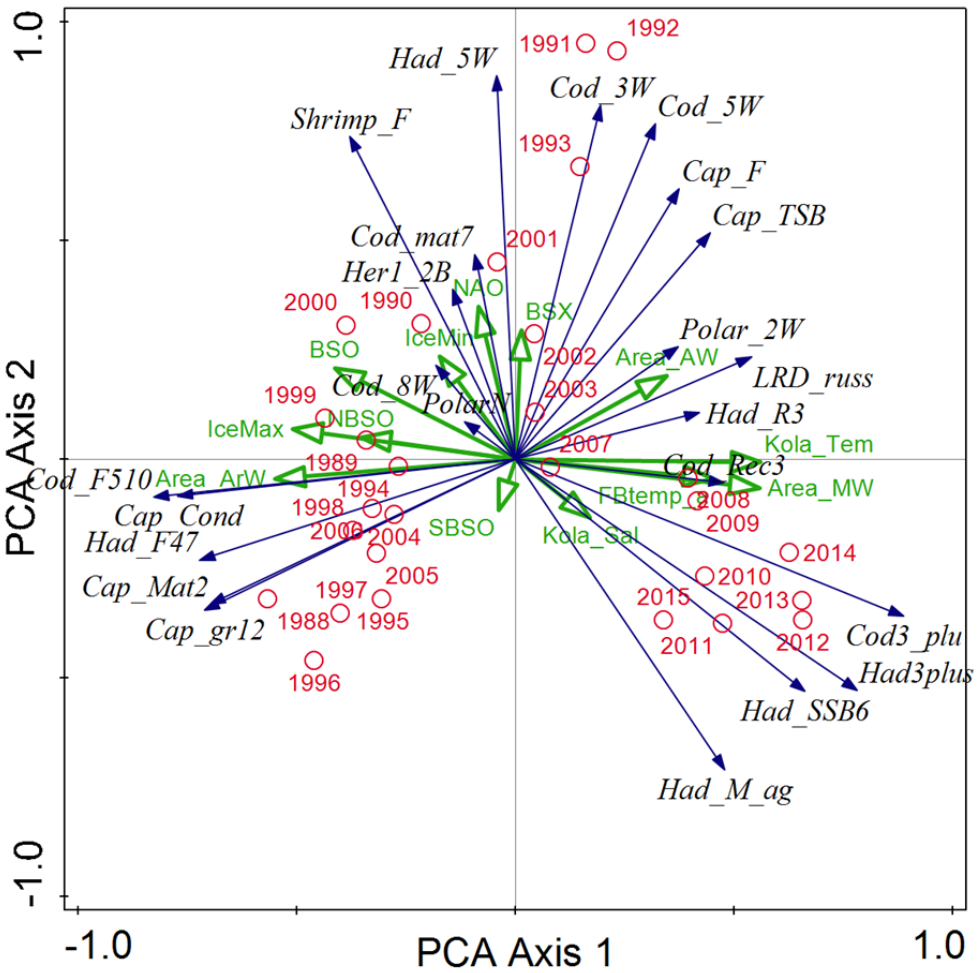


Figure 2.2.6. Same as Figure 2.2.4 but with environmental (abiotic) variables projected as passive variables onto the biplot.

The overall change in the Barents Sea has been from cold conditions, low demersal stocks levels and high fishing pressure in the 1980's to warm conditions (Chapter 3.1), large demersal stocks (Chapter 3.6) and lowered fishing pressure (Chapter 3.9.1), in recent years (Figure 2.2.7).

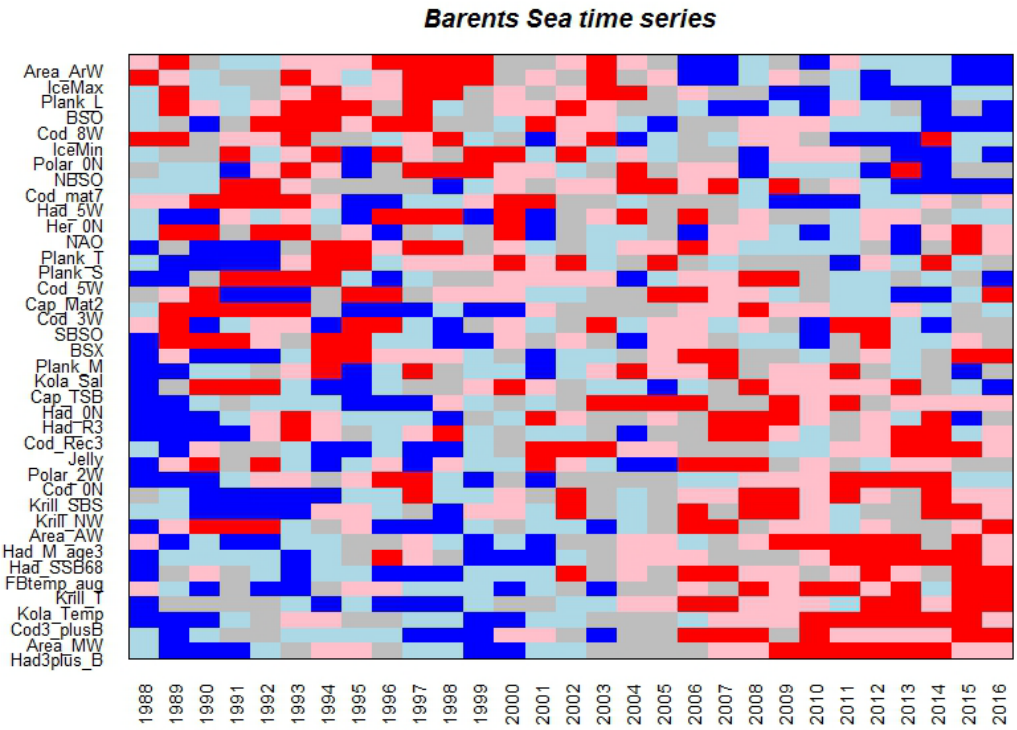


Figure 2.2.7. Time-series of annual means of abiotic and biotic variables in the Barents Sea sorted by trend. Blue means value below the 1988-2016 average and red means above the 1988–2016 average.

2.3 Barents Sea ecosystem vulnerability assessment

A fundamental challenge in developing IEAs that reliably inform EBM is to provide assessment tools that are process - oriented and address whole ecosystem properties, such as biodiversity, that closely relate to ecosystem vulnerability. The above challenge will require an integration of information on demographic characteristics, ecological interactions and ecosystem functions of component species. Trait-based approaches and foodweb analysis can provide the required information, which, if properly integrated and communicated, will inform EBM on fundamental aspects of ecosystem vulnerability (Levin and Lubchenco, 2008).

The vulnerability of an ecosystem to environmental stress is a function of the sensitivity and adaptive capacity of its components, i.e. species, and of the whole. Among the properties that stand out as core components of ecosystem robustness are functional diversity, functional redundancy and foodweb modularity (Levin and Lubchenco, 2008). To address the areal based Ecosystem Vulnerability Assessment of the Barents Sea demersal resources, we relied on the integration of trait-based approaches and foodweb analysis to assess species and ecosystem properties affecting ecosystem vulnerability. Trait-based approaches break down information on life history, behaviour, and other relevant phenotypic characteristics into response traits and effect (or functional) traits. Response traits determine the vulnerability of a species to a specific environmental stressor like fishing, whereas effect traits provide information on ecosystem functions of species (Lavorel and Garnier, 2002). Response traits data allow to rank species according to their vulnerability, an approach that has been particularly fruitful in the context of assessment of vulnerability to fishing (Le Quesne and Jennings, 2012). Rank data can be averaged across species present in a given area or location to provide a measure of community vulnerability (Wiedmann *et al.*, 2014a). Effect traits data allow to classify species according to their ecosystem functions and provide the basis for the

assessment of collective properties of ecosystems such as functional diversity, which affects the adaptive capacity of ecosystems, and functional redundancy, which affects the sensitivity of ecosystems (Wiedmann *et al.*, 2014b). Finally, foodweb data allow to measure species properties, such as centrality, and ecosystem properties, such as foodweb modularity, that depend on the configuration of ecological interactions connecting ecosystem components.

In 2015, the project VULRES performed a vulnerability analysis of the benthos, demersal fish and pelagic fish of the Barents Sea ecosystem. Three prominent properties of Barents Sea demersal fish communities influencing ecosystem vulnerability to trawling all displayed substantial spatial variability with clear geographical patterns (Figure 2.3.1). Through time (2004–2012), the spatial patterns changed, displaying trends associated with increasing water temperatures and decreasing sea ice coverage. Fish sensitivity to trawling, assessed on the basis of life-history characteristics of fish that affect demographic growth rates, showed a sharp gradient, with average fish sensitivity (averaged ranks) at stations falling rapidly in a Northeast direction (Figure 2.3.1). Fish functional diversity, estimated on the basis of a functional traits dendrogram, displayed a clear gradient with diversity dropping towards the East (Figure 2.3.1). Finally, the average number of fish feeding links (degree centrality) showed a strong reduction towards the North indicating that there is a lower foodweb connectivity in the Arctic reaches of the Barents Sea (Figure 2.3.1).

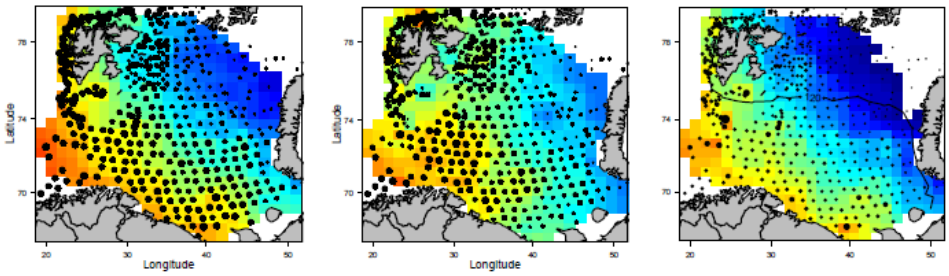


Figure 2.3.1. Barents Sea demersal fish community in 2004. Fish sensitivity to trawling (left panel), functional diversity (mid panel) and foodweb degree centrality (right panel). Highest values in red, lowest values in blue (circle size is proportional to measured value at a station).

The temporal trends showed a systematic increase in sensitivity, functional diversity and degree centrality towards the North, with the Arctic reaches of the Barents Sea experiencing the most rapid and extensive changes in ecosystem vulnerability (Figure 2.3.2).

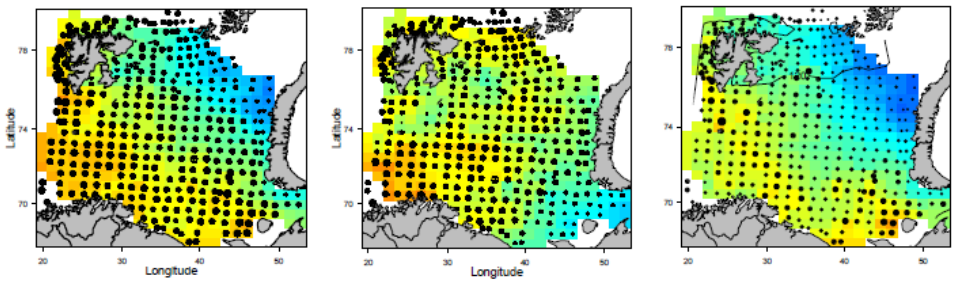


Figure 2.3.2. Barents Sea demersal fish community in 2012. Fish sensitivity to trawling (left panel), functional diversity (mid panel) and foodweb degree centrality (right panel). Highest values in red, lowest values in blue (circle size is proportional to measured value at a station).

The pelagic fish community (pelagic trawl catches) also displayed extensive spatial variation with regard to the above three properties, with patterns partly resembling those observed for demersal fish (Figure 2.3.3). The temporal changes in spatial patterns were also substantial, and apparently related to the climatic variability and to the fluctuating abundances of some of the dominant pelagic fish species.

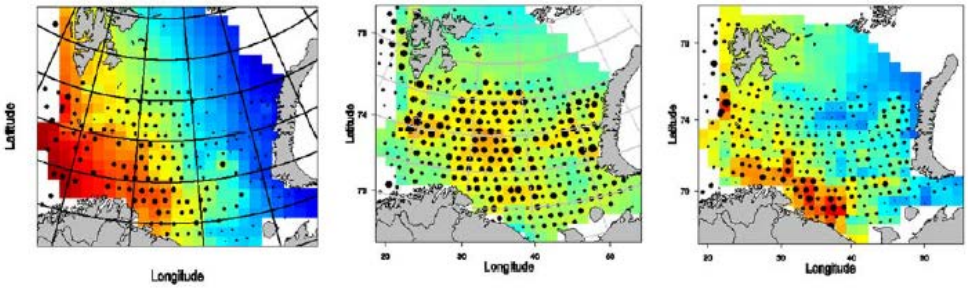


Figure 2.3.3. Barents Sea pelagic fish community in 2004. Fish sensitivity to trawling (left panel), functional diversity (mid panel) and foodweb degree centrality (right panel). Highest values in red, lowest values in blue (circle size is proportional to measured value at a station).

The VULRES findings on Barents Sea ecosystem vulnerability assessment highlight strong spatial heterogeneity in vulnerability of all functional groups currently included in the analyses. Further, the temporal trends show a strong influence of climate variability resulting in systematic change in spatial patterns of vulnerability. The findings have clear implications for an ecosystem approach to spatial management of the Barents Sea.

3 Current state of the Barents Sea ecosystem components

3.1 Oceanographic and climatic conditions

The Barents Sea is a shelf sea of the Arctic Ocean. Being a transition area between the North Atlantic and the Arctic Basin, it plays a key role in water exchange between them. Atlantic waters enter the Arctic Basin through the Barents Sea and the Fram Strait (Figure 3.1.1). Variations in volume flux, temperature and salinity of Atlantic waters affect hydrographic conditions in both the Barents Sea and the Arctic Ocean and are related to large-scale atmospheric pressure systems.

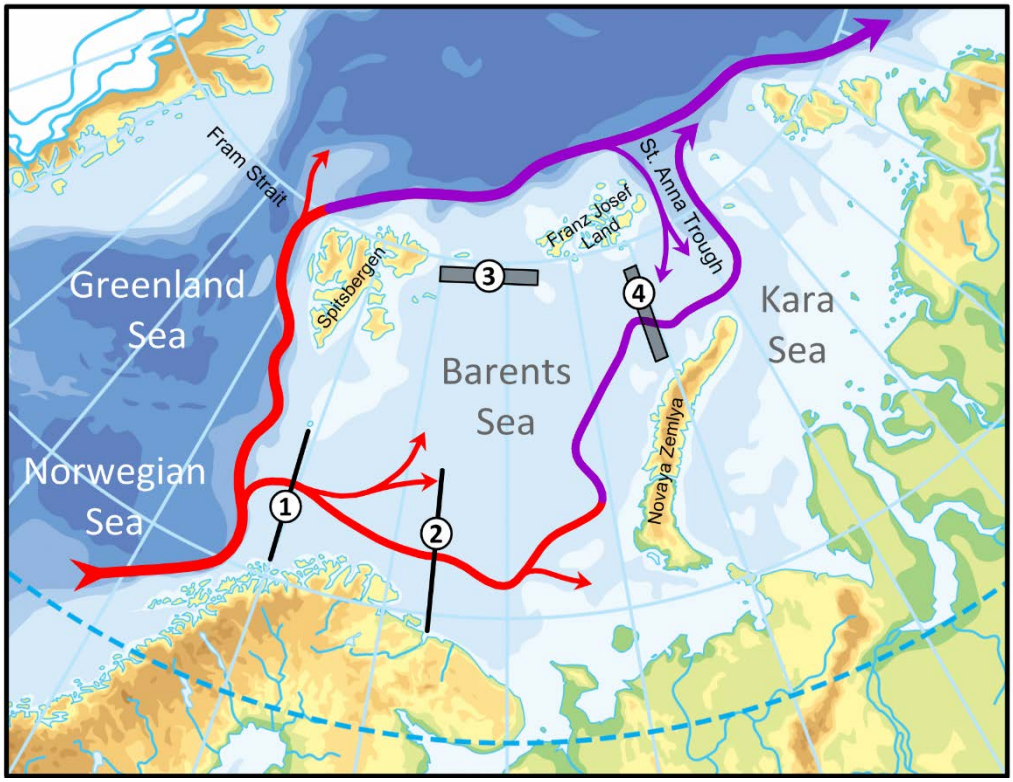


Figure 3.1.1. The main paths of Atlantic waters in the Barents Sea as well as Fugløya–Bear Island Section (1), Kola Section (2) and boxes in the northwestern (3) and northeastern (4) Barents Sea.

Air pressure, wind and air temperature

In 2016, winter (December–March) NAO index dropped to 1.01 after the third highest (since 1899) positive value of 1.87 observed in 2015. Over the Barents Sea, easterly winds prevailed in the first half of the year and southwesterly winds – in the second half. In 2016, the number of days with winds more than 15 m/s was larger than usual most of the year. It was less than or close to normal only in January (western and central parts of the sea) and April (eastern part). In summer 2016, the storm activity in the Barents Sea was the highest since 1981.

Air temperature (http://nomad2.ncep.noaa.gov) averaged over the western (70–76°N, 15–35°E) and eastern (69–77°N, 35–55°E) Barents Sea showed that positive air temperature anomalies prevailed over the sea during 2016 (Figure 3.1.2). Higher positive anomalies (up to 7.5°C in February) were found in the east. The positive anomalies in the western part of the sea in May and in the eastern part in February, July and September were the highest since 1948. As a result, the 2016 annual mean air temperature anomalies in the western and eastern Barents Sea were also the highest since 1948.

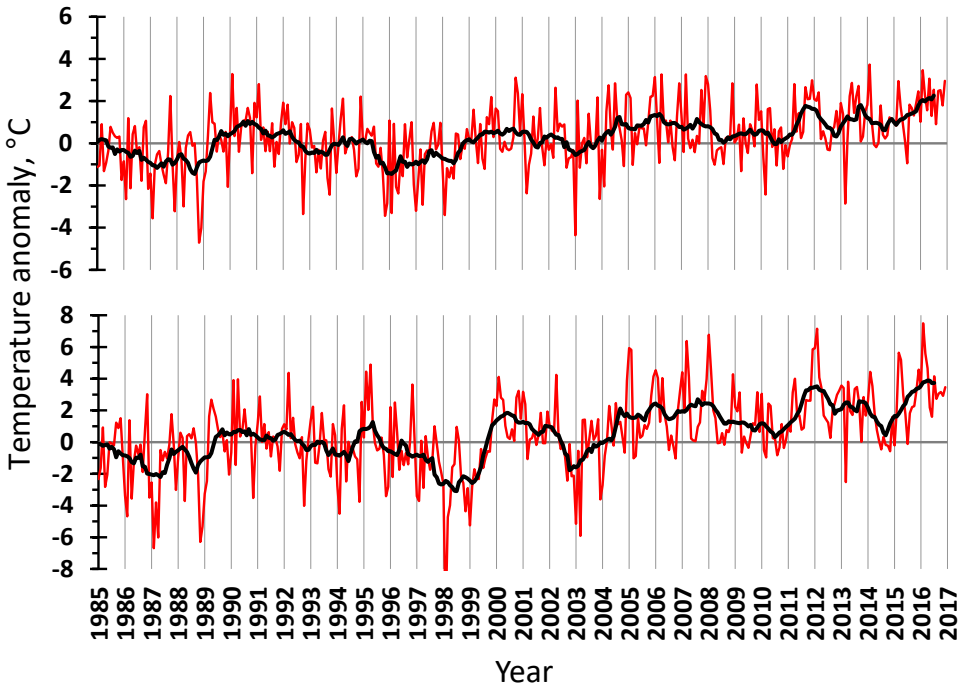


Figure 3.1.2. Air temperature anomalies in the western (upper) and eastern (lower) Barents Sea in 1985–2016. The red line shows monthly values, the black one – 11-month running means.

Ice conditions

At the end of 2015 and beginning of 2016, meteorological conditions over the Barents Sea resulted in decreasing the sea ice coverage. Ice formation was going very slowly at the beginning of 2016; the ice coverage (expressed as a percentage of the sea area) was 17–25% lower than normal (Figure 3.1.3). In March–April, the seasonal maximum of ice coverage, there was almost no increase in the ice coverage compared to that early in the year: in January and February, the ice coverage was 32 and 30% respectively, whereas, in March and April, it was 32 and 31% which was 26–30% lower than normal (Figure 3.1.4). From March to July, the ice coverage of the Barents Sea was the lowest since 1951. From July to September, there was no ice in the Barents Sea. In July, it happened for the first time since 1951 (see Figure 3.1.4). In autumn, freezing started in the northern Barents Sea in October (see Figure 3.1.4), when ice appeared near the Franz Josef Land Archipelago; the ice coverage was 2% which was 13% less than normal. In November and December, the ice coverage was 25–26% less than average and it was the lowest since 1951. Overall, the 2016 annual mean ice coverage of the Barents Sea was the lowest since 1951 being 22% lower than normal and 7% lower than in 2015.

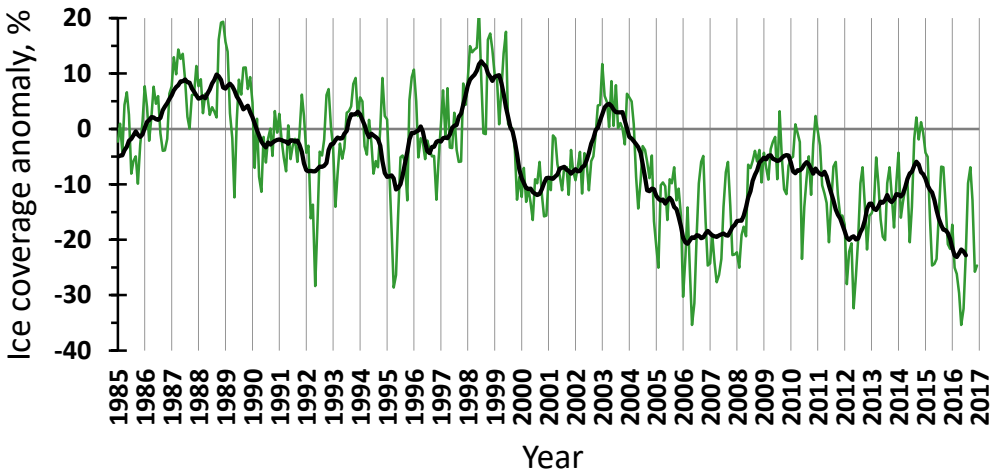


Figure 3.1.3. Ice coverage anomalies in the Barents Sea in 1985–2016. The green line shows monthly values, the black one – 11-month running means.

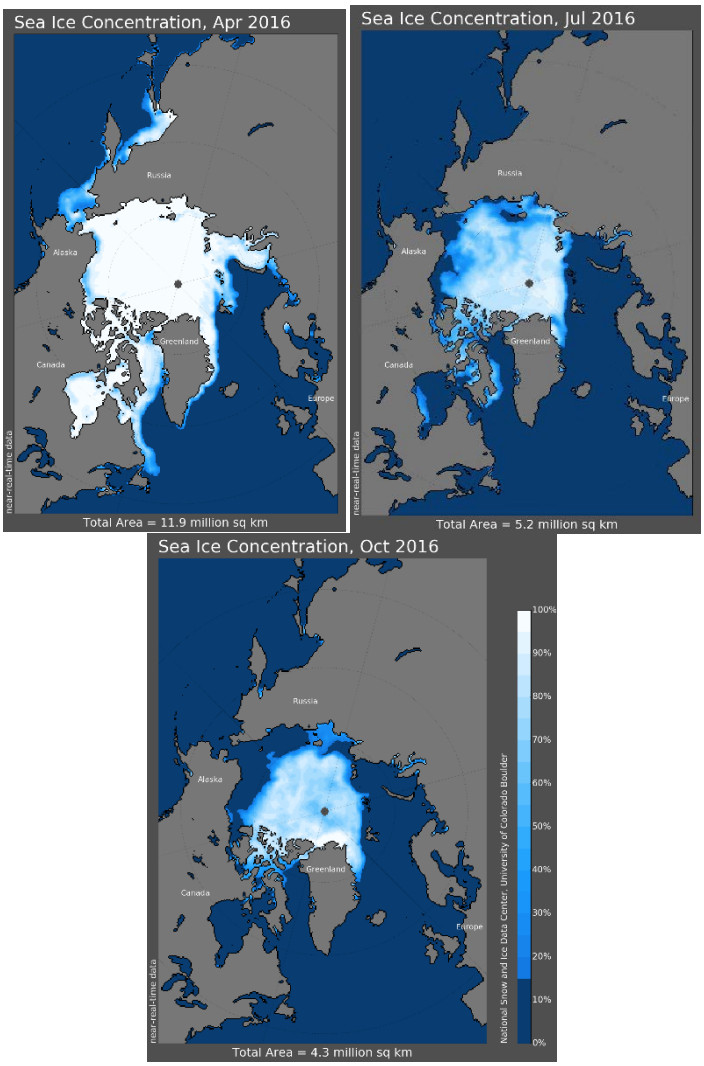


Figure 3.1.4. Ice concentrations in April, July and October 2016.

Currents and transports

The volume flux into the Barents Sea varies with periods of several years, and was significantly lower during 1997–2002 than during 2003–2006. In 2006, the volume flux

was at a maximum during winter and very low during fall. After 2006, the inflow has been relatively low. Throughout 2015 and in winter 2016, the inflow was around 1 Sv larger than the long-term average (Figure 3.1.5). The exception was March 2016, when the volume flux was temporarily smaller than average. The dataseries currently stops in May 2016, thus no information about summer, fall and early winter 2017 is yet available.

Complementing the observed volume flux, numerical modelling suggests that the volume flux into the Barents Sea through the BSO was above average during February and March followed by a drop below average in April, as opposed to the temporary low observed in March (Figure 3.1.6). In the months June through August, the modelled eastward volume transport was generally below average, with the lowest value in June when the flux was 2 standard deviations below the monthly average. Modelled transports are not yet available for the period September through December. Similarly to the inflow to the western Barents Sea, the modelled outflow through the northeastern Barents Sea (BSX) was above normal during February and March, and close to or lower than normal during the period April through August. In the SBSO, between the Kola Section and Novaya Zemlya, the eastward volume transport was generally close to or below average throughout the year, except for a strong uptick of 0.2 Sv, corresponding to 1 standard deviation, in August. In the NBSO, between Svalbard and Franz Josef Land, the volume transport (positive southward) was more variable, but with a strongly negative anomaly in April. Note, however, that the model has been found to be accurate for annual mean and standard deviation of the volume transports, while the modelled monthly averages are usually weakly, yet statistically significantly correlated with observations (Lien *et al.*, 2013, 2016).

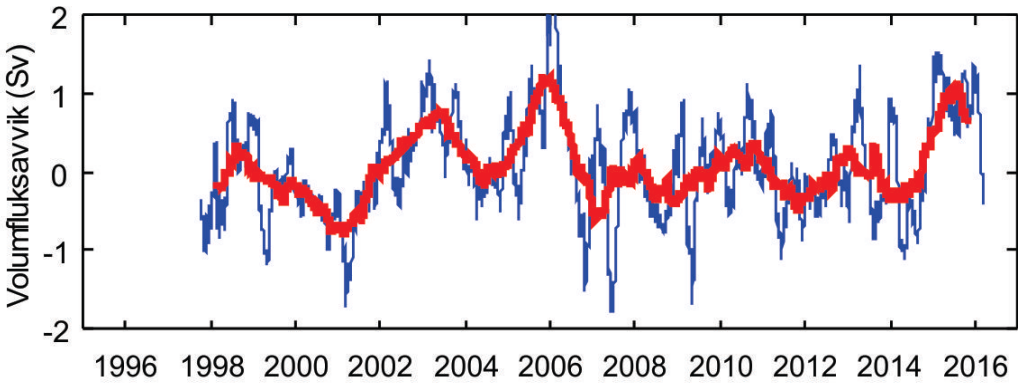


Figure 3.1.5. Volume flux anomalies through the Fugløya–Bear Island Section.

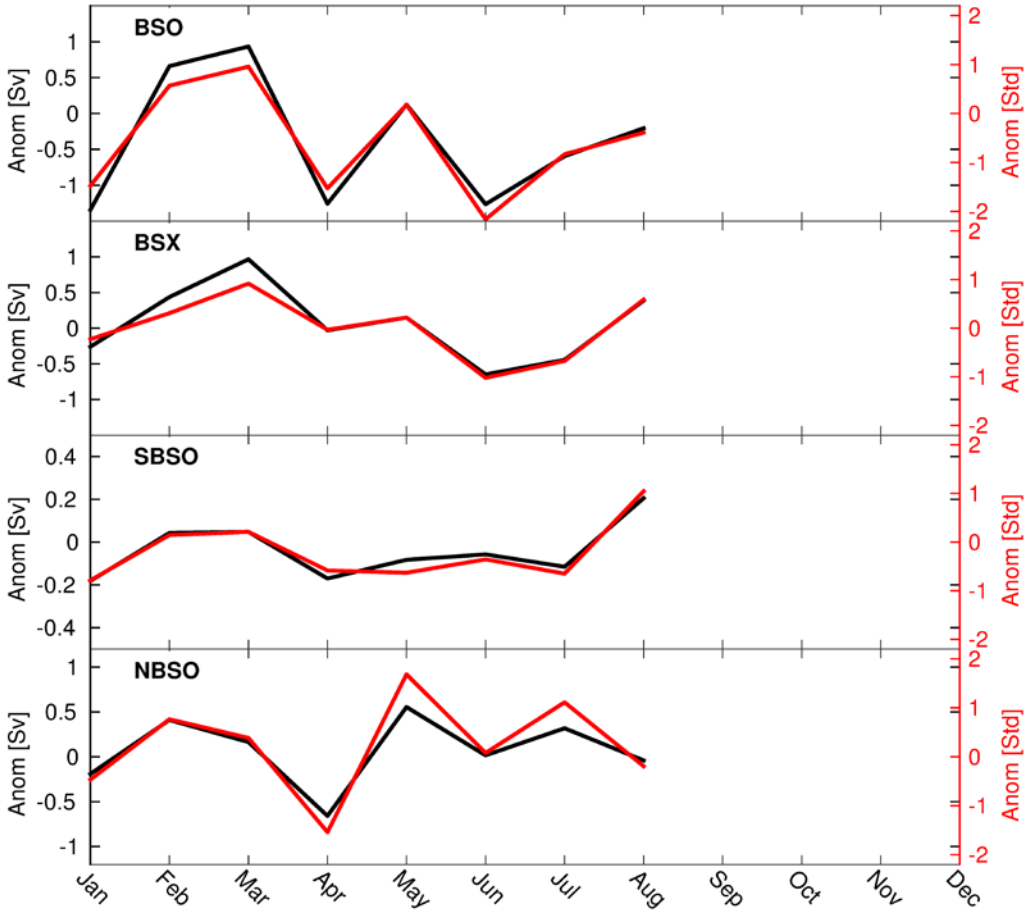


Figure 3.1.6. Modelled volume flux anomalies relative to 1961–1990 average.

Temperature and salinity in standard sections and northern boundary regions

The Fugløya–Bear Island Section covers the inflow of Atlantic and Coastal water masses from the Norwegian Sea to the Barents Sea, while the Kola Section covers the same waters in the southeastern Barents Sea. Note a difference in the calculation of the temperatures in these sections; in the Fugløya–Bear Island Section the temperature is averaged over the 50–200 m depth layer while in the Kola Section the temperature is averaged from 0 to 200 m depth. In 2016, the temperature of the Atlantic Water flowing into the Barents Sea through the Fugløya–Bear Island Section (50–200 m) was 1°C above the long-term average early in the year and around 0.7°C above the long-term mean in summer and autumn (Figure 3.1.7). On average, the 2016 temperature was comparable to the temperature in 2015 (Figure 3.1.7).

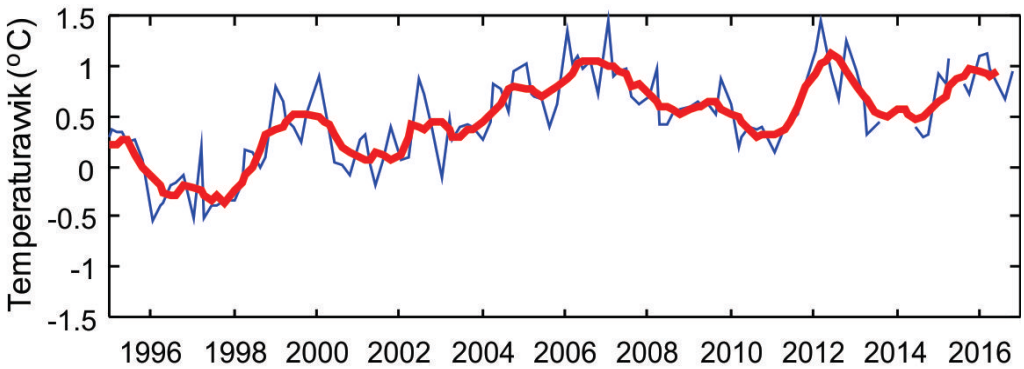


Figure 3.1.7. Temperature anomalies in the 50–200 m layer in the Fugløya–Bear Island Section.

According to the available observations along the Kola Section, from January to May 2016, coastal and Atlantic waters in the 0–200 m layer had large positive temperature anomalies exceeding 1°C (Figure 3.1.8). The temperature anomalies in the coastal waters (March–May, November), the Murmansk Current (January, March, April) and the Central branch of the North Cape Current (January) were the highest since 1951. As a result, January–May averaged temperature was the highest in the coastal waters and as large as a record-high value of 2012 in the Atlantic waters of the central part of the section. Compared to 2015, the coastal and Atlantic waters were warmer (by up to 0.8°C) during all the observation period in 2016.

In 2016, the salinity of the coastal and Atlantic waters (the Murmansk Current) in the Kola Section was lower than normal and compared to 2015 (Figure 3.1.8). The coastal waters were much fresher than normal with negative salinity anomalies reaching –0.3 in the first half of the year. The salinity of the Atlantic waters in the outer part of the section (the Central branch of the North Cape Current) was close to both the average and that in the previous year.

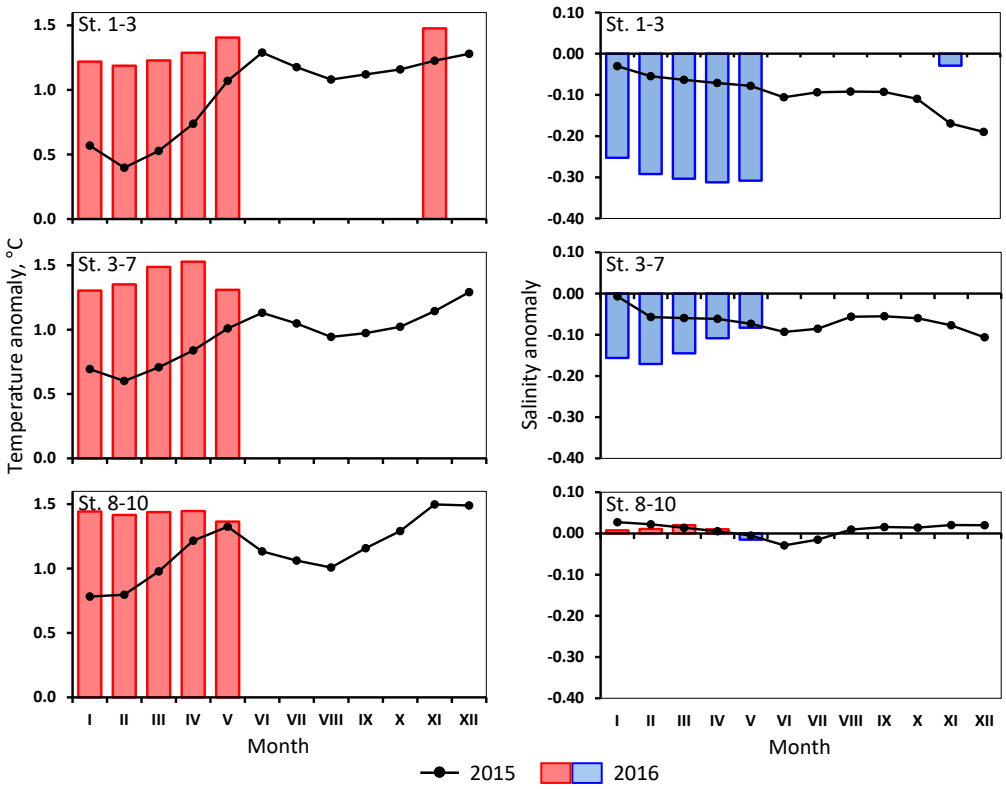


Figure 3.1.8. Monthly mean temperature (left) and salinity (right) anomalies in the 0–200 m layer in the Kola Section in 2015 and 2016. St. 1–3 – Coastal waters, St. 3–7 – Murmansk Current, St. 8–10 – Central branch of the North Cape Current.

Spatial variation in temperature and salinity (surface, 100 m and bottom)

Sea surface temperature (SST) (http://iridl.ldeo.columbia.edu) averaged over the southwestern (71–74°N, 20–40°E) and southeastern (69–73°N, 42–55°E) Barents Sea showed that positive SST anomalies prevailed in both areas during 2016 (Figure 3.1.9). The positive anomalies in the east were much higher than in the west (by up to 3.7–4.0°C in July–August). The SST anomalies in the southwestern part of the sea in October–December, as well as in the southeastern part in February–May and July–December were the highest since 1982. As a result, the 2016 annual mean SST anomalies in the

southwestern and southeastern parts of the Barents Sea were also the highest since 1982.

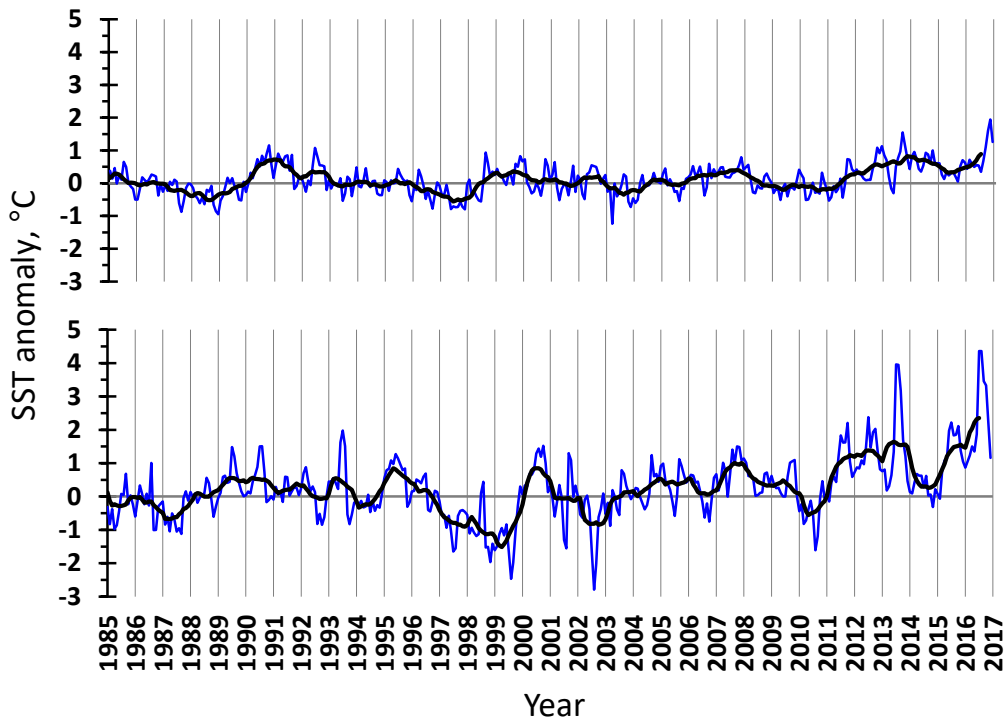


Figure 3.1.9. Sea surface temperature anomalies in the western (upper) and eastern (lower) Barents Sea in 1985–2016. The blue line shows monthly values, the black one – 11-month running means.

In August–September 2016, the joint Norwegian-Russian ecosystem survey was carried out in the Barents Sea. The surface temperature was on average 1.8°C higher than the long-term means (1931–2010) all over the Barents Sea (Figure 3.1.10). The largest temperature anomalies (>2.5°C) were mainly observed in the eastern and southeastern parts of the sea and resulted from anomalously warm air masses over those areas. The smallest positive anomalies (<0.5°C) were found in the southwestern Barents Sea. Compared to 2015, the surface temperature was higher (by 1.1°C on average) in most of the sea (two thirds of the surveyed area), especially in the northwestern and southeastern parts. The surface waters were on average 0.4°C colder than in 2015 mostly in the southwestern and central Barents Sea.

Arctic waters were mainly found, as usual, in the 50–100 m layer north of 77°N. The temperature at 100m depth was higher than the long-term means (on average, by 1.5°C) all over the Barents Sea (Figure 3.1.11). Compared to 2015, the 100 m depth temperature was higher (on average, by 0.5°C) in most of the sea (five sixths of the surveyed area). Negative differences in temperature between 2016 and 2015 (–0.3°C on average) were found only in some local areas.

The bottom temperature was in general 1.6°C above average throughout the Barents Sea (Figure 3.1.12). The largest temperature anomalies (>2.5°C) were mainly observed over the Spitsbergen Bank and in the Pechora Sea. Compared to 2015, the bottom temperature was on average 0.8°C higher almost all over the Barents Sea. Small negative differences in temperature between 2016 and 2015 were on average –0.2°C and were found only in about 6% of the surveyed area (mainly in the southwestern part of the sea).

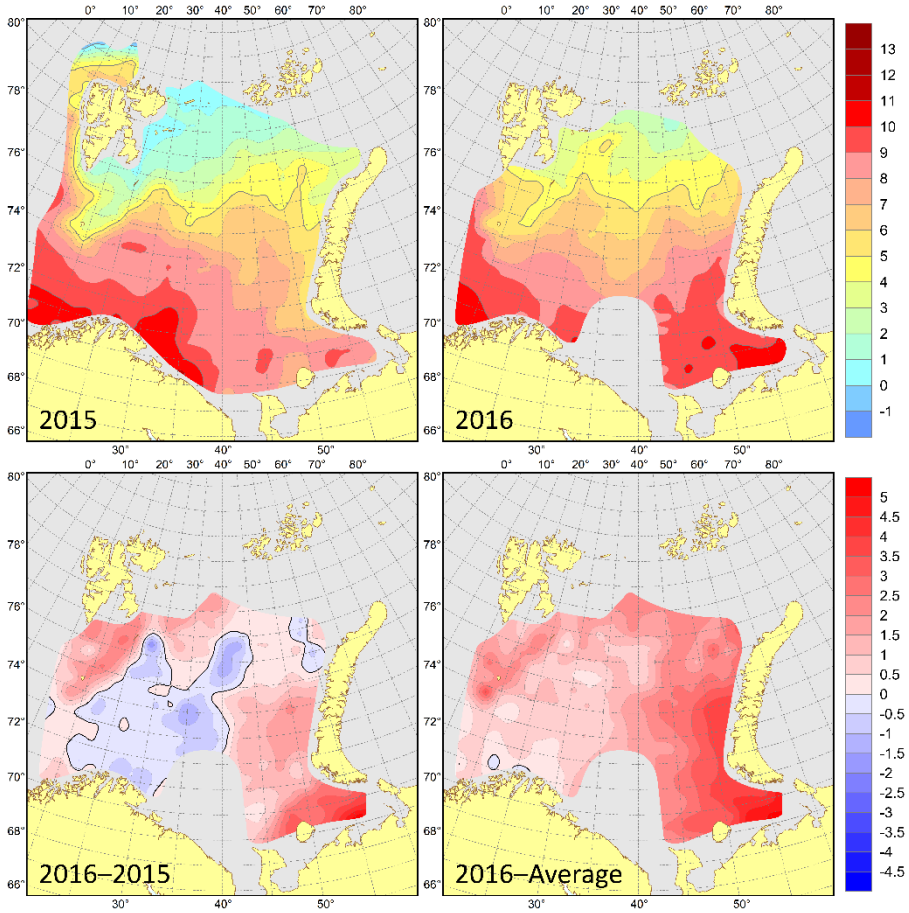


Figure 3.1.10. Surface temperatures (°C) in August–September 2015 (upper left) and 2016 (upper right), their differences between 2016 and 2015 (lower left, °C) and anomalies in August–September 2016 (lower right, °C).

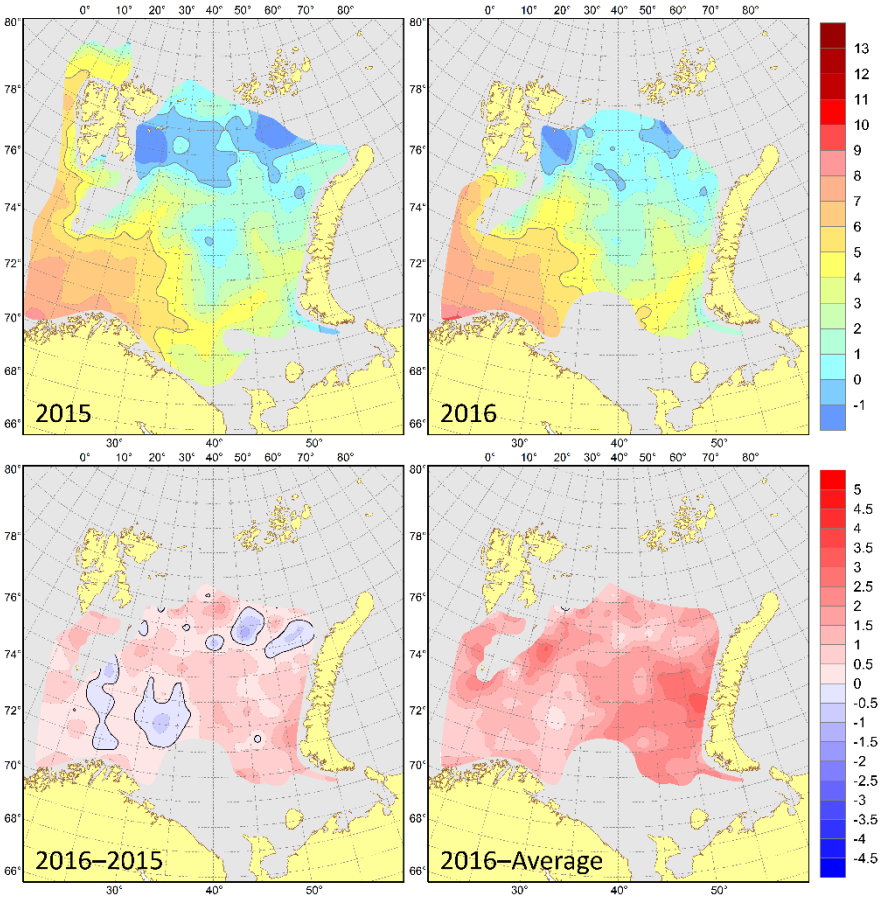


Figure 3.1.11. 100 m depth temperatures (°C) in August–September 2015 (upper left) and 2016 (upper right), their differences between 2016 and 2015 (lower left, °C) and anomalies in August–September 2016 (lower right, °C).

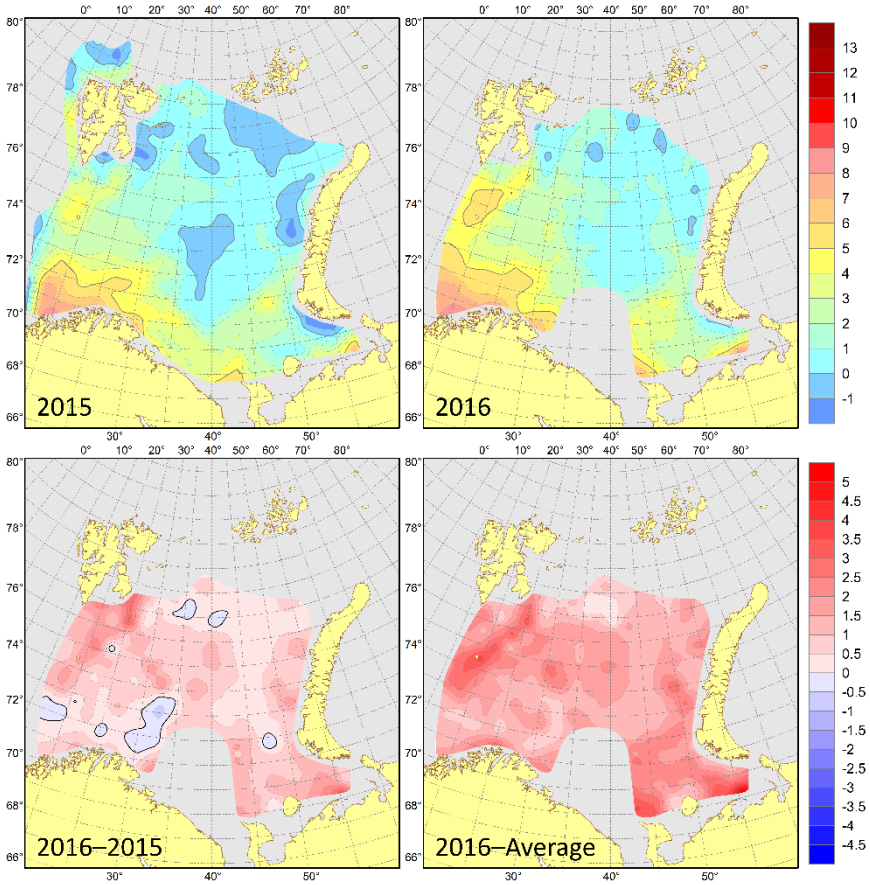


Figure 3.1.12. Bottom temperatures (°C) in August–September 2015 (upper left) and 2016 (upper right), their differences between 2016 and 2015 (lower left, °C) and anomalies in August–September 2016 (lower right, °C).

The surface salinity was on average 0.5 higher than the long-term mean (1931–2010) almost all over the Barents Sea with the largest positive anomalies (>0.5) mainly north of 75°30'N (especially in the area of the Great Bank) and east of 48°E (especially west and south of Southern Island of the Novaya Zemlya Archipelago) (Figure 3.1.13). The large negative anomalies were only observed north of Kolguev Island. In August–September 2016, the surface waters were saltier than in 2015 in about 60% of the surveyed area with the largest positive differences in the Pechora Sea, along the Novaya Zemlya Archipelago and south of the Spitsbergen Archipelago. Negative differences in salinity between 2016 and 2015 were mainly found in the central and northeastern Barents Sea as well as north of Kolguev Island.

The 100 m salinity was higher than the long-term means (on average, by 0.1) in about 80% of the surveyed area (Figure 3.1.14). Small negative anomalies were only observed in some areas, especially in the southwestern and southeastern Barents Sea. Compared to 2015, negative differences in salinity between 2016 and 2015 prevailed in the Barents Sea and occupied almost two thirds of the surveyed area. The positive differences were mainly found in the southwestern part of the sea.

The bottom salinity was slightly higher than the long-term means (by up to 0.1) in about four fifths of the surveyed area and it was close to that in 2015 (Figure 3.1.15). Negative anomalies were mainly found in the southeastern Barents Sea, especially in the Pechora Sea. The largest differences in salinity between 2016 and 2015 were observed in shallow waters between Bear and Hopen Islands (positive values) and in the southeastern Barents Sea (negative values).

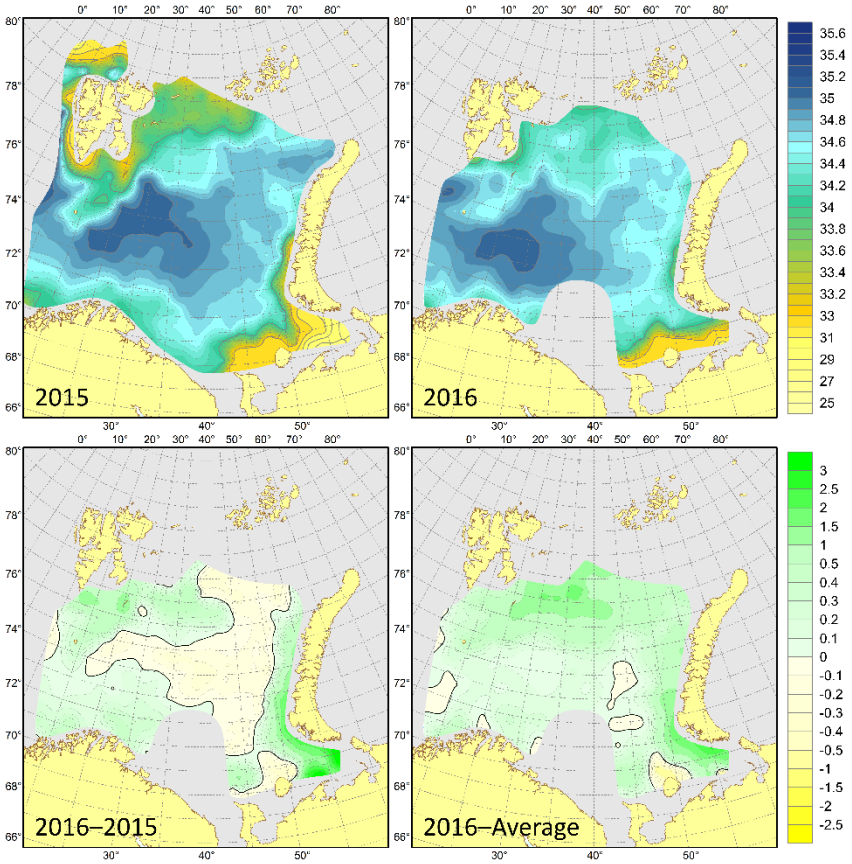


Figure 3.1.13. Surface salinities in August–September 2015 (upper left) and 2016 (upper right), their differences between 2016 and 2015 (lower left) and anomalies in August–September 2016 (lower right).

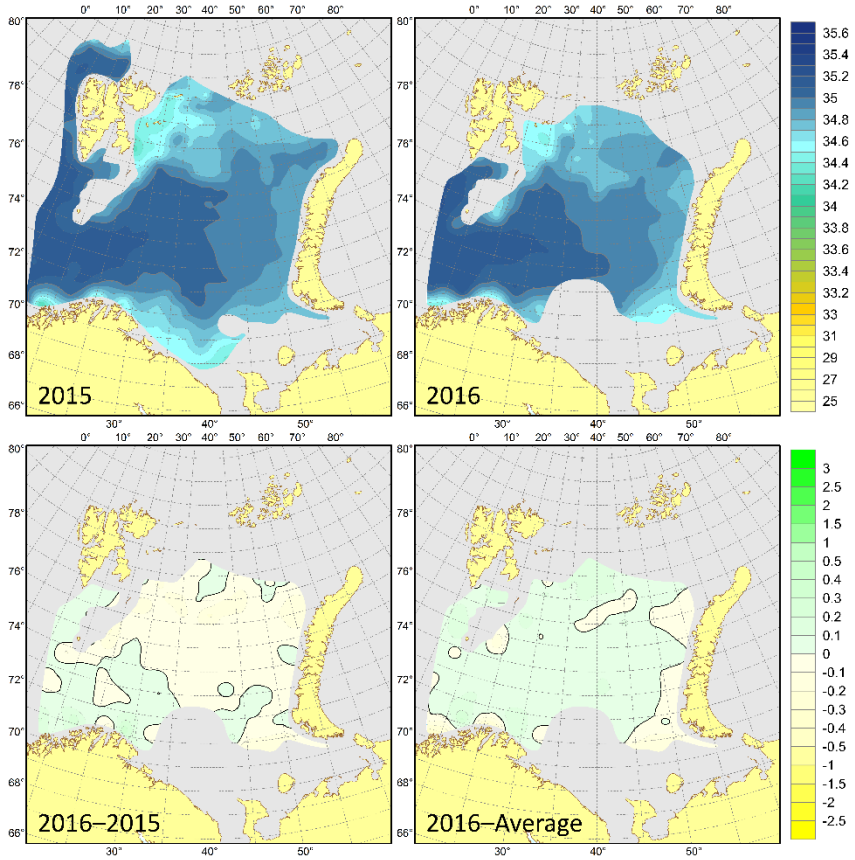


Figure 3.1.14. 100 m salinities in August–September 2015 (upper left) and 2016 (upper right), their differences between 2016 and 2015 (lower left) and anomalies in August–September 2016 (lower right).

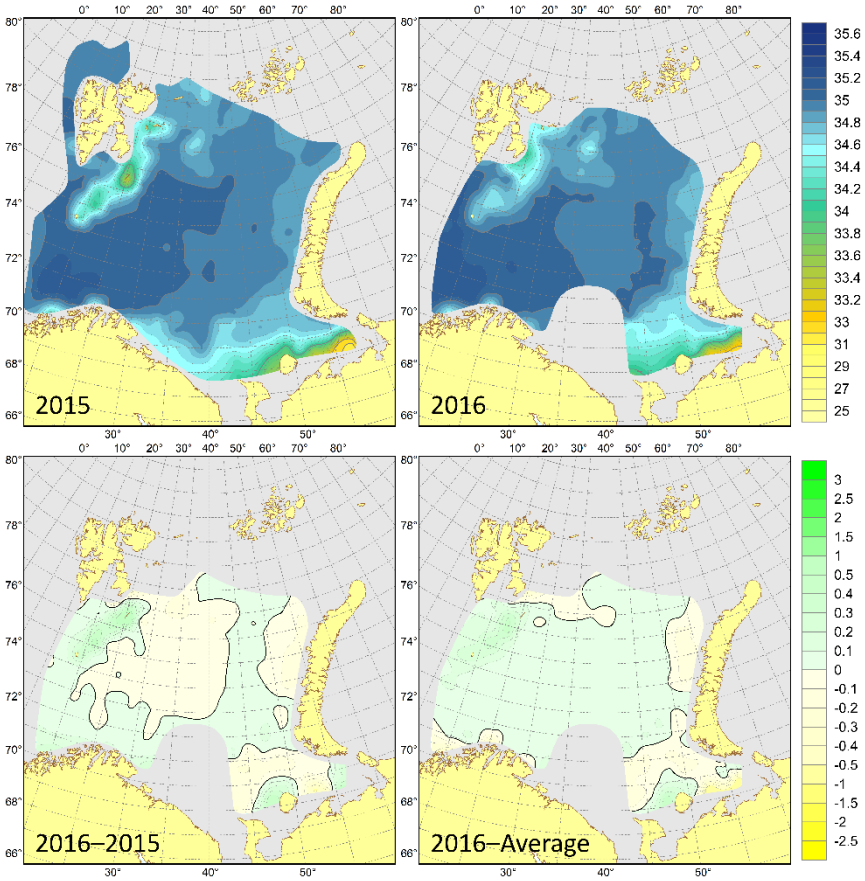


Figure 3.1.15. Bottom salinities in August–September 2015 (upper left) and 2016 (upper right), their differences between 2016 and 2015 (lower left) and anomalies in August–September 2016 (lower right).

Area of water masses

In the past decades, the area of Atlantic and mixed waters has increased, whereas that of Arctic waters has decreased (Figure 3.1.16). In August–September 2016, the area covered by Atlantic waters was the largest, whereas the area covered by Arctic waters was the smallest since 1965.

In August–September 2016, at 50, 100 m and near the bottom, the area covered by warm water (above 3°C) was the largest whereas the area covered by cold water (below 0°C) was the smallest since 2000 (Figure 3.1.17). Since 2000, the area covered by cold bottom water was the largest in 2003 and rather small in 2007, 2008, 2012 and 2016; in 2016, it reached a record low value since 1965 – the year when the joint autumn surveys started.

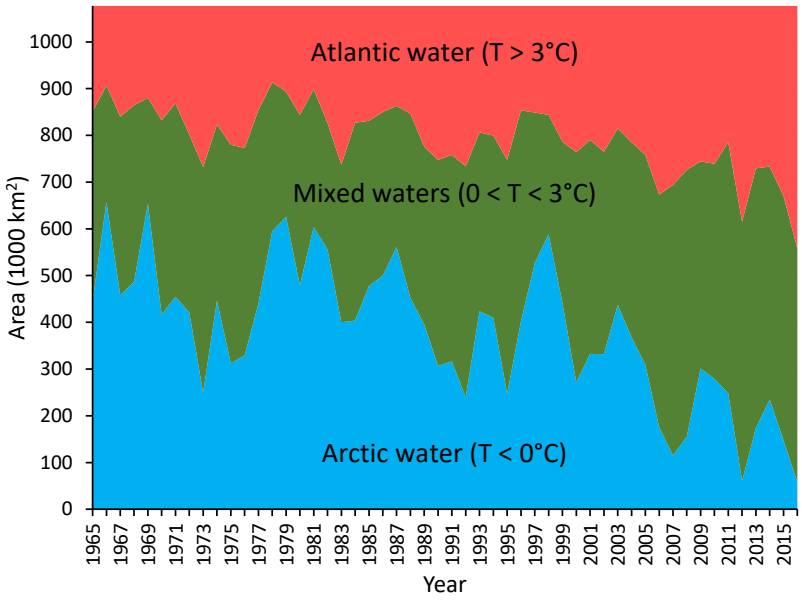


Figure 3.1.16. Area of water masses in the Barents Sea (70–79°N, 20–60°E) in August–September 1965–2016 (based on 50–200 m averaged temperature).

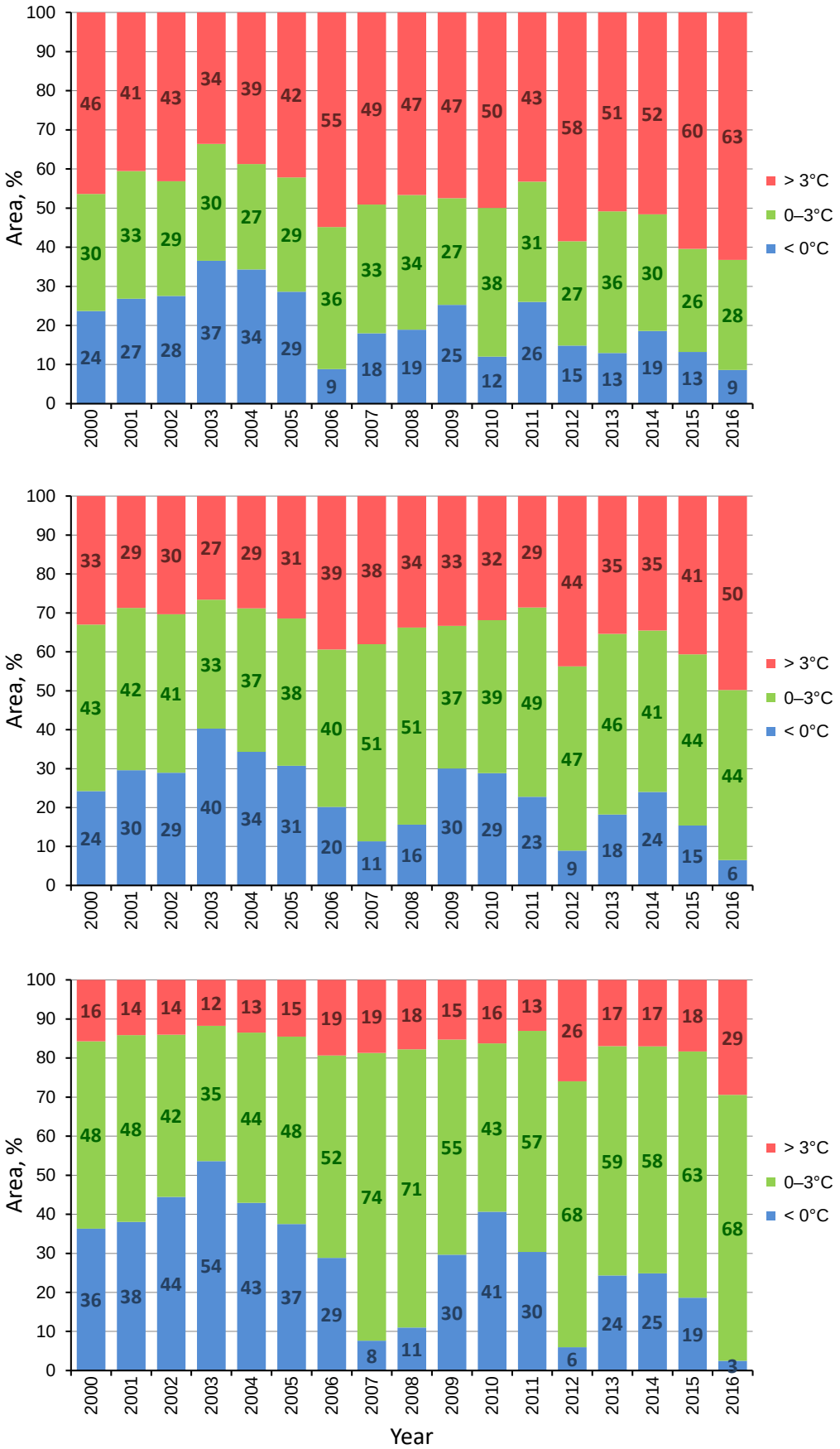

Area, %
Year
> 3°C
0–3°C
< 0°C
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016
46 41 43 34 39 42 55 49 47 47 50 43 58 51 52 60 63
30 33 29 30 27 29 36 33 34 27 38 31 27 36 30 26 28
24 27 28 37 34 29 9 18 19 25 12 26 15 13 19 13 9
33 29 30 27 29 31 39 38 34 33 32 29 44 35 35 41 50
43 42 41 33 37 38 40 51 51 37 39 49 47 46 41 44 44
24 30 29 40 34 31 20 11 16 30 29 23 9 18 24 15 6
16 14 14 12 13 15 19 19 18 15 16 13 26 17 17 18 29
48 48 42 35 44 48 52 74 71 55 43 57 68 59 58 63 68
36 38 44 54 43 37 29 8 11 30 41 30 6 24 25 19 3

Figure 3.1.17. Areas covered by water with different temperatures at 50m (upper panel), 100 m (middle panel) and near the bottom (lower panel) in the Barents Sea (70–79°N, 20–60°E) in August–September 2000–2016.

3.2 Phytoplankton and primary production

The phytoplankton development in the Barents Sea is typical for a high latitude region with a pronounced maximum in biomass and productivity during spring. During winter and early spring (January-March) both phytoplankton biomass and productivity are quite low. The spring bloom is initiated during mid-April to mid-May and may vary strongly from one year to another. The bloom duration is typically about 3–4 weeks and it is followed by a reduction of phytoplankton biomass mainly due to the exhaustion of nutrients and grazing by zooplankton. Later in autumn when the increasing winds start to mix the upper layer and bring nutrients to the surface a short autumn bloom can be observed. However, the time development of this general description can vary geographically. For instance, the spring bloom at the ice edge in the Barents Sea can sometimes take place earlier than in the southern regions due to early stratification, a product of the ice melting.

Satellite data

Daily Net Primary Production (NPP) and open water area (OW) were calculated from satellite data as described in detail in Arrigo and Van Dijken (2015). Satellite-derived surface Chl a (Sat Chl a, Level 3, 8 day binned) was based on SeaWiFS retrievals for the years 1998 through 2002. MODIS/Aqua data are used 2003 onwards, using the latest reprocessing (R2014.0 for SeaWiFS and R2014.0/R2014.0.1 for MODIS/Aqua)). The work done here is in collaboration with Professor Kevin Arrigo and Gert van Dijken from the Stanford University, USA.

Interannual and Seasonal variability of Chl *a*

One of main aims in our ongoing work is to validate satellite data using observations. Previously published results from the Fugløya- Bjørnøya (FB) section show that the seasonal dynamics and magnitude of the Satellite Chl *a* concentration is highly correlated with the observed in situ Chl *a* concentrations, both for the upper 20 m and 50 m (Dalpadado *et al.,* 2014). In their study, the seasonal dynamics of *in situ* Chl *a* and mesozooplankton biomass at the FB section show that the development of zooplankton starts with a lag time of one month after the initiation of the phytoplankton bloom, and that maximum biomass occurs from June through September. We have spatial *in situ* Chl *a* observations mostly from the autumn months (Aug. and Sep.) in the Barents Sea. Comparing near real-time satellite and in situ observations show that there are significant positive relationships between the two variables, providing that both types of data have a good coverage (Figure 3.2.1).

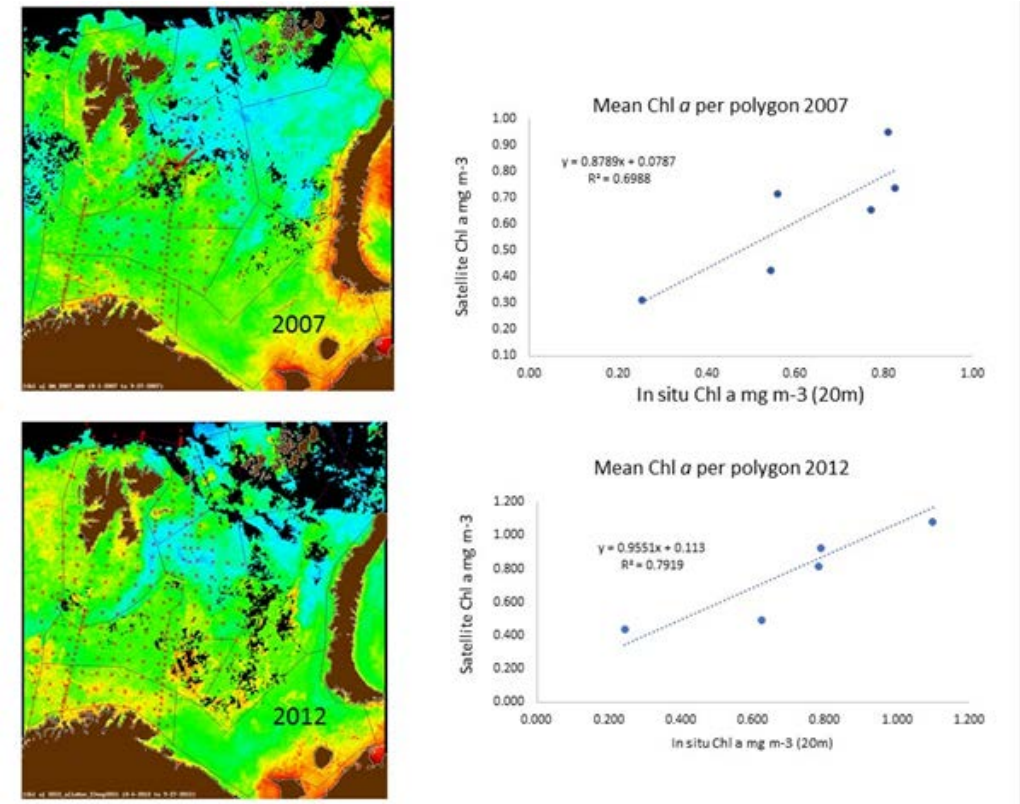


Figure 3.2.1. Near real-time satellite data from autumn on chlorophyll concentrations together with locations of *in situ* observations (maps) and relationship between the two variables (graphs).

As remote sensing data provide good spatial and temporal coverage, we use s these data to explore interannual variability of chlorophyll concentrations. Satellite data from the Barents Sea showed that there is large year-to-year variability of Chl *a* concentrations, with a general increasing trend over the years (Figure 3.2.2).

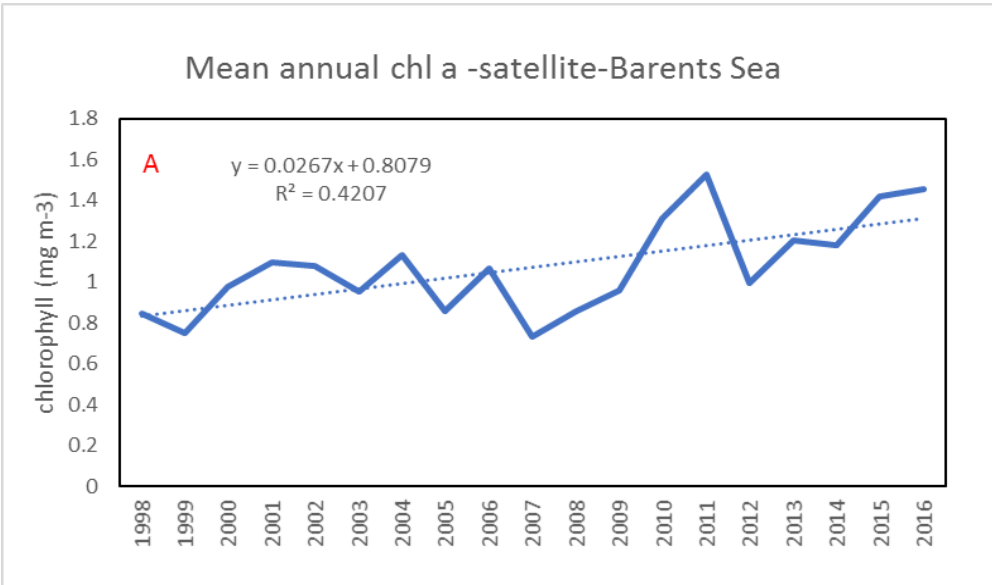


Figure 3.2.2. Interannual variability of satellite based Chl *a* - average annual mean.

Net Primary Production (NPP)

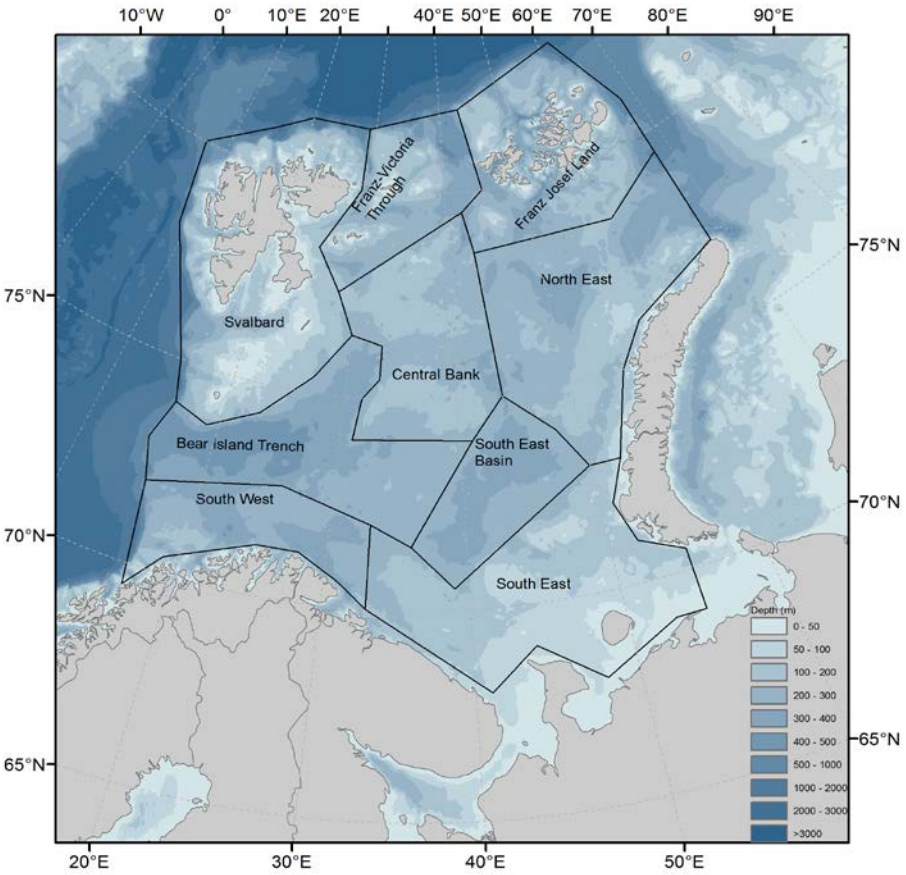


Figure 3.2.3 Polygon regions in the Barents Sea. Note that two of the polygons (Central Bank and Bear Island Trench) are additional divided in the Zooplankton work: Central Bank is further divided into two regions (Great and Central Banks) and Bear Island Trench into three (Bear Island Trench, Hopen Deep and Thor Iversen Bank).

Remote sensing data were explored using the polygon areas shown in Figure 3.2.3.

Satellite based Net Primary Production (NPP) of the total polygon area show that there is significant interannual variability of the net primary production during the period 1998–2016. However, the general trend shows that NPP has increased over the years in the Barents Sea (Figure 3.2.4). The increase is mainly due to the fact that ice coverage has been reduced leading to larger ice-free areas and longer growth period (Figure 3.2.7-9; Dalpadado *et al.*, 2014; Arrigo and Van Dijken, 2011; 2015). Furthermore, the mean production per unit area in general has also increased over the years. Our results show that the mean daily production rate (mg C M-2 day-1) averaged over the growing season has increased considerably since 2010, from 446 (1998–2009) to 596 mg C M-2 day-1 (2010–2016) during the first half of the year (not shown). The NPP in the eastern regions (South East and North east polygons) has increased significantly during the study period (Figure 3.2.3). The NPP in the Svalbard region was highest among the northern polygons, showing also an increasing trend over the years (Figure 3.2.5). The NPP in the south west polygon showed large interannual variability, with no marked increasing trends (not shown).

The new production (NP) estimated using nitrogen consumption (seasonal drawdown of nitrate in the water column) for the Fugløya-Bjørnøya (FB) and Vardø Nord (VN) sections from March to June show that the results were comparable to satellite

NPP values (Rey *et al.,* in prep). In their study, primary production is of the same order in both sections indicating that most production from March to June is based on winter nitrate. Their results show that the yearly NP was about 60% of the total NPP production indicating that nearly half of the annual production occurs during the spring bloom and is fuelled by winter nutrients. A study by Sakshaug *et al*. (2009) also show that new production can contribute ca. 50% of the total production in the Barents Sea.

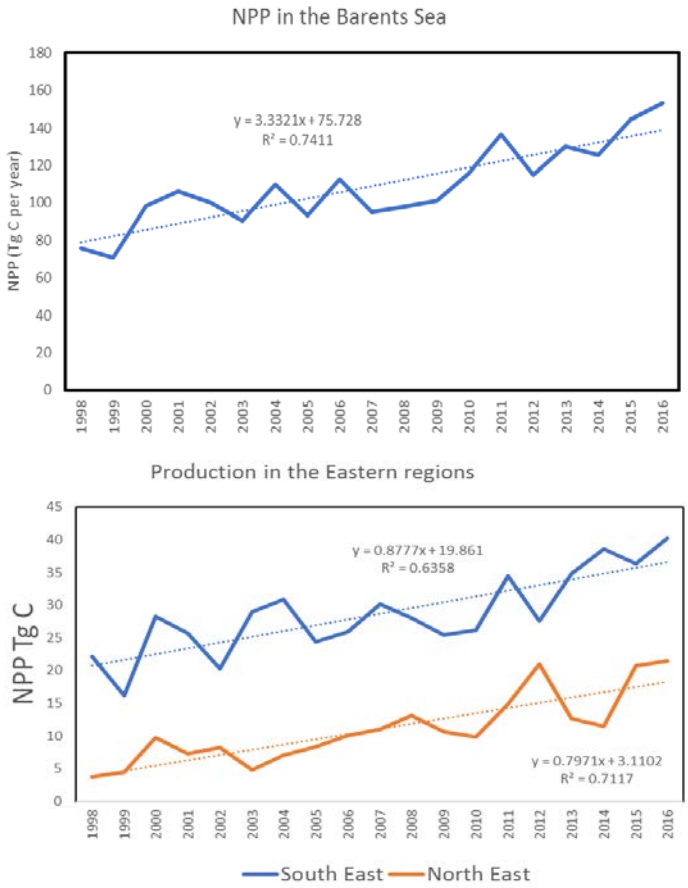


Figure 3.2.4. Annual net primary production (NPP- satellite based) in the Barents Sea. Note that 2016 data are processed only until mid-September.

Figure 3.2.5 Annual net primary production (NPP- satellite based) in the South East and North East polygons.

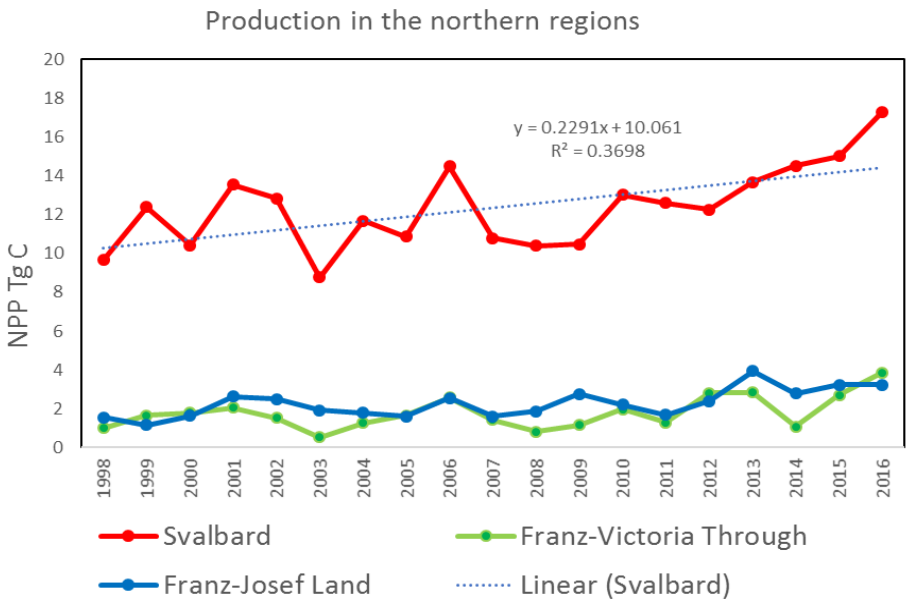


Figure 3.2.6. Annual net primary production (NPP- satellite based) in 3 northern polygon areas.

Open Water Area (OWA)

The concentration of sea ice in the Arctic has dropped by ca. 9% per decade since 1978 and has been accompanied with reduced sea-ice thickness and duration (Arrigo and Van Dijken, 2015 and references therein). Due to reduction of sea ice, the OWA (maximum ice free waters in late summer or autumn) in the Barents Sea has increased over the years, possibly leading to higher NPP in the region. Satellite based Open Water Area (OWA) estimates confirm this (Figure 3.2.7A). The increase is most significant in the North East and South East polygons (Figure 3.2.7B).

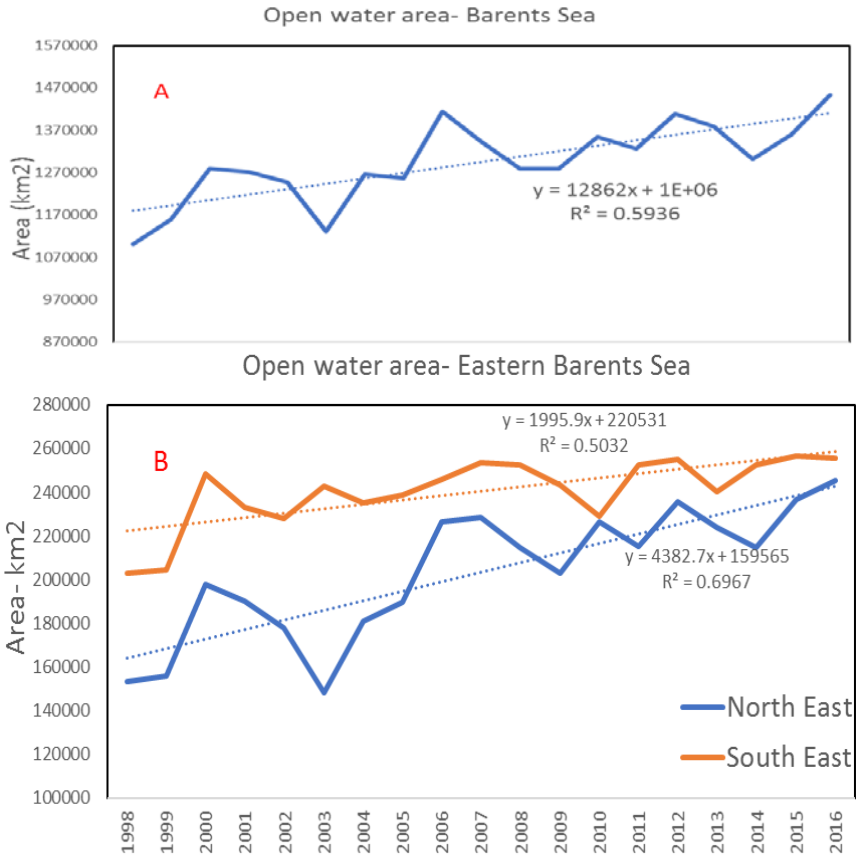


Figure 3.2.7. Open water area A), whole Barents Sea and B) Eastern Barents Sea

There was a significant relationship of increasing satellite-based NPP with increasing OWA (Figure 3.2.7). In addition, NPP was also related to increasing chlorophyll a concentration (Figure 8). The increasing trend in NPP shown in Figure 3.2.8 is therefore a reflection of an increase in both OWA and average biomass of phytoplankton (Chlorophyll *a*).

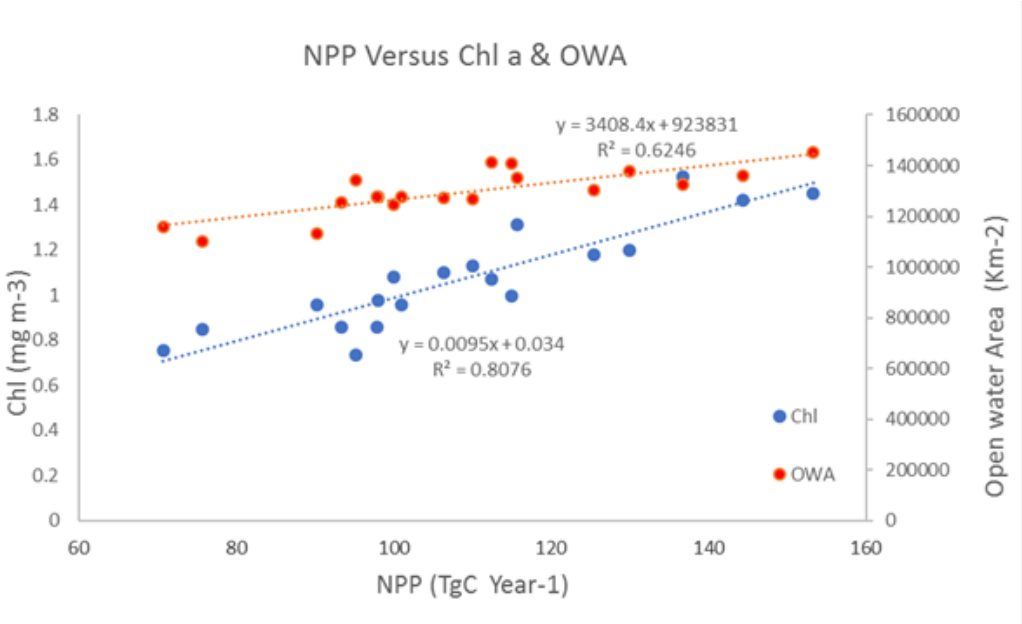


Figure 3.2.8. Relationship between satellite derived NPP and Chl a and Open Water Area (OWA).

Growing season

We have defined the length of the growing season as the number of days between start and end of seasonal phytoplankton growth. Start of growing season = first day that there is a valid chlorophyll pixel in a polygon. End of growing season = last day that there is a valid chlorophyll pixel in a polygon. Remote sensing results showed that the growing season has increased from an average of 166 to 174 days between the periods 1998-2005 and 2006-2016 (Figure 3.2.9).

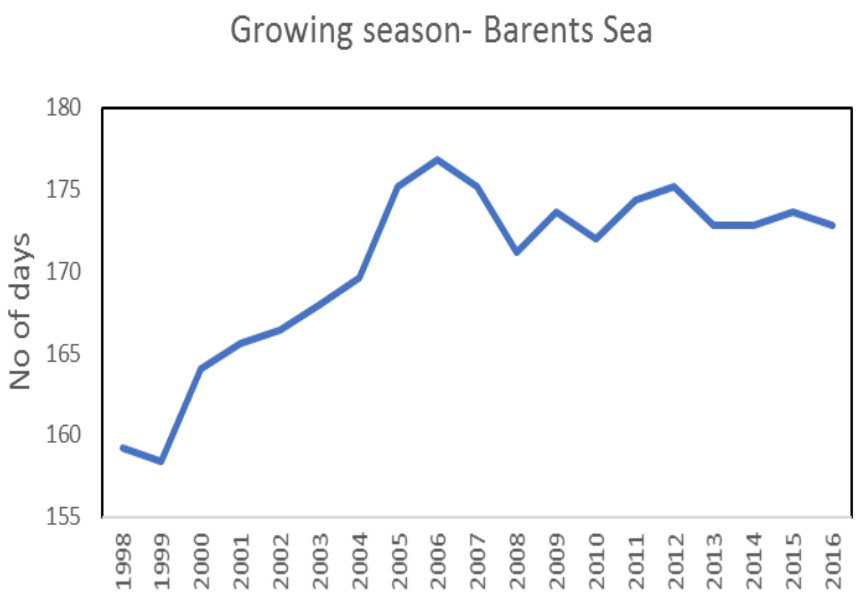


Figure 3.2.9. Average length of the growing season (number of days) in the Barents Sea.

Key points

1. Validations performed on in situ observations and satellite data show that for the Barents Sea, the model by Arrigo *et al.* (2008) gives reasonable results that compare well with observed measurements (Dalpadado *et al.*, 2014, Rey *et al.* (in prep) and ongoing TIBIA work)

2. Spatially integrated production (NPP) has increased over the years in most polygon regions. A noteworthy increase is observed in the Eastern regions (North East and South East), where sea ice coverage has diminished over the years.

3. There is a highly significant relationship between Chlorophyll, Open water area (ice-free area) and integrated production (NPP). The increase in ice-free area provides improved habitat for phytoplankton growth as the growing season (length of number of days with open water) has increased.

4. Our investigations reveal that the major part of annual production has taken place by day 200. Published work also show that nearly half of the annual production occurs during the spring bloom and is fuelled by winter nutrients.

3.3 Zooplankton

Mesozooplankton biomasses

The mesozooplankton plays a key role in the Barents Sea Ecosystem by channelling food from primary producers to animals higher in the foodweb.

The main features of the distribution patterns show similarities across years, although some be-tween-year variability is apparent. Challenges in covering the same area each year are inherent in such large-scale monitoring, and interannual variation in ice cover is one reason for this. This implies that the average biomasses estimated for the different years in some cases are not directly comparable. In 2016, like in the preceding years, the highest biomasses (>10 g m^{-2}) were in the west-ern and northern parts of the survey area, including northwest and north of Svalbard/Spitsbergen and south of Franz Josef Land. In addition, a subregion towards the southeast (ca. 73-75°N, 40-50°E) displayed elevated levels in 2016 as in earlier years. Comparatively lower biomasses (<3 g m^{-2}) were typical on the Svalbard Bank (northeast of Bear Island), in the central Barents Sea, and in easterly and south-easterly parts of the survey area the last years (Figure 3.3.1.)

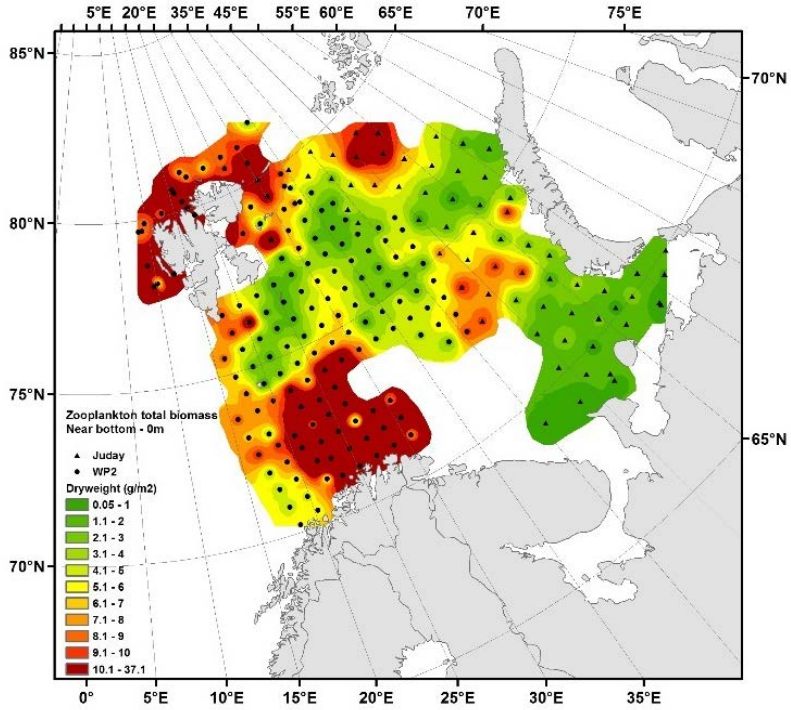


Figure 3.3.1. Distribution of zooplankton biomass (dry weight, g m^{-2}) from bottom-0 m in autumn 2016 (upper panel). Data based on samples obtained during the joint Norwegian-Russian (IMR/PINRO) ecosystem survey in late August – early October. Interpolation made in ArcGIS v.10.3, module Spatial Analyst, using inverse data weighting (default settings).

In the Norwegian waters of the Barents Sea, mesozooplankton biomass is size-fractionated (180–1000 µm, 1000–2000 µm and >2000 µm) before weighing. For the smallest size-fraction, the 2016 average biomass was similar to the average for the last 20 years, while for the intermediate size-fraction, the 2016 average biomass was above the average for the last 20 years (Figure 3.3.2). In contrast, for the largest size-fraction, the area-averaged values have displayed a decreasing trend during the ca. 10 last years, and in 2016 the biomass for the largest size-fraction was in the lower part of the range for the time-series. Based only on Norwegian data, which represent the longest time-series, average zooplankton biomass for the sum of all size-fractions in August-October 2016 was estimated to be 7.7 g dry-weight m^{-2} in the western-central Barents Sea. This is somewhat lower than measured in 2015, 8.7 g dry-weight m^{-2}, but still above the average for the last 20 years (1997–2016, 7.1 g dry-weight m^{-2}).

Combined Russian and Norwegian data covering the entire Barents Sea provided an estimated average zooplankton biomass of 6.6 g dry-weight m^{-2} in 2016. This estimate is not directly comparable with those for 2015 (7.3 g m^{-2}) and 2014 (6.7 g m^{-2}), since the areas covered in 2016 differed from those in the two previous years. In the Russian sector alone, average biomass in 2016 was estimated to be 3.9 g dry weight m^{-2}, which again is difficult to compare with the values for earlier years due to an incomplete coverage in the southern part of the monitoring area in 2016.

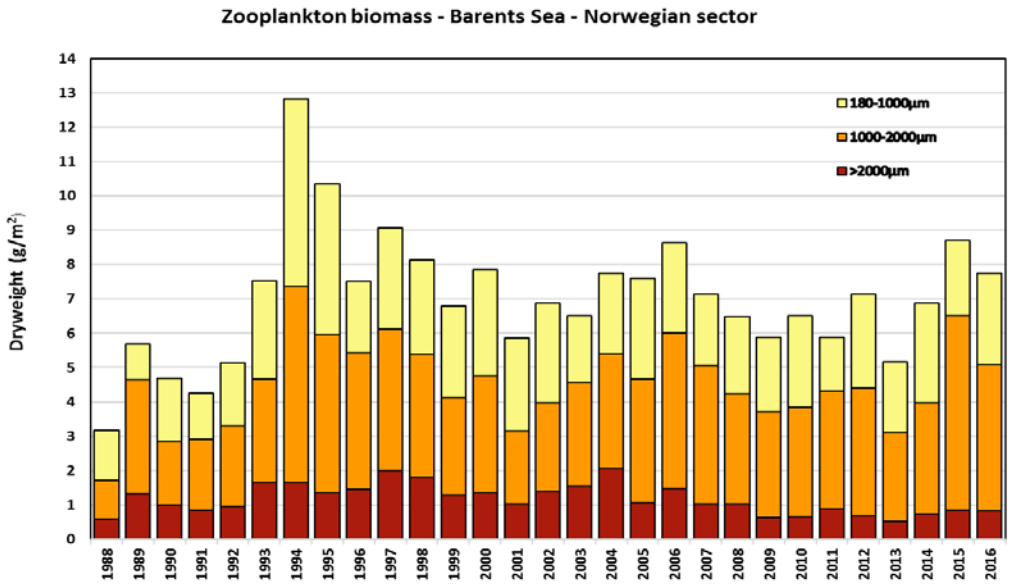


Figure 3.3.2. Time-series of mean zooplankton biomass from bottom – 0m (dry-weight, g m^{-2}) for the western and central Barents Sea for the Norwegian part of the autumn ecosystem-survey, 1988–2016. Data are shown for the three size-fractions (0.18-1 mm, 1–2 mm, >2 mm) based on wet sieving.

Zooplankton biomass can vary considerably between years and appears to be controlled largely by predation pressure, e.g. from capelin, although its yearly impact could also vary between regions. The capelin stock size was relatively high during 2008–2013, hence exerting a high predation pressure on zooplankton. In 2014, the capelin stock-size had decreased, and in 2015 and 2016 the stock declined further to very low levels, most likely easing the pressure on their prey. In addition, processes such as transport of plankton from the Norwegian Sea into the Barents Sea, primary production (see section above), and local production of zooplankton, are likely to contribute to the observed variability of the zooplankton biomass in the Barents Sea. Zooplankton biomass can vary considerably between years and appears to be controlled largely by predation pressure, e.g. from capelin, although its yearly impact could also vary between regions.

Zooplankton biomass in subareas of the Barents Sea

Zooplankton biomass data from the late 1980s up to 2016 have been processed by gridding, and mean biomass values have been calculated for each of the subareas (or polygons) described previously (Figure 3.3.2). IMR has monitored zooplankton biomass (dry-weight) in three size-fractions since the 1980s, while the joint IMR-PINRO coordinated monitoring of total zooplankton biomass started in 2002. The IMR-sampling included many stations in the eastern Barents Sea during the 1990s. The total IMR dataset from 1989–2016 comprises nearly 4000 stations sampled with vertical net (mainly WP2) and in addition there are almost 1000 stations taken with 1-m2 MOCNESS. We have combined the IMR data from 1989 with the joint IMR-PINRO data from 2002 to provide time-series of zooplankton biomass also for the eastern Barents Sea.

The zooplankton biomass in the subareas in the southwestern Barents Sea influenced by inflowing Atlantic water has shown stable or declining trends since year 2000, following a pronounced peak in 1994 (Figure 3.3.3). The Bear Island Trench subarea has shown an increase after 2004, which appears to reflect an increase in *Calanus finmarchicus* with evidence of a second generation predominant in autumn in the Atlantic water (Aarflot *et al.*, manuscript in preparation, Skjoldal *et al.*, manuscript in

preparation). The biomass in the 'downstream' subareas, Thor Iversen Bank to the south of Central Bank and Hopen Deep, has not reflected this increase.

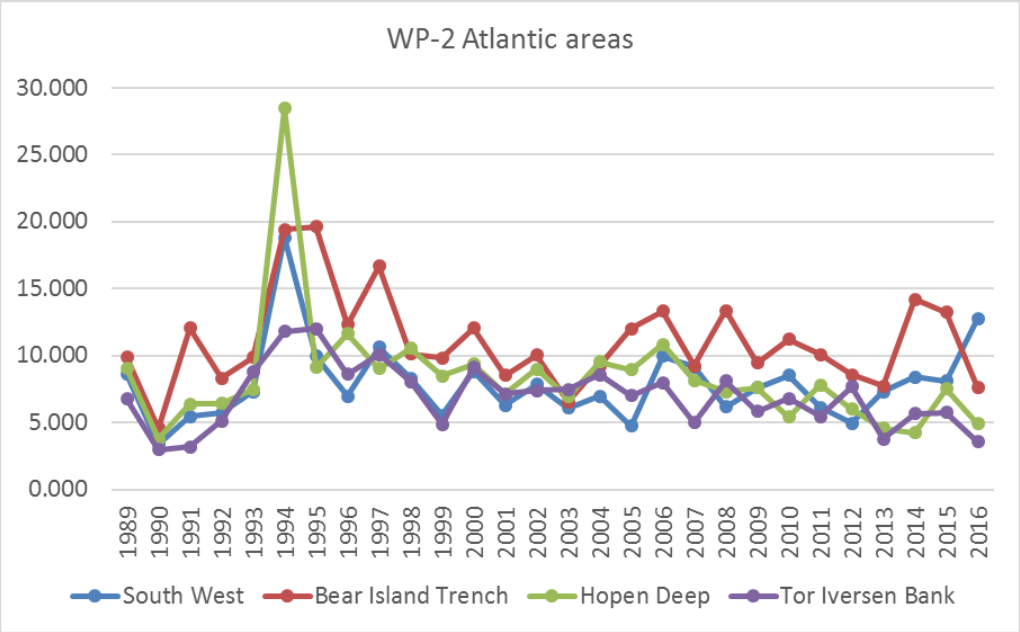


Figure 3.3.3. Time-series of total zooplankton biomass for four subareas located in the inflow region of Atlantic water in the western Barents Sea.

The zooplankton biomass in the Central Bank and Great Bank subareas has shown declining trends since the peak in 1995 (one year later than the 1994 peak in the Atlantic water) (Figure 3.3.4). The bio-mass showed some increase in the period when the capelin stock was low in 2002–2005 with biomass levels around 6–7 g dw m^{-2}. It is noticeable that after the last capelin collapse in 2014–2015 there was little sign of recovery of the zooplankton biomass in 2016 in these central areas that are part of the traditional feeding areas of capelin.

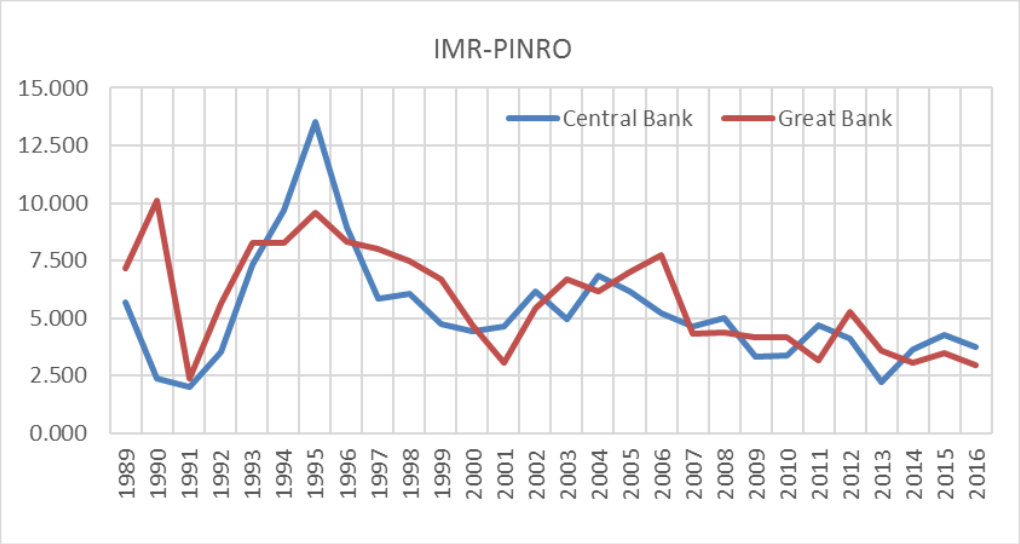


Figure 3.3.4. Time-series of total zooplankton biomass (dry weight, g m^{-2}) for the Central Bank and Great Bank based on combined IMR-PINRO data, 1989–2016.

Zooplankton biomass showed an increase in the South-East Basin after 2005 (Figure 3.3.5), similar to the trend showed 'upstream' in the Bear Island Trench subarea (Figure 3.3.3). The trend for the Thor Iversen Bank, which lies in between these two subareas, did not show a similar increase. The biomass in the South-East region has typically been lower than in other subareas and has shown a decrease in the most recent years (Figure 3.3.5). The incomplete spatial coverage in 2016 may have influenced the mean values for the subareas in the southeastern part of the Barents Sea (see map in Figure 3.3.1).

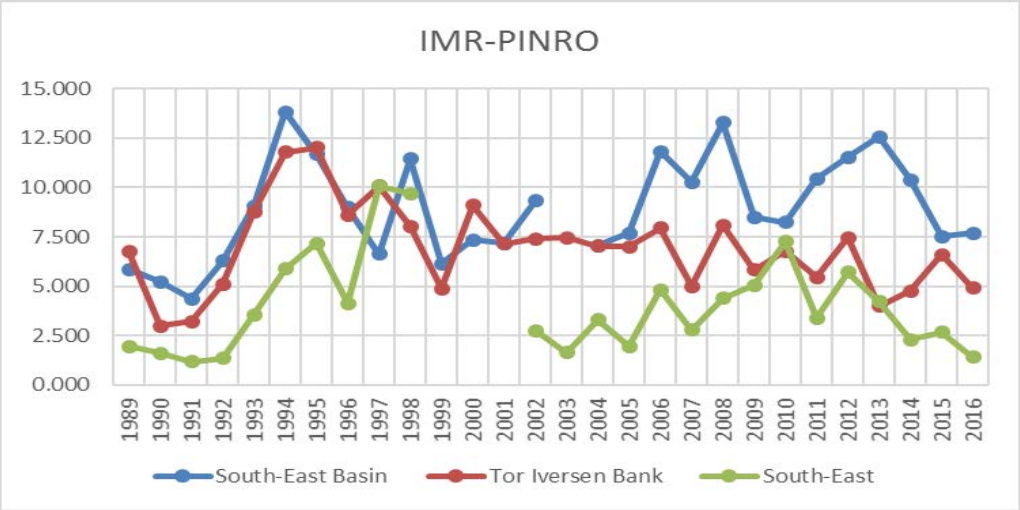


Figure 3.3.5. Time-series of total zooplankton biomass for the Thor Iversen Bank, South-East Basin and South-East subareas based on combined IMR-PINRO data, 1989–2016.

The mean biomass values for 2016 for the various subareas are shown in Figure 3.3.6 together with the mean biomass for the 2002-2016 period based on the joint PINRO-IMR survey results. Figure 3.3.7 shows a similar plot for the size-fractioned results from the IMR surveys where the long-term mean values are for the 1989-2016 period.

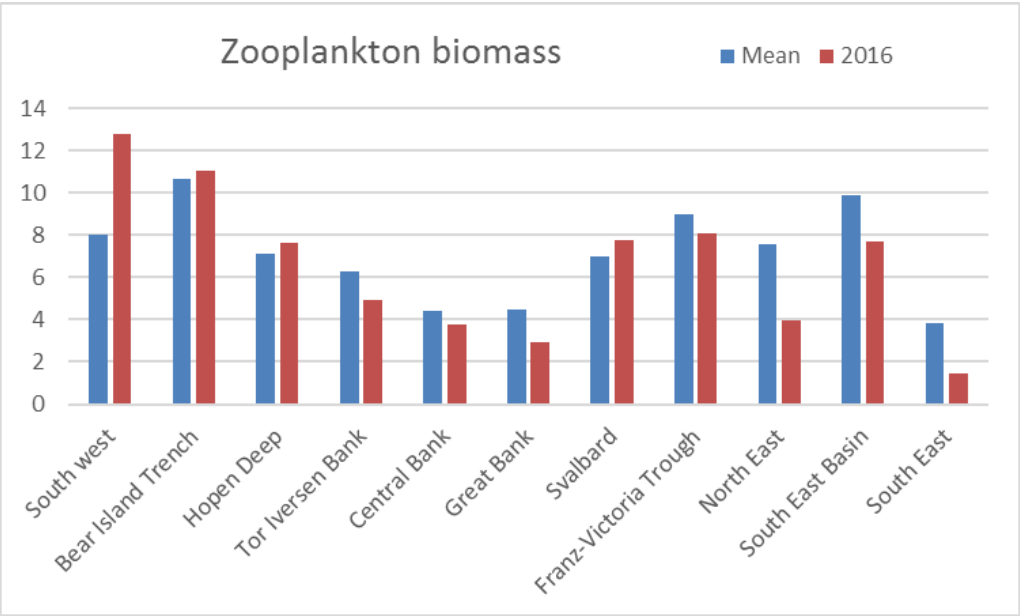


Figure 3.3.6. Zooplankton biomass (total) in 2016 compared to the mean biomass (2002–2016) for the various subareas of the Barents Sea.

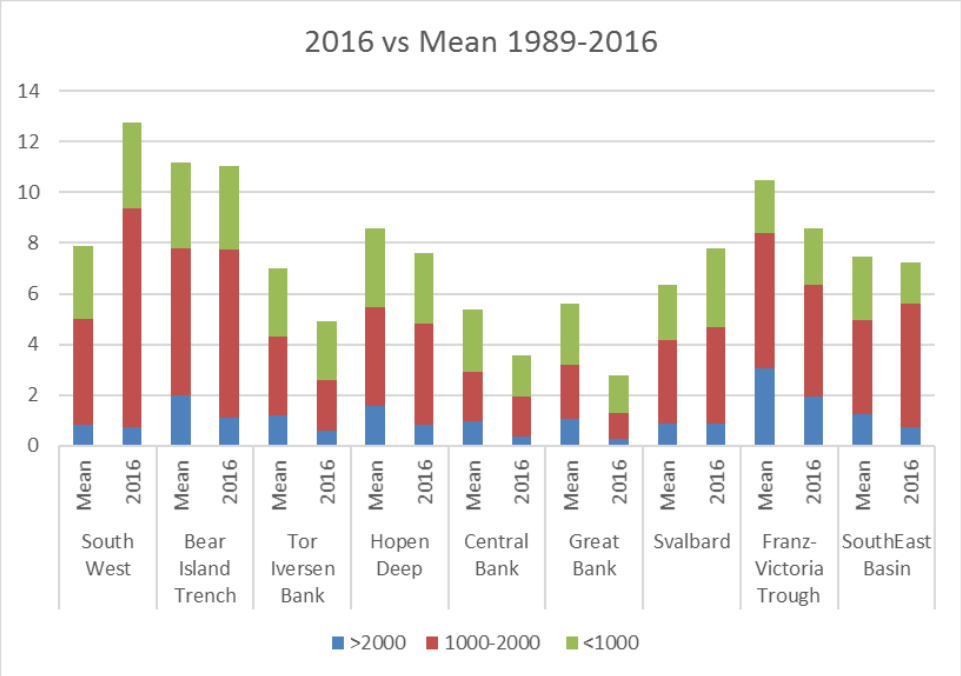


Figure 3.3.7. Zooplankton biomass in three size-fractions in 2016 compared to the long-term mean biomass (1989–2016) for various subareas of the Barents Sea surveyed by IMR.

The biomass in 2016 for the SW subarea was higher than the mean (by >50%). The biomass in 2016 was close to, or slightly higher than, the mean for the 2002-2016 period for the Bear Island Trench, Hopen Deep, and Svalbard subareas. The biomass was lower than the 2002–2016 mean for the Central Bank and Great Bank, and for the subareas in the eastern Barents Sea being up to 50% lower or more for the North-East and South-East subareas (Figure 3.3.7). The IMR results are in general agreement, showing higher biomass in the South-West subarea, and lower biomass for the Thor Iversen, Central Bank and Great Bank subareas. One notable feature is a consistently lower contribution by the largest size fraction (>2 mm) in 2016 compared to the long-term mean. This effect is particularly pronounced for the Central and Great Bank areas.

Mesozooplankton species-composition

The Russian investigation along the Kola section in May 2016 showed that copepods were the dominant group of zooplankton at this time, comprising on average 87% in abundance and 85% in biomass, and with *Calanus finmarchicus* as the dominant species. The abundance of *C. finmarchicus* in 2016 (395 941 ind. m^{-2}) was much higher than in 2015 (23 864 ind. m^{-2}) and similar to in 2014 (381 417 ind. m^{-2}), and somewhat lower than the long-term mean (Figure 3.3.8). In the southern part of the section the abundance of *C. finmarchicus* was lower than in the northern part, and the highest values were observed at 72°00′ and 73°30′ N. In the *C. finmarchicus* population, individuals of all stages were present, but while CI-CIV stages dominated on most stations, individuals of the early stages CI-CII prevailed on the northern stations.

Abundance of the arctic *C. hyperboreus* in 2016 was slightly higher than in 2015 (77 and 68 ind. m^{-2} respectively) and much lower than in 2014 (210 ind. m^{-2}), as well as lower than the long-term mean (Figure 3.3.8). The highest abundance of *C. hyperboreus* was observed the northernmost stations of the Kola section. Older copepodites CIV-CV of *C. hyperboreus* represented its population. The other arctic species, *C. glacialis*, was completely absent from the Kola section in 2016 (Figure 3.3.8).

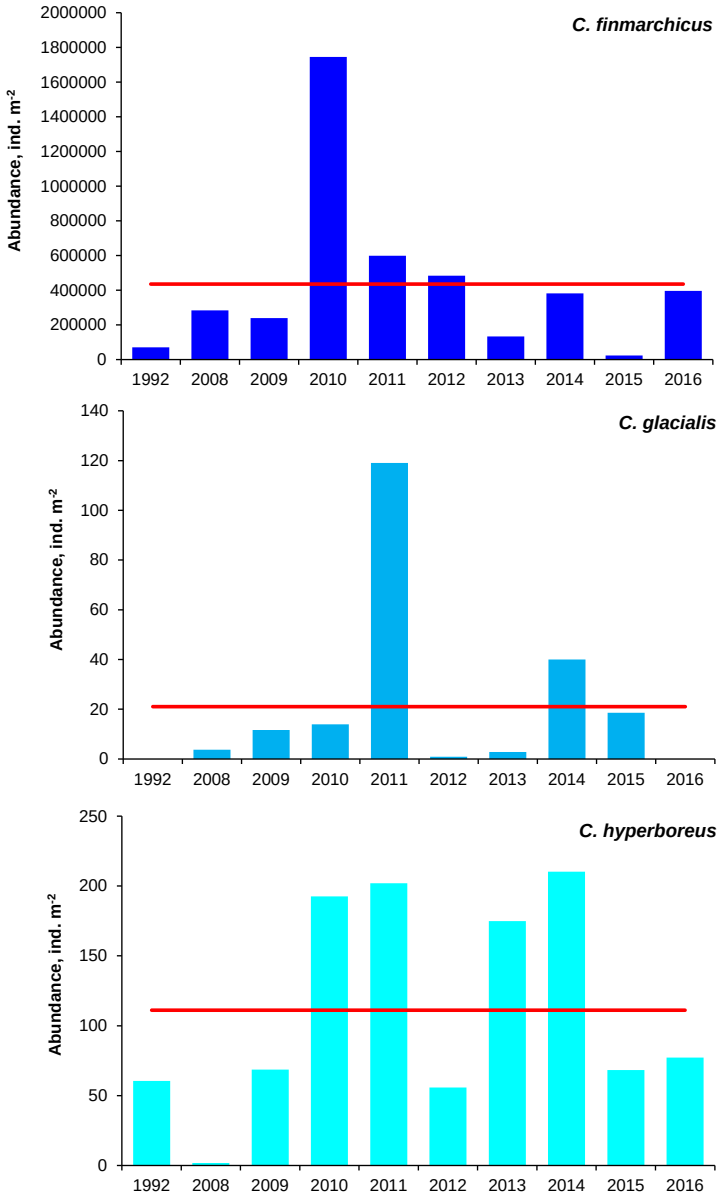


Figure 3.3.8. Interannual mean abundances of three copepod species along the Kola section in May/June in 1992 and 2008-2016, ind. m^{-2}.

Russian investigations of mesozooplankton communities in the northern Barents Sea (north of approximately 75°N) in the joint ecosystem survey in August-September 2015 showed continued tendencies revealed in previous years. Copepods were the most abundant group of zooplankton (88% of total zooplankton numbers), while the second most abundant group were heteropods (8.6%). In 2015, total abundance of copepods decreased, while abundance of heteropods increased compared to in 2014. Copepods and chaetognaths represented the most important groups in terms of biomass (74 and 11% of total zooplankton biomass, respectively), and both these decreased from 2014 to 2015. The heteropods displayed a similar biomass both years, which in any case was very low compared to copepods and chaetognaths. The biomasses of other groups generally decreased, but their contribution to the total biomass was very low compared with the dominant groups. The small species *Oithona similis* and *Pseudocalanus minutus* were the most abundant among copepods (53 and 37% of total copepod abundance) in the northern Barents Sea, while the larger species *Calanus glacialis*, *C. finmarchicus* and

Metridia longa represented only 1.4–3.9% (Figure 3.3.9). Abundances as well as biomasses of all these copepod species declined from 2014 to 2015. In 2015 the total abundance and biomass of zooplankton decreased by a factor of 1.4 and 1.9, respectively, in the northern Barents Sea compared to 2014. *C. glacialis* was the dominant species among copepods in terms of biomass (48% of total copepod biomass) (Figure 3.3.10).

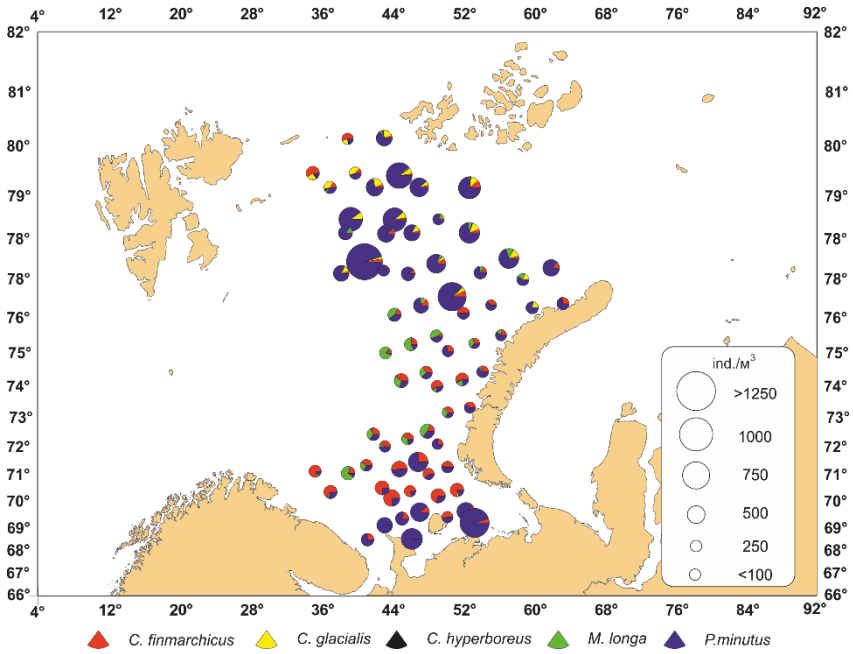


Figure 3.3.9. Abundance (ind. m^{-3}) of the most abundant copepod species without *Oithona similis* (bottom-0m) in the eastern Barents Sea (based on the PINRO samples from the PINRO/IMR ecosystem survey in August-September 2015).

In the southern Barents Sea, copepods were the dominant group in terms of both abundance and biomass (94 and 77%, respectively). Among copepods, small *O. similis* and *P. minutus* were the most abundant species (79 and 13% of total abundance of copepods, respectively), while the larger species *C. finmarchicus* contributed only 7% (Figure 3.3.9). However, the biomass of copepods was mainly formed by *C. finmarchicus* (65% of total copepod biomass), *M. longa* (22%) and *P. minutus* (10%) (Figure 3.3.10). In 2015, the total zooplankton abundance increased by factor of 2, while the total biomass decreased slightly compared to 2014 in the southern Barents Sea.

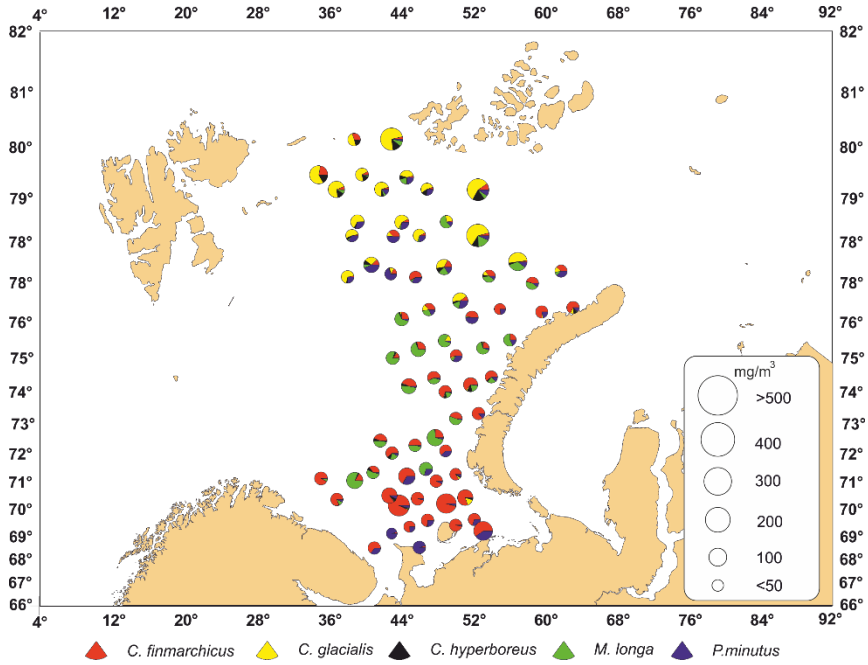


Figure 3.3.10. Biomass (mg wet-weight m^{-3}) of the most abundant copepod species without *Oithona similis* (bottom-0m) in the eastern Barents Sea (based on the PINRO samples from the PINRO/IMR ecosystem survey in August-September 2015).

The Fugløya-Bear Island (FB) transect is located at the western entrance to the Barents Sea. Normally, 5 to 8 stations with fixed positions are sampled depending on weather conditions, and the transect is generally covered 5-6 timer per year. Zooplankton samples collected between 1995 and 2016, from four locations representing different water masses (coastal, Atlantic, and mixed Atlantic/Arctic), have been analysed taxonomically. Annual averages including all seasons for the abundance of the species *Calanus finmarchicus, C. glacialis and C. hyperboreus* are shown for each of the 4 stations in Figure 3.3.11. *C. finmarchicus*, which is by far the most common of these species, displays large interannual variations in abundance. High abundances were recorded during 2010 along most of the transect except at the northernmost position (74°00'N). Despite some exceptions, *C. finmarchicus* tends to be most abundant at the station located at 73°30'N, and following very low abundances at all stations in 2013, it has been present in considerable numbers along the transect during the last 3 years 2014-2016.

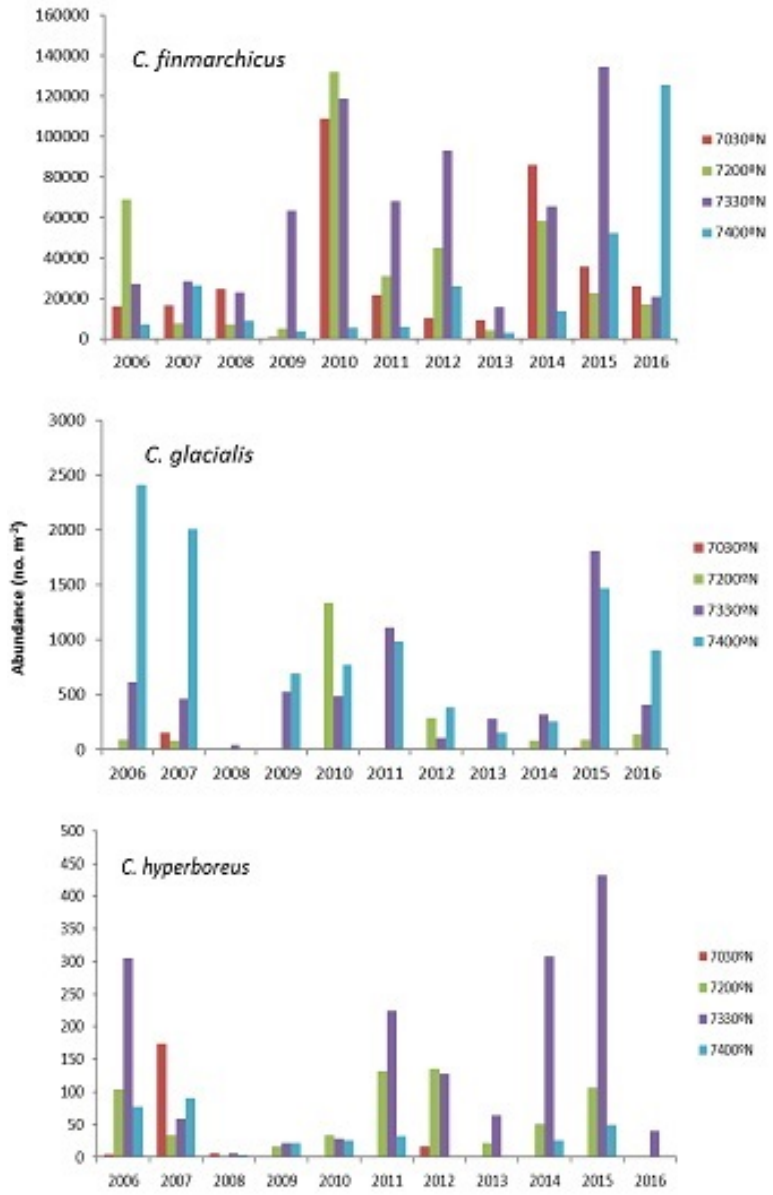


Figure 3.3.11. Copepodite abundances for 3 *Calanus* species recorded along the Fugløya-Bjørnøya section during the period 2006–2016. The bars represent the annual averages of the 5-6 coverages per year (except for 4 and 3 coverages in 2012 and 2013, respectively). Each station is shown separately.

As expected, *C. glacialis* displays its highest abundance at the two northern-most stations (Figure 3.3.11), where Atlantic and Arctic waters mix. The abundance of this species is subject to large interannual variations. The numbers of *C. glacialis* along the FB transect seem to have decreased during the period 2006–2014, with a very low abundance recorded in 2008, and with low levels also during 2012–2014. However, the registered abundances were much higher again in 2015 and 2016. The abundance of the larger species *C. hyperboreus* along the FB transect has generally been low throughout the time-series, and very few individuals of this species were recorded in 2016 (Figure 3.3.11). The time-series for *C. hyperboreus* shows a strong year-to-year variability, but no unidirectional trends.

Calanus helgolandicus, a more southerly species which spawns during autumn, has regularly been observed at the Fugløya – Bear Island transect, particularly during the period from December to February (Dalpadado *et al.*, 2012). This species is similar in appearance to *C. finmarchicus*. In recent years, it has been observed more frequently in the North Sea and southern parts of the Norwegian Sea (Svinøy transect). During winter, the ratio of *C. helgolandicus* to *C. finmarchicus* along the Fugløya – Bear Island transect has been found to increase. At this time of the year, however, *C. finmarchicus* is normally overwintering in deeper waters. There is no evidence of an increase in the relative proportion *C. helgolandicus* over the years along the FB transect, which suggests that this species has not increased in absolute abundance at the entrance to the Barents Sea.

Krill

Krill (euphausiids) represent the most important group of macrozooplankton in the Barents Sea, followed by hyperiid amphipods. Krill play a significant role in the Barents Sea ecosystem, facilitating transport of energy between different trophic levels. There are mainly three species of krill in the Barents Sea; *Thysanoessa inermis* associated with Atlantic water in the western and central Barents Sea, *Thysanoessa raschii* found mainly in the shallow waters in the southeastern Barents Sea, and *Meganytiphanes norvegica* associated with the inflowing Atlantic water, particularly during warm periods. *Meganyctiphanes norvegica* is the largest species reaching a maximum length of about 4.5 cm, while Thysanoessa inermis and *T. raschii* reach lengths of about 3 cm.

Krill were collected in the Barents Sea during the PINRO winter survey with a zooplankton net attached to the bottom trawl. The Russian investigation of euphausiids during the Russian winter survey in October-December 2015 showed a continued rather high abundance of euphausiids (Figure 3.3.12). Still, compared to in 2014, the estimated abundance of euphausiids in the Barents Sea in 2015 had decreased – from 1637 to 803 ind. 1000 m^{-3} in the southern part and from 1656 to 1638 ind. 1000 m^{-3} in the northwestern part. These estimates are much higher than the long-term means – 568 and 939 ind. 1000 m^{-3}, respectively. The distribution of the euphausiid species was typical for warm years (Figure 3.3.13). *Thysanoessa inermis* (most areas) and *T. raschii* (south-eastern areas) were typically the most abundant species, *T. longicaudata* occurred mainly in the south-western areas and *Meganyctiphanes norvegica* was distributed widely in the Barents Sea.

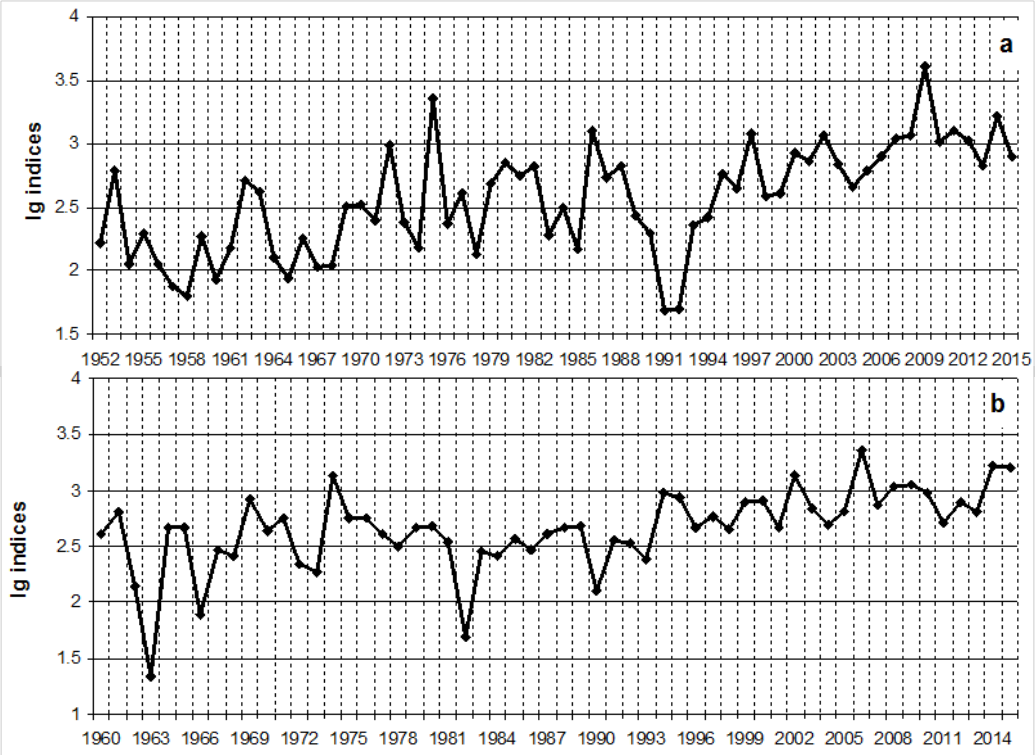


Figure 3.3.12. Abundance-indices of euphausiids (log10 of number of individuals per 1000 m³) in the near–bottom layer of the Barents Sea based on data from the Russian winter survey during October-December, 1959-2015. Based on trawlnet catches in bottom layer. a) Southern Barents Sea. b) Northwestern Barents Sea.

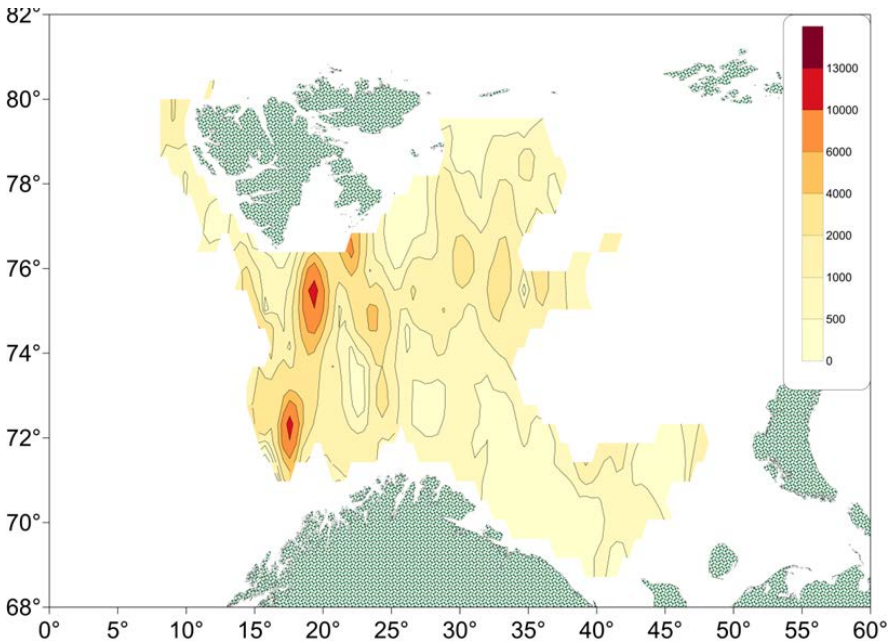


Figure 3.3.13. Distribution of euphausiids (ind. per 1000 m^{-3}) in the near-bottom layer in the Barents Sea based on data from the Russian winter survey during October-December 2015.

The information on krill presented below is based the joint Norwegian-Russian Barents Sea Ecosystem surveys in autumn 2016, and is modified from Eriksen *et al.* (2012). Based on catch-data from pelagic trawls covering the upper layers (0–60 m) of the Barents Sea during August-October 2016, krill were more widely distributed than in the

previous years (Figure 3.3.14). For comparison, the highest catches in 2013 were generally made in the central area, in 2014 in the western area, and in 2015 mostly south and southeast of Svalbard/Spitsbergen). In August-October 2016, *Meganyctiphanes norvegica* and *Thysanoessa inermis* were widely distributed in the Barents Sea, *Thysanoessa longicaudata* occurred mostly in the western areas, and *Thysanoessa raschii* mainly in the eastern areas. (Figure 3.3.15). The average night-catches in 2016 (13.5 g wet-weight m^{-2}) and 2015 (14.2 g m^{-2}) were similar, and higher than the long-term average (7.5 g m^{-2}) (Figure 3.3.16). During night, krill typically migrate to upper water layers to feed, and are then in general caught in larger numbers than during day when trawling in the uppermost 60 m.

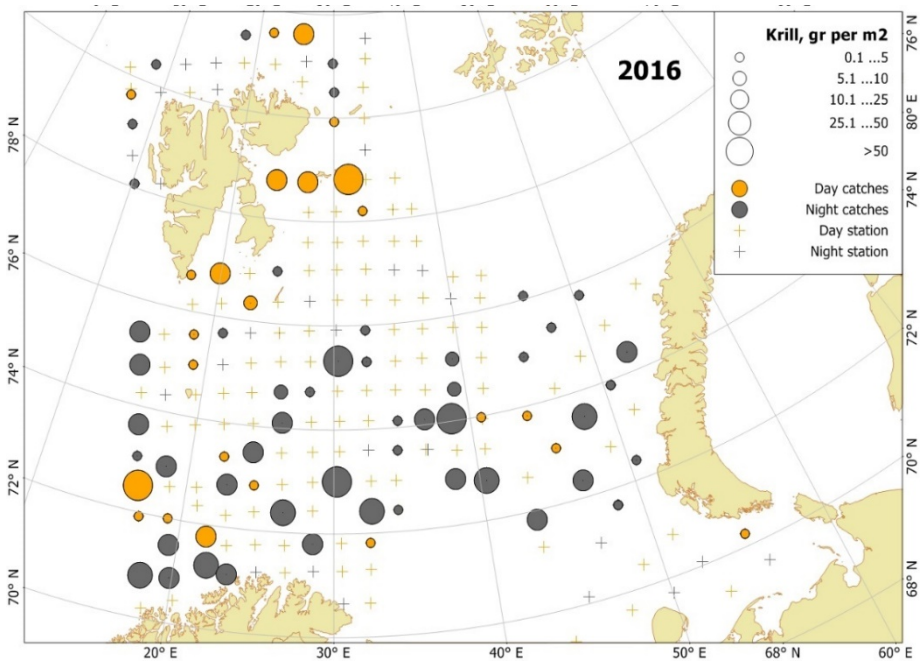


Figure 3.3.14. Krill distribution based on sampling with pelagic 0-group fish trawl in the 60-0 m layer during the joint ecosystem survey in August–October 2016. The unit is g wet-weight m^{-2}.

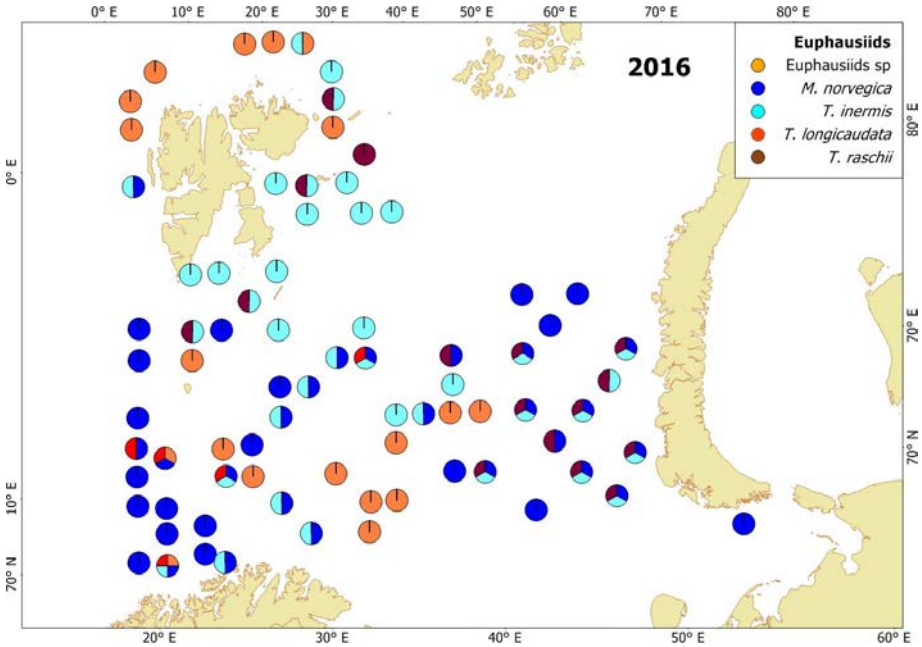


Figure 3.3.15. Distribution of krill species, based on pelagic trawl stations both day and night, covering the upper waters (0-60 m) in the Barents Sea in August-October 2016. The proportions are based on wet-weights. The unit is grammes of wet-weight m^{-2}. Figure from Eriksen *et al.* (2017).

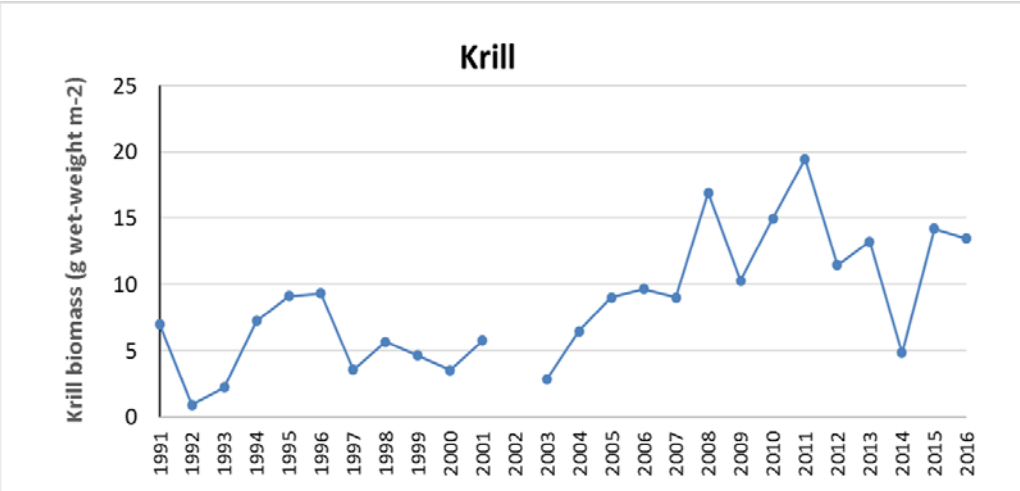


Figure 3.3.16. Mean biomass of krill (g wet-weight m^{-2}) sampled with pelagic 0-group fish-trawl within the 60-0 m layer in the Barents Sea (based on night catches) from 1991 to 2016. Based on data from the joint autumn ecosystem-survey.

Hyperiid amphipods

Hyperiid amphipods are the second most important group of macrozooplankton in the Barents Sea. During the Russian winter survey in the Barents Sea in 2015, hyperiid abundance had increased sharply, and concentrations were estimated to 56 ind. 1000 m^{-3}. In previous years, the concentrations of hyperiids were estimated to 23 ind. 1000 m^{-3} in 2012, and to 13 and 12 ind. 1000 m^{-3} in 2013 and 2014, respectively. As in previous years, *Themisto libellula* was the dominant species. The distribution during the PINRO winter survey in 2015 is shown in Figure 3.3.17.

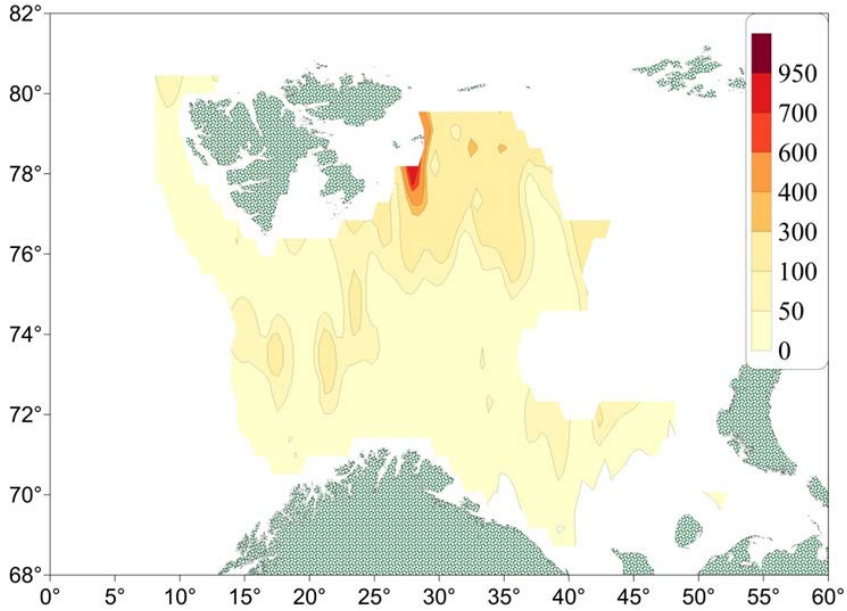


Figure 3.3.17. Distribution of hyperiids (ind. per 1000 m³) in the near bottom layer in the Barents Sea based on data from the Russian winter survey in October-December 2015.

The following information is based on the joint Norwegian/Russian Barents Sea Ecosystem survey in autumn 2016, and the text and Figures below are extracted and partly modified from Eriksen *et al.* (2017). The catches from pelagic trawls covering the upper layers (0-60 m) of the Barents Sea in August-October 2016 revealed the presence of amphipods in the northern Barents Sea (Figure 3.3.18). In 2012 and 2013, amphipods were lacking in the pelagic catches. In 2014 some restricted catches were taken north for Svalbard/Spitsbergen, and in 2015 several large catches were made east of Svalbard/Spitsbergen. In 2016, the largest catches were made north and east of Svalbard/Spitsbergen, and mainly consisted of the Arctic species *Themisto libellula*. In 2016, the estimated biomass of amphipods was 430 thousand tonnes for the covered area, which was slightly lower than estimated in 2015. In addition to *Themisto* sp., small catches of *Hyperia galba*, which is biologically associated with jellyfish, were made in the northern part of the central area. Other hyperiids (from genuses Hiperia and Hyperoche) also occurred, but their abundances were very low.

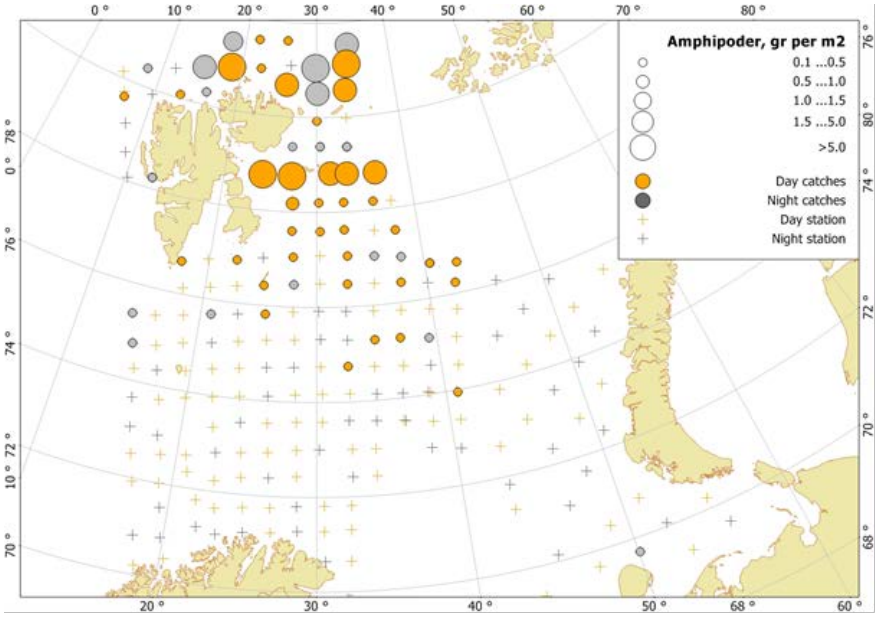


Figure 3.3.18. Hyperiid amphipod distribution, based on trawl stations covering the upper water layers (60-0 m), in the Barents Sea in August-October 2016. Figure from Eriksen *et al*. (2017).

Chaetognaths

During the Russian winter surveys, chaetognath concentrations increased from 734 ind. 1000 m^{-3} in 2012 to 1022-1198 ind. 1000 m^{-3} in 2013–2014, reaching 1225 ind. 1000 m^{-3} in 2015. Such high abundances of predatory chaetognaths may affect the abundances and biomasses of other groups of mesozooplankton. Distribution of chaetognaths in late 2015 is shown in Figure 3.3.19.

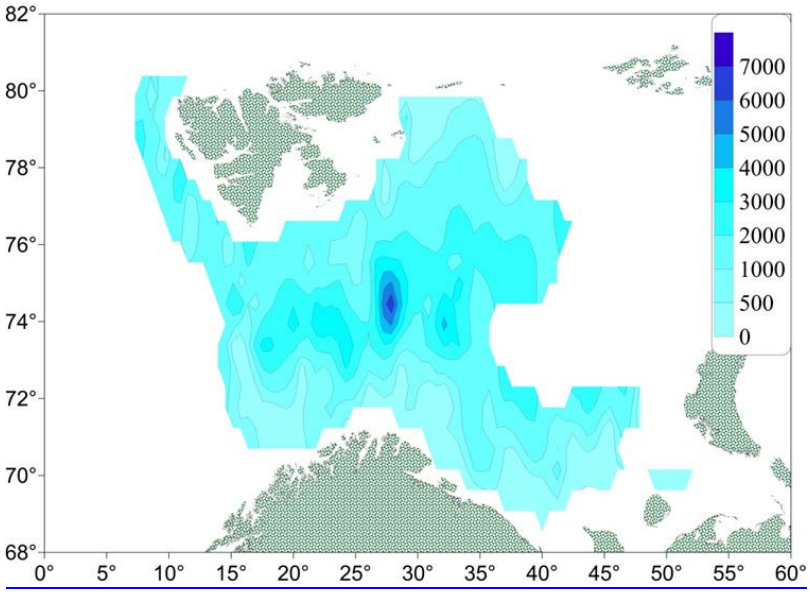


Figure 3.3.19. Distribution of chaetognaths (ind. per 1000 m^3) in the near bottom layer in the Barents Sea based on data from the Russian winter survey in October-December 2015.

Jellyfish

The geographic distributions and estimated abundances (biomass) of gelatinous zooplankton presented here are based on data collected during the joint Norwegian/Russian Barents Sea Ecosystem survey in autumn 2016, using the standard pelagic trawl

for the depth-stratum of 0-60 m. The Figures and text below are modified from Falkenhaug *et al.*, 2017. Trawling is a harsh sampling method for gelatinous zooplankton, and the data presented here should be considered as semi-quantitative data. The trawl does not sample the entire water column, the filtered volume of water is not known, and small and fragile species will may pass through the meshes of the trawl and are easily destroyed in the codend. The Harstad trawl probably has a higher catchability for large, robust scyphozoans (P*eriphylla periphylla*, *Cyanea capillata*) than for the smaller *Aurelia aurita*, and even more so than for fragile taxa such as ctenophores and small medusa (Falkenhaug *et al*., 2017). Nevertheless, we here consider that the error in catchability is constant for each taxon, allowing taxon-specific comparisons between years and between stations.

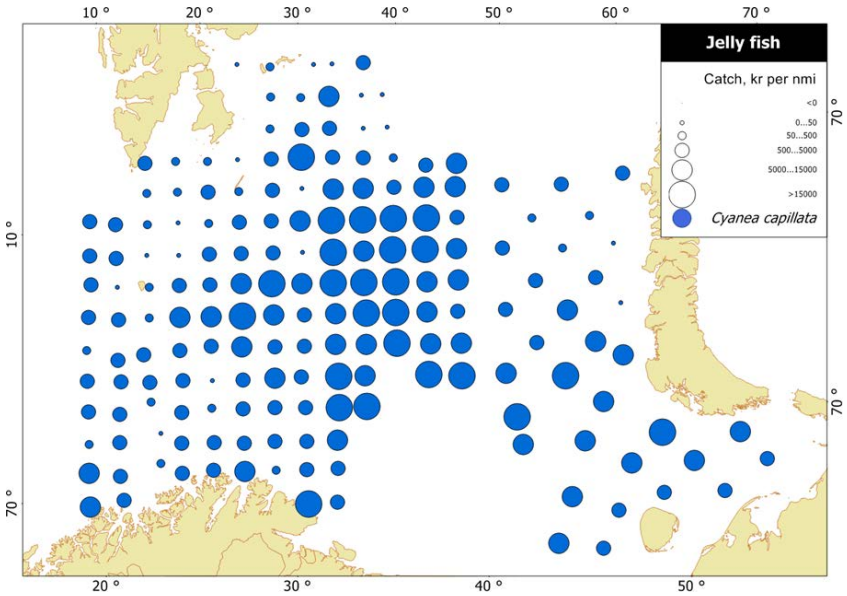


Figure 3.3.20. Distribution of *Cyanea capillata* (wet-weight; kg per sq nm) in the Barents Sea, August-October 2016. Catches from standard pelagic trawl, 0-60 m depth, both day and night. Figure by Elena Eriksen – see Falkenhaug *et al*. (2017).

In 2016, lion's mane jellyfish (*Cyanea capillata*; Scyphozoa) was the most common jellyfish species both regarding catch-weight and occurrence (average catch of 21.9 kg per nm), and it was distributed across the entire survey area (Figure 3.3.20). The biomass per station was generally lower than in 2015. The horizontal distribution of *C. capillata* in 2016 was similar to in 2014 and 2015, with the highest biomasses located in the central and south-eastern area.

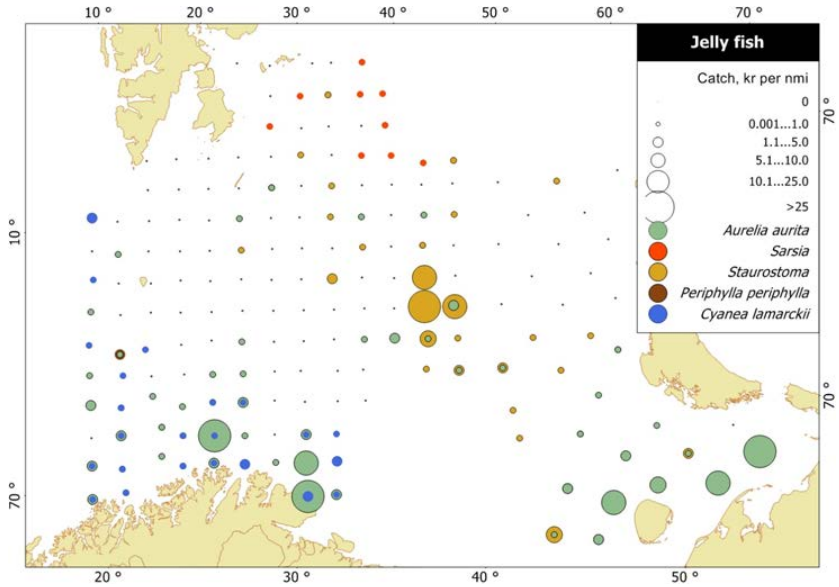


Figure 3.3.21. Distribution of five taxa of gelatinous plankton (wet-weight; kg per sq nm) in the Barents Sea, August-October 2016. Catches from standard pelagic trawl 0-60 m depth, both day and night. Figure from Falkenhaug *et al.* (2017).

The moon jellyfish (*Aurelia aurita*; Scyphozoa) was the second most abundant jellyfish species by total weight (average catch of 1.2 kg per nautical mile), and mainly distributed in the southern part of the survey area (Figure 3.3.21). The whitecross jellyfish (*Staurostoma mertensii*; Hydrozoa) is a common arctic species. In August-October 2016, this species was distributed from the northern to the south-eastern part of the survey area, with maximum abundances in the central Barents Sea (Figure 3.3.21). The blue stinging jellyfish (*Cyanea lamarckii*; Scyphozoa) is considered a more temperate species than *C. capillata*, but in recent years this species has been indicated to increase its distributional range northward. During the Barents Sea Ecosystem cruise 2016, *C. lamarckii* was registered at 32 stations in the western area, with an average catch of 0.1 kg per nm. It is believed that *C. lamarckii* is unable to reproduce in the Barents Sea, and that the presence of this warm-temperate species may be linked to the inflow of Atlantic Water.

The estimated total biomass of *C. capillata* in upper water layers (0–60 m) of the Barents Sea in August-October 2016 was 1.6 million tonnes (Figure 3.3.2). This was less than in 2015 (2.5 million tonnes), and close to the long-term mean 1980–2016 (1.2 million tonnes). During the last 6 years (2011–2016), the estimated total biomass of jellyfish has been above the long-term mean.

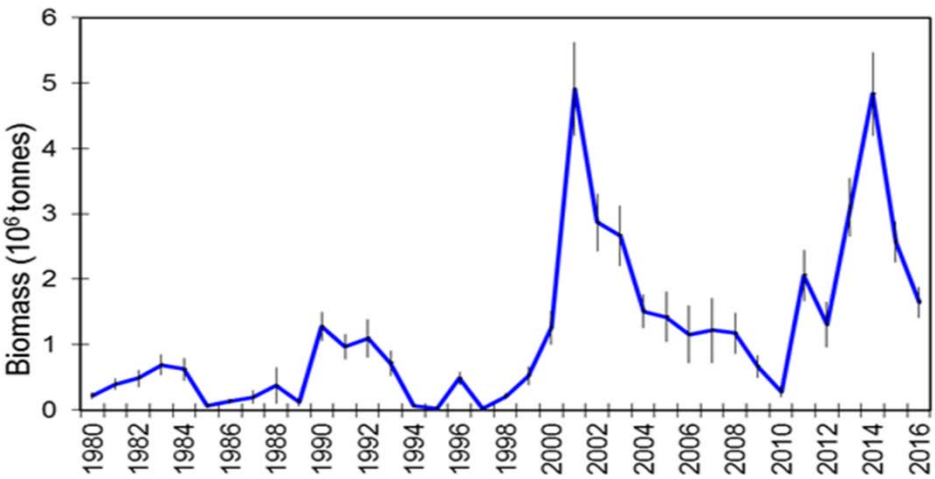


Figure 3.3.22. Estimated jellyfish biomass for the Barents Sea, in million tonnes with 95% confidence interval (grey line) for the period 1980–2016. Estimates based on autumn trawl-catches covering the upper layer (60–0 m). Note that until 2013, all jellyfish are included in estimates presented in the Figure, while from 2014 onwards only *Cyanea capillata* is represented (Eriksen, 2012)

3.4 Benthos and shellfish

Benthos

Benthos is one of the main components of the marine ecosystems. It can be stable in time, characterizing the local situation, and is able to show the ecosystem dynamics in retrospective. It is also dynamic and shows pulses of new species distribution, such as the snow crab and the king crab, and changes in migrating benthic species (predatory and scavenger species such as sea stars, amphipods and snails with or without sea anemones). The changes in community structure and composition reflect natural and anthropogenic factors. There are more than 3000 species of benthic invertebrates registered in the Barents Sea (Sirenko, 2001), but here we only present the megafaunal component of the benthos collected by trawl and registered (species, abundance and biomass) during the join Russian-Norwegian Ecosystem survey. This includes mainly large bodied animals with long lifespans. This investigation started in 2005, but compared with the timelines of plankton and fish investigations, this is a short timeline. This means that interpretation of long-term trends in the megabenthic data must be considered with respect to this limitation.

Benthos collection

Benthos. catch with the standard demersal trawl at the Ecosystem Surveys, have been registered annually by benthic taxonomic specialists since 2005 on board Russian vessels, while annually 2007–2013 and in 2015–2016 on board Norwegian vessels. The identification has been to lowest possible taxonomic level, but in case there were no specialist available on board (2007–2008 in northern Barents Sea in Norwegian sector), the benthos bycatch has been identified to main benthos groups. There is ongoing work between IMR and PINRO to harmonize and improve species identification and benthos catchability in the trawl among the specialists and vessels. Several publications have been made based on the fine taxonomic resolution data (Anisimova *et al.*, 2011; Jørgensen *et al.*, 2015a; Jørgensen *et al.*, 2015b).

Megafaunal description

The distribution of the large benthos groups shows that Porifera (mainly the *Geodia* group) dominates in biomass in the west, while Echinodermata (mainly brittlestars) dominates in the east. In the NE, Cnidaria (soft corals, such as the sea pen *Umbellula encrinus*, and sea anemones) dominates together with Echinodermata, while Crustacea dominates together with the Echinodermata in the SE (Figure 3.4.1).

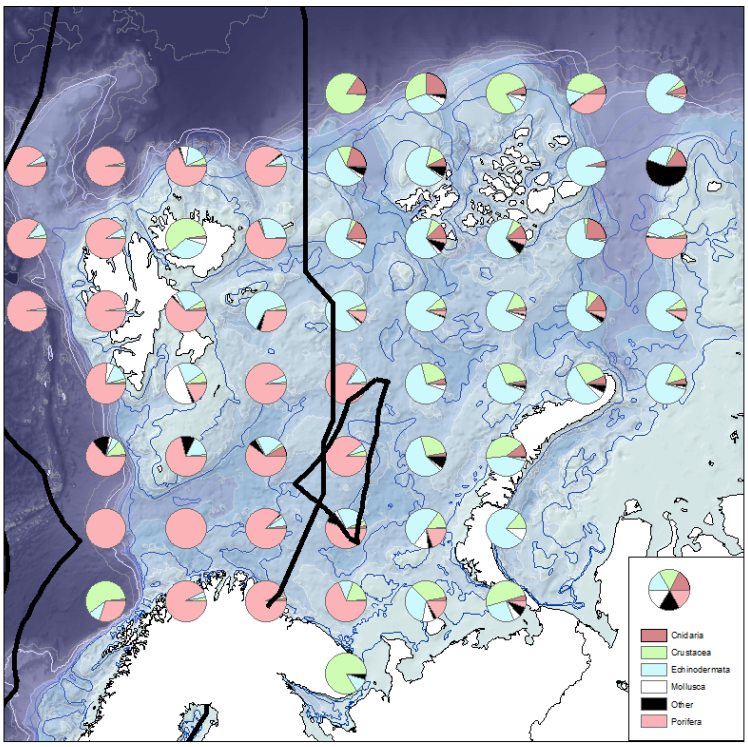


Figure 3.4.1. The main benthos group distribution (in biomass). The data are the integrated mean for the period 2009–2014.

Statistical analyses of data from the monitoring show that there are four distinct zones of benthos in the Barents Sea (Jørgensen *et al.*, 2015a, Figure 3.4.2). These four zones are characterized with temperate species in the southwestern part, cold-water species in the eastern part, arctic species in the northern and northeastern part, and an area in the eastern Barents Sea where the snow crab, a new non-indigenous large benthic species, are expanding. The period with warmer water entering the Barents Sea has led to migration eastwards and northwards of temperate species and groups (Jørgensen *et al.*, 2015a). The retreating ice front opens for new areas for human impact as well as imposing changes in the planktonic production and annual cycles, with possible impact on the benthic zones.

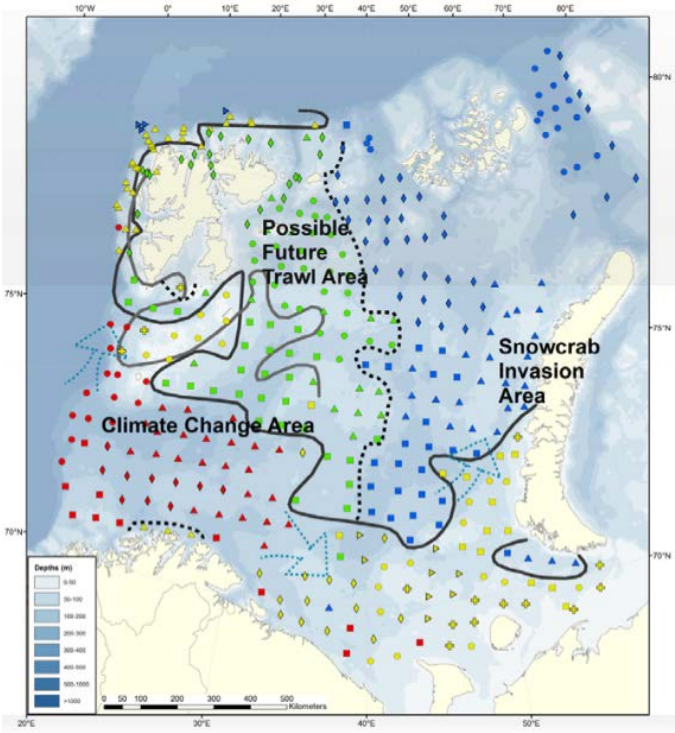


Figure 3.4.2. The baseline map of the Barents Sea mega-benthic zones in 2011, based on fauna similarity (see Jørgensen *et al.*, 2015a for methodology, results and discussion) with the northern (green and blue) and southern (yellow and red) region where the black full line is illustrating the "benthic polar front" in 2011. The grey full line is the approximately oceanographic Polar Front. Dotted line: Is partly illustrating a west-east division. Red: South West subregion (SW) Yellow: Southeast, banks and Svalbard coast (SEW). Green: North West and Svalbard fjords (NW). Blue: North East (NE). Source: IMR.

The status of the megabenthos in 2016 and possible trends.

In the short "long-term" monitoring of the distribution of benthos (g/nm trawling) shows relative stable large-scale patterns with high biomass particularly in the SW, but also stable, though changing biomass in the north east. The central part of the Sea is fluctuating in biomass and shows that the biomass distribution has a high level of spatial and temporal variety (Figure 3.4.3) which are difficult to explain due to the short period of monitoring.

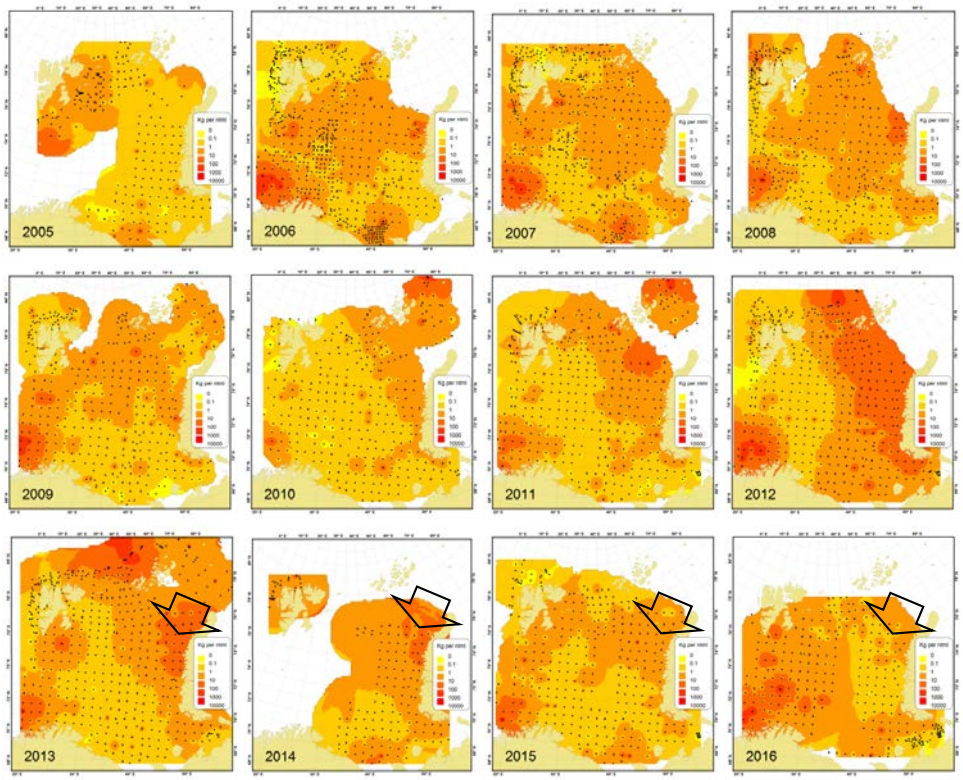


Figure 3.4.3. The annual Interpolated biomass (log) distribution of the Barents Sea from 2005 to 2016. In 2012, the biomass of the Russian zone was overestimated and shall be considered as an error. In 2005 and in 2014 only parts of the Norwegian zone was covered.

In order to estimate the long-term dynamic of the benthos state, the interannual changes of the mean biomas total for the sea and separetely in four sectors (NE, NW, SW and SE) was analysed.

The total Barents sea

The 2005–2016 fluctuation in total mean biomass of the Barents Sea (excluding large, i.e. >1 T, sponge catch in the SW) shows a decreasing trend from 2007 to 2010 (Figure 3.4.4). The biomass fluctuation from 2010 and onwards is not possible to identify due to missing data in 2012 and 2014 (i.e. technical problems and missing coverage of the benthos). The biomass of 2016 seem to be at the mean value and in the range of interannual variations (Figure 3.4.5), but due to missing data, a longer time serie is neccessary.

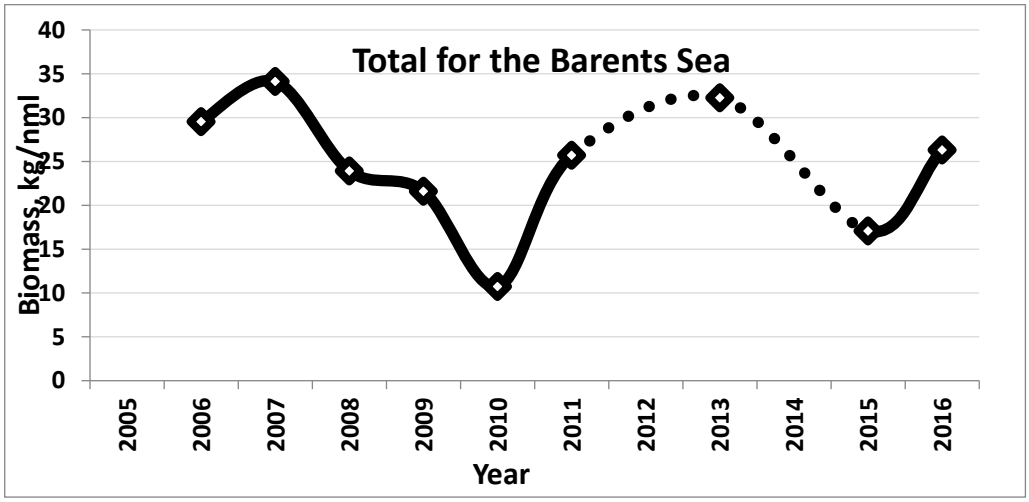


Figure 3.4.4. The annual total mean biomass (kg/n.ml) of the Barents Sea from 2005–2016. Broken line mean missing coverage. Total Barents Sea = South of 80°N and 15°E but excluding all stations W and N of Svalbard to 62°E and all sponge catches >1 T excluded.

Northwest (NW) and southwest (SW)

Although sponge catches >1 T was excluded the biomass in the SW was higher than in the NW during the period of long-term monitoring. The mean biomass of the NW, SW and the total Barents Sea was at the lowest in 2010 (Figure 3.4.5). Since then all three values was increasing until 2013. The value for 2014 is unknown due to missing coverage, but the mean biomass was observed from 2015 and 2016 to the highest measured (54 and 39 kg/nml respectively) for the western Barents Sea since 2005. The long-term variation of the mean biomass of the NW, SW and the total Barents Sea show strong correlations. This might indicate that the western Barents Sea are driven by a factor common for the total Barents Sea.

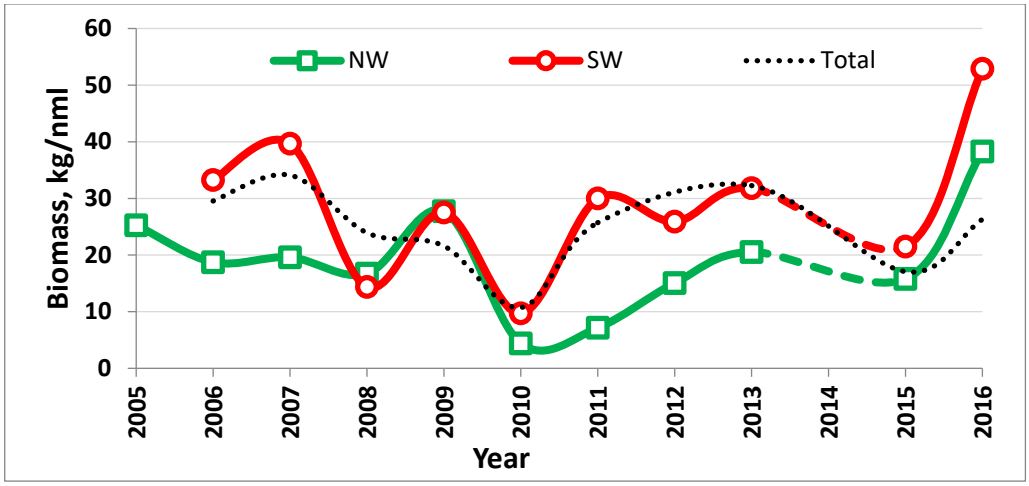


Figure 3.4.5. The interannual mean biomass fluctuation of the SW (red, all <1 T catches of sponges excluded) and NW (green) from 2005–2016. The dotted line is the Barents Sea mean biomass (see also Figure y3). NW = 74–80°N and 15–40°E but excluding all stations W and N of Svalbard, SW = 65–74°N and 10–40°E. All stations west and north of Svalbard and all sponge catch >1 T excluded.

Southeast (SE) and northeast (NE)

In the SE area (Figure 3.4.6) benthos had a record high maximum in 2007 (60 kg/nml), due to one extra-large catch of king crab, but has stayed low (<25 kg/nml) all years after this, and below the total Barents Sea mean. The SE are experiencing high level of commercial trawling which might be the cause of the low benthos-biomass. This become

more evident when the SE is compared to the high biomass of benthos in the NE which have no trawling activity (Ljubin *et al.*, 2011).

The highest biomass (sponge catch >1 T excluded) in the Barents Sea was recorded in the NE (>60 kg/n.ml). In most of the measured years, the biomass in the NE was above the total Barents Sea mean (Figure y5). But from 2013 and ongoing, the mean biomass (see also black arrows in Figure 3.4.6) was reducing, and was record low (<20 kg/nml) in 2016, and below the total Barents Sea mean.

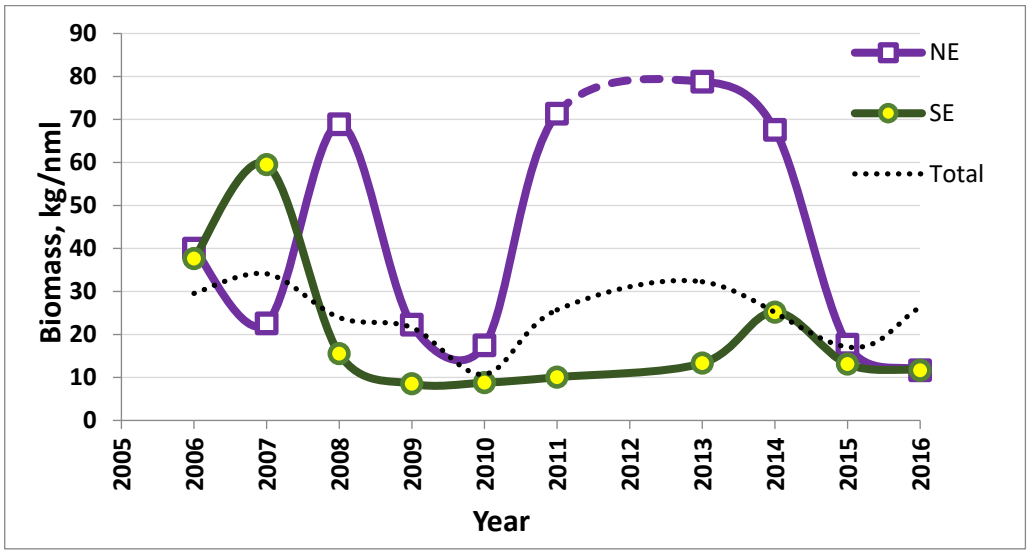


Figure 3.4.6. The interannual mean biomass fluctuation of the SE (red line with yellow circles) and NE (blue). The dotted line is the Barents Sea mean biomass (see also Figure y3). NE=74-80°N and 40-62°E, SE=65-74°N and 40-62°E.

The area of reduced benthos biomass after 2013 (black arrows in Figure 3.4.3. for 2013-2016) are overlapping with the maximum distribution of the snow crab (see below) and with increasing bottom temperatures (chapter 3.1). We therefore suggest the strong decrease in benthos biomass to be an effect of multiple impact factors.

State of selected benthic species

Snow crab

The snow crab is a new species in the Barents Sea. There are several theories of the appearance of crab including invasion via ballast water or natural spreading from the west or east. The first record of the crab was done in 1996 (Figure 3.4.7) and regular annual investigation of the snow crab population started on the Ecosystem Survey in 2004.

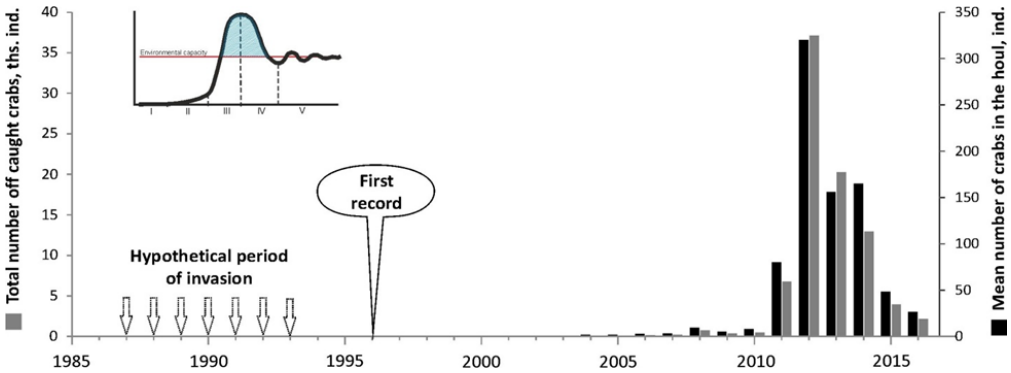


Figure 3.4.7. The invasion period, the first record, and the dynamics (data from Ecosystem Survey 2004–2016) of the snow crab population in total number of individuals (grey) and mean number of individuals (black) per trawl (Strelkova, 2016).

Since these early observation, the crab has mainly been recorded west of Novaya Zemlya (Figure 3.4.8) and studies on size structure of the population show two strong generations of snow crab juveniles in 2009 and in 2012 (Figure 3.4.9). The 2009 generation resulted in a subsequent increase in abundance in 2011–2014 while the 2012 generation will have a peak in nearest future.

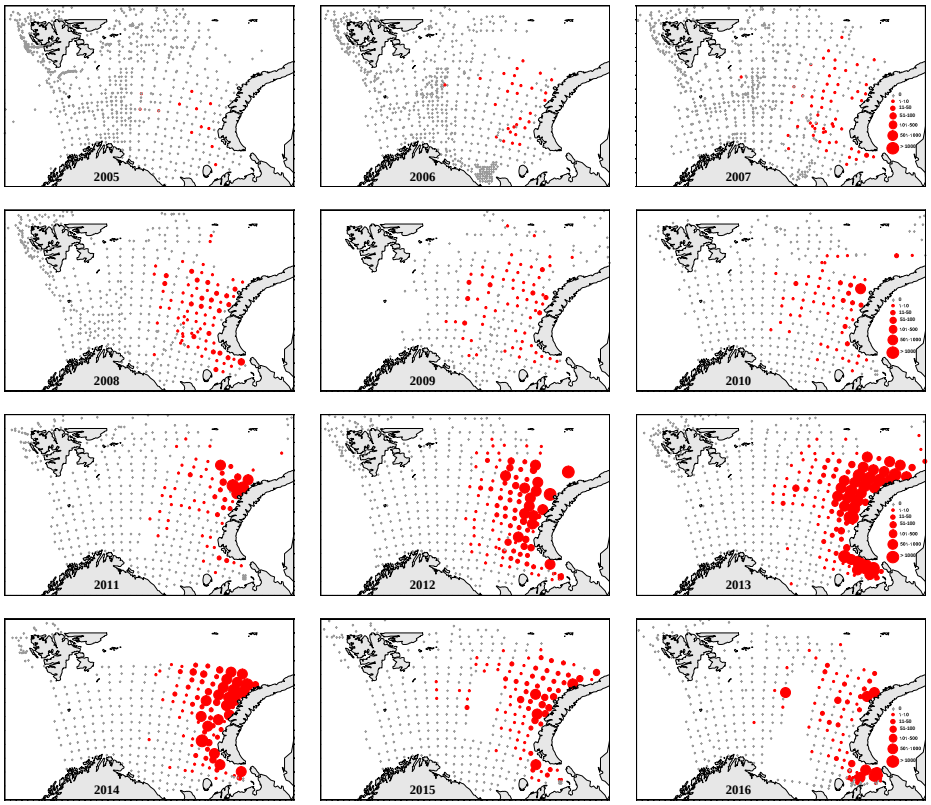


Figure 3.4.8. The dynamics of the snow crab population in number of individuals of the Barents Sea from 2005–2016 (according to Strelkova, 2016 with additional data of 2016).

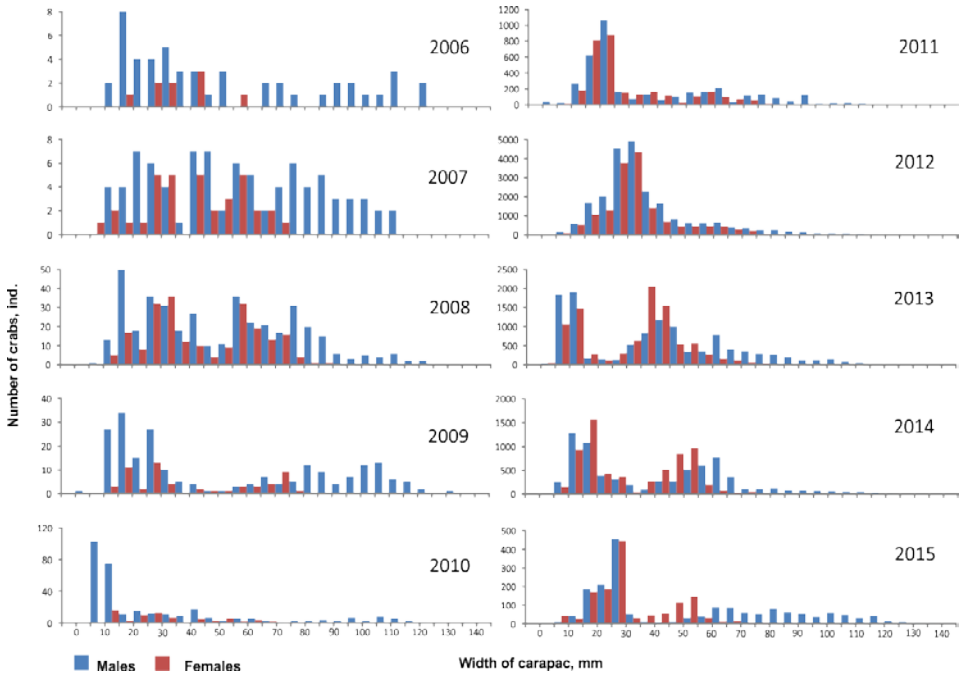


Figure 3.4.9. The sex and size structure of the snow crab population from 2006–2015 (Bakanev and Pavlov, 2016)

In 2012 the abundance of snow crabs in the Barents Sea reached a maximum, and started to decrease from 2013 to 2016 (Figure 3.4.9). This resulted in a reduction of the snow crab population to half of the size compared to the peak years. But as this species lives seasonally patchy, and often in dense pods, stock assessment is difficult, with autumn samplings giving the most reliable assessments (Mullowney *et al.*, 2014)

The calculation of the population abundance index (Bakanev *et al.*, 2016) show that the snow crab population reached 4346 millions individuals in 2012 that was spread across an area of 569 000 km² (Table 3.4.1).

Table 3.4.1. The spreading area, mean abundance and total stock indices of the snow crab in the Barents Sea 2004–2014 (Bakanev *et al.*, 2016).

Year	Spreading area in thousand km	Mean abundance ind. /km²	Abundance index mill ind.
2004	44	1	0.63
2005	130	3	2.21
2006	262	7	5.24
2007	336	19	14.31
2008	447	116	86.38
2009	514	36	26.91
2010	557	76	56.25
2011	605	1144	849.63
2012	569	5854	4346.32
2013	662	3071	2280.25
2014	452	2234	1658.43

Analysis of the snow crab distribution show a temperature preference from -1.9 to 9.3°C, with the densest aggregations from -1.5 to 3.0°C (temperature optimum) (Bakanev *et al.*, 2016). This means that the temperature is the strongest factor limiting the spread of the snow crab to the south and western part of the Barents Sea. This could also explain that the Ecosystem Survey did not record a significant spread of crab toward the west during 2004–2016. Probabilistic estimation of the snow crab distribution in the Barents Sea (Bakanev, 2016) shows that if the bottom temperature will decrease with 1°C, the snow crab is expected to spread westward and reach the Hopen Deep and the areas round Svalbard (Figure 3.4.10B), but if the temperature increase by 1°C, the population is not expected to reach the Hopen Deep or the shallower parts of the sea around Svalbard.

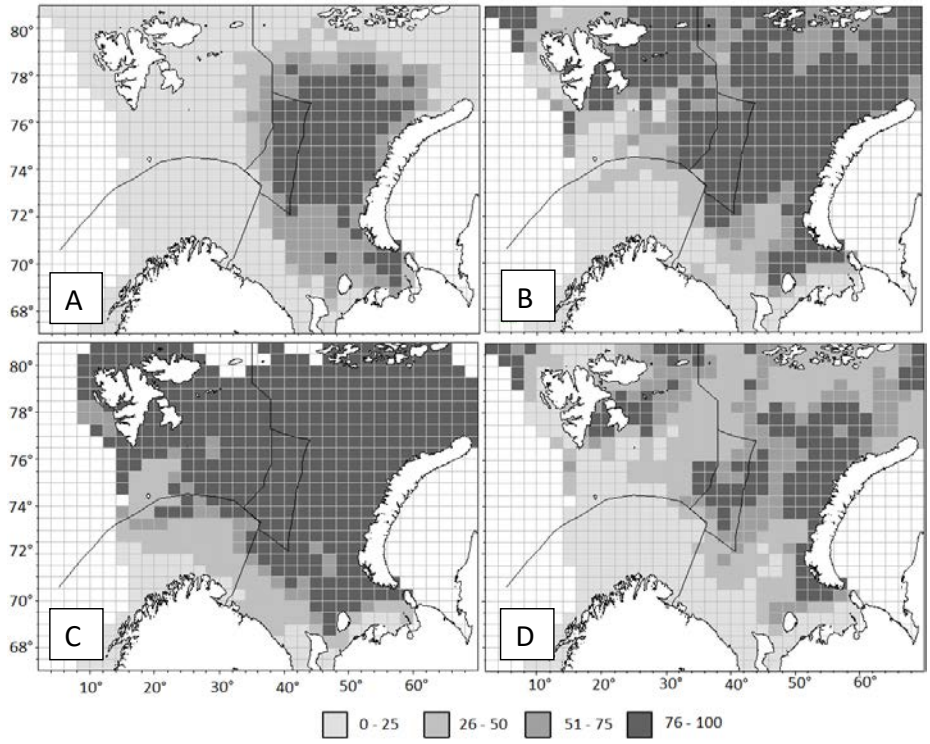


Figure 3.4.10. The probability of occurrence (%) of snow crab in the Barents Sea in 2010–2014 (A) and a forecast of the distribution if the water temperature stay at the long-term mean (B) in the case of temperature decrease of 1°C (C) and an increase of 1°C (Bakanev, 2016).

The temperature is not limiting the eastward spread of the snow crab. This was shown by the PINRO trawl investigation in 2007 and in 2013 in the Kara Sea and St. Anna trough, where the number of snow crabs increased from zero to several individuals per station (Figure 3.4.11).

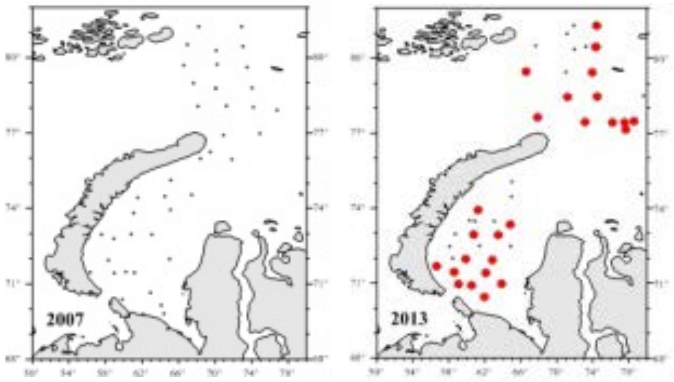


Figure 3.4.11 Station coverage of PINRO trawl surveys and ecosystem surveys into the Kara Sea and St. Anna trough in 2007 and 2013 without (black dots) or with (red dots) snow crab records (according to Strelkova, 2016)

Northern shrimp

Northern shrimp (*Pandalus borealis*) is widely distributed in the Barents Sea (Figure 3.4.12). The highest densities are recorded on silty grounds on the slopes of banks, troughs and the northern continental slope facing the Arctic basin, as well as in the western fjords and northern sound of the Svalbard. Usually are the highest densities found in the frontal zones between the Arctic and boreal waters, but has in the recent years shifted eastwards (NIPAG 2015). The optimum bottom temperatures for the densest concentrations of the northern shrimp are between 0 and 2°C. (Berenboim, 1992).

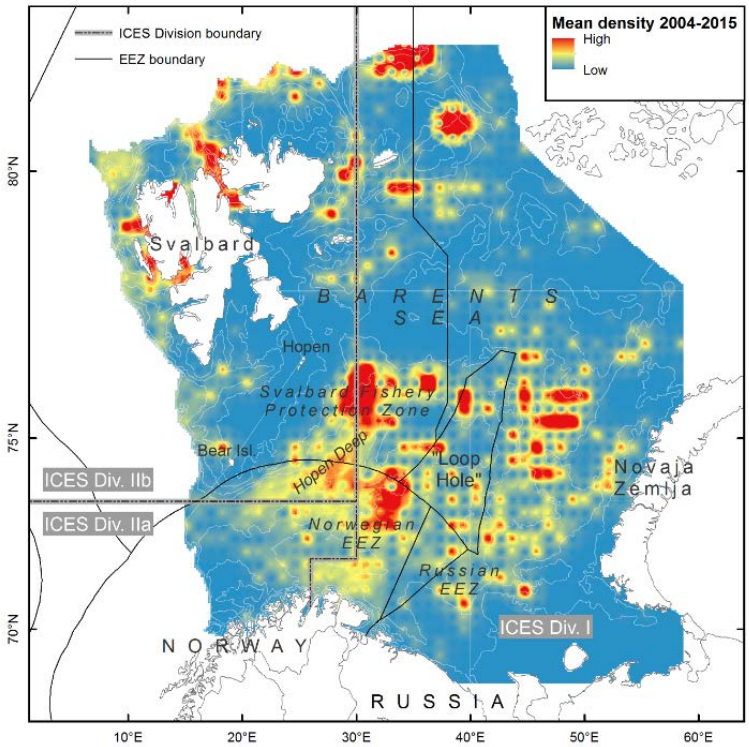


Figure 3.4.12. The mean density of *Pandalus borealis* in the Barents Sea from 2004 and 2015 with highest values in red.

After a minimum shrimp stock size in the last half of the 1980s, the size of stock has increased but is fluctuating. The results from the ecosystem survey in 2015 and 2016 (Figure 3.4.13) suggest a slight increase in the stock compared to 2014 and an estimate slightly above the average for the ecosystem survey period (2004-2016).

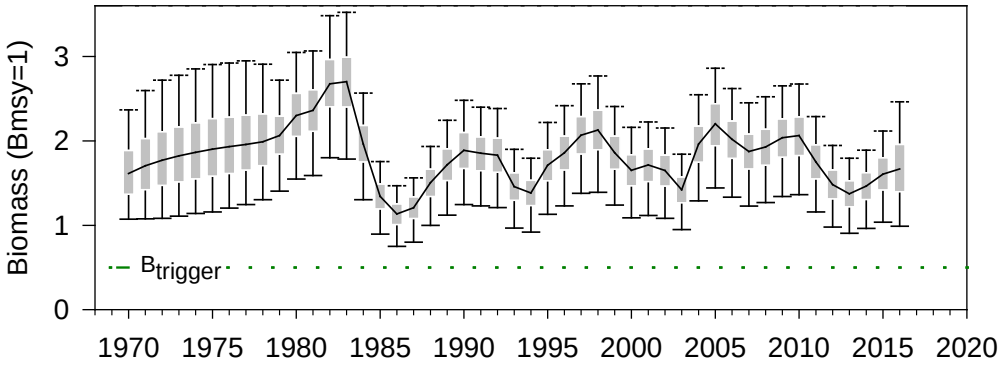


Figure 3.4.13. The temporal development in the shrimp stock 1970–2016 (relative abundance estimates from assessment model, provided by C. Hvingel), in ICES Subareas 1 and 2.

3.5 Pelagic fish

Total biomass

Zero group fish are important consumers on plankton and prey of other predators and therefore an important element in the transfer of energy between trophic levels in the ecosystem. The total biomass of 0-group (cod, haddock, herring, capelin, polar cod, and redfish), was 1.95 million tonnes in August-September 2016, which is slightly above the long-term mean of 1.76 million tonnes (Figure 3.5.1). The biomass was dominated by capelin and herring. Most of the biomass was distributed in the central and northern-central part of the Barents Sea.

Capelin, polar cod and young herring and blue whiting constitute the bulk of pelagic fish biomass in the Barents Sea. The total biomass of the main pelagic species (age 1 and older fish) in the Barents Sea in 1986–2016 has fluctuated between about 0.5 and 9 million tonnes. The main driver of this variation has been fluctuations of the capelin stock. In 2016 the cumulative biomass of capelin, herring and polar cod was below the long-term mean (Figure 3.5.2).

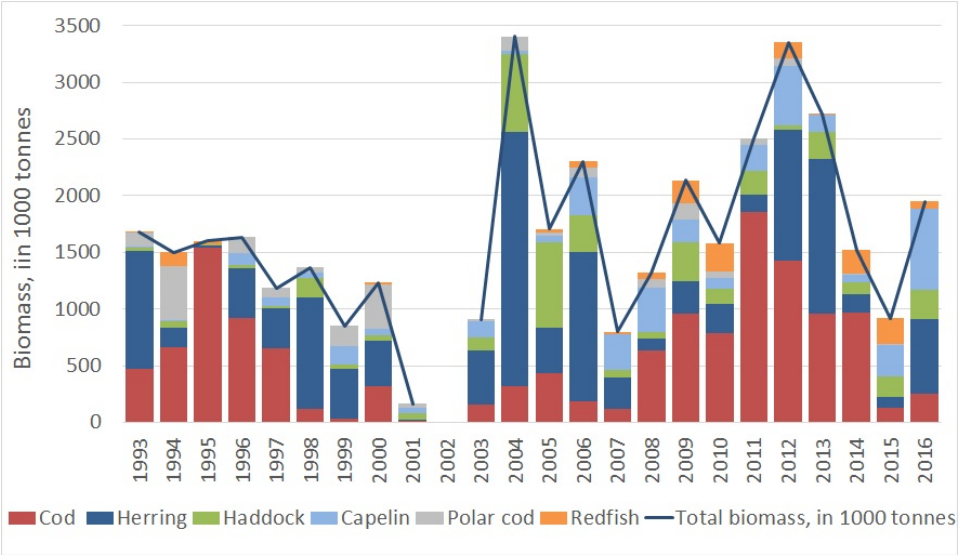


Figure 3.5.1. Biomass of 0-group fish species in the Barents Sea, August-October 1993-2016.

Capelin, young herring and polar cod constitute the bulk of pelagic fish biomass in the Barents Sea. In some years (e.g. 2004–2007), blue whiting (*Micromesistius poutassou*) also has a significant biomass but only in the western, deeper part of the sea. The total biomass of the main pelagic species in the Barents Sea in 1986–2016 has fluctuated between about 0.5 and 9 million tonnes. The main driver of this variation has been fluctuations of the capelin stock. In 2016 the cumulative biomass of capelin, herring, polar cod, and blue whiting was only half of the long-term mean (Figure 3.5.2).

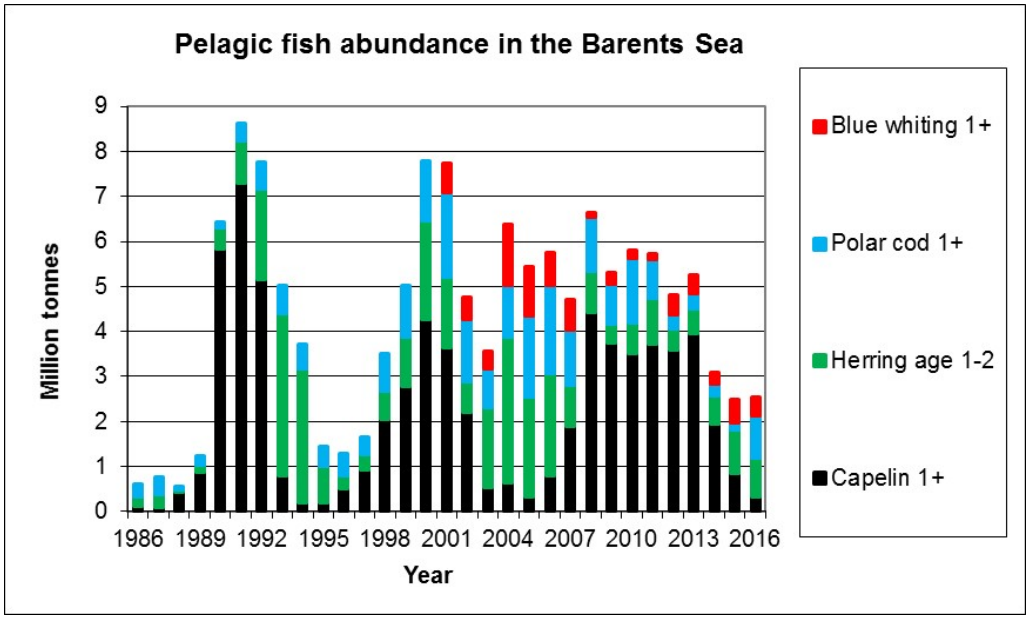


Figure 3.5.2 Biomass of main pelagic fish species (excluding 0-group stage) in the Barents Sea, August-October 1986–2016.

Capelin
Young of the year

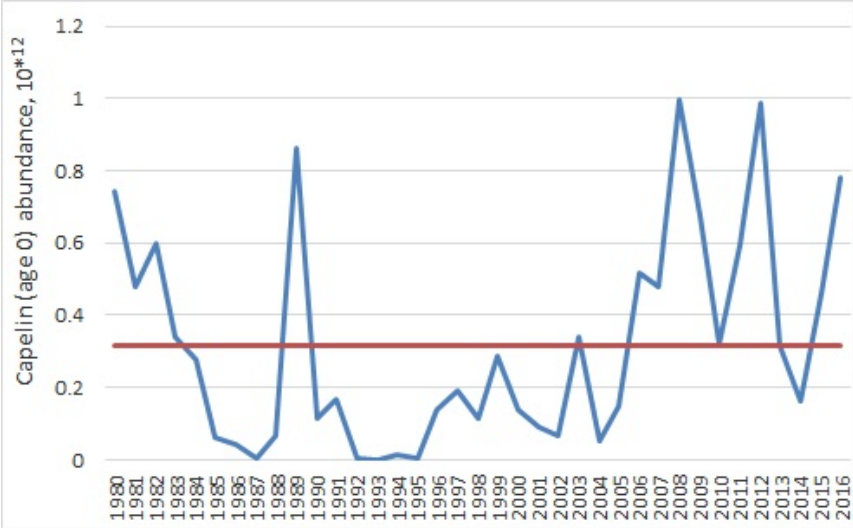


Figure 3.5.3. 0-group capelin abundance in the Barents Sea 1980-2016. Orange line shows long-term mean for the period 1980-2016, while blue line indicate 0-group abundance fluctuation.

The 0-group capelin was distributed widely in the Barents Sea with more dense concentrations in the north-central Barents Sea, as in 2016. The area around Svalbard/Spitsbergen Archipelago were covered one month later than the main area and the southern Barents Sea was not completely covered, thus the results should be interpreted as minimum values. Most of the 0-group capelin likely originates from spring-spawning, however some were most likely from summer spawning. The average fish length was 5.6 cm which is larger than in 2013-2015 and close to the long-term mean (5.5 cm). The large size of 0-group capelin may most likely indicate suitable living conditions during summer and increases the chance to survive through winter. The capelin length varied from 1.5 to 7.6 cm, however the length of most of the fish (89%) was between 4.6 and 7 cm. The abundance index of 0-group capelin in 2016 was very high and almost 3 times higher than the long-term mean (Figure 3.5.3).

Older capelin

The total capelin stock in 2016 is estimated at about 0.3 million tonnes, which is the lowest value observed since 2005 and far below the long-term mean level (about 3 million tonnes). The capelin stock is now into its fourth collapse in the last 30 years (Figure 3.5.4).

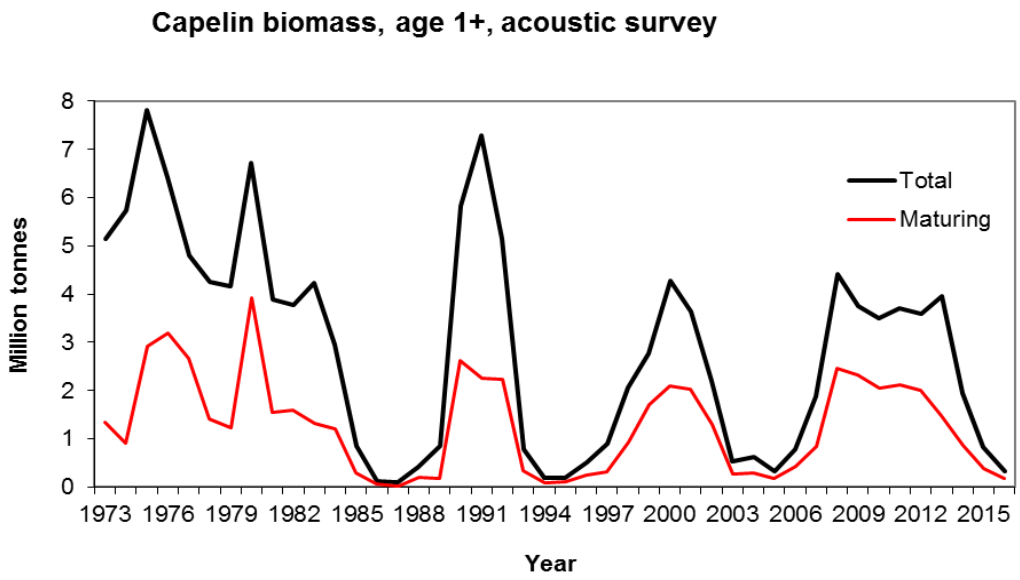


Figure 3.5.4. Capelin biomass 1973 – 2016. Maturing stock (>14cm) and total.

The geographical density distribution of capelin is shown in Figure 3.5.5. The distribution was similar to the one in 2015, but less capelin was found in the eastern areas and very little capelin was found north of King Karls Land. The capelin aggregations were also in general smaller than in 2015. The total stock is estimated at about 0.33 million tonnes, which is well below the long-term mean level of about 3 million tonnes, and about 40% of the stock size estimated for 2015. About 55% (0.18 million tonnes) of the 2016 stock has length above 14 cm and is considered to be maturing. The stock in 2016 was composed of relatively low abundances of all age groups (Figure 3.5.6).

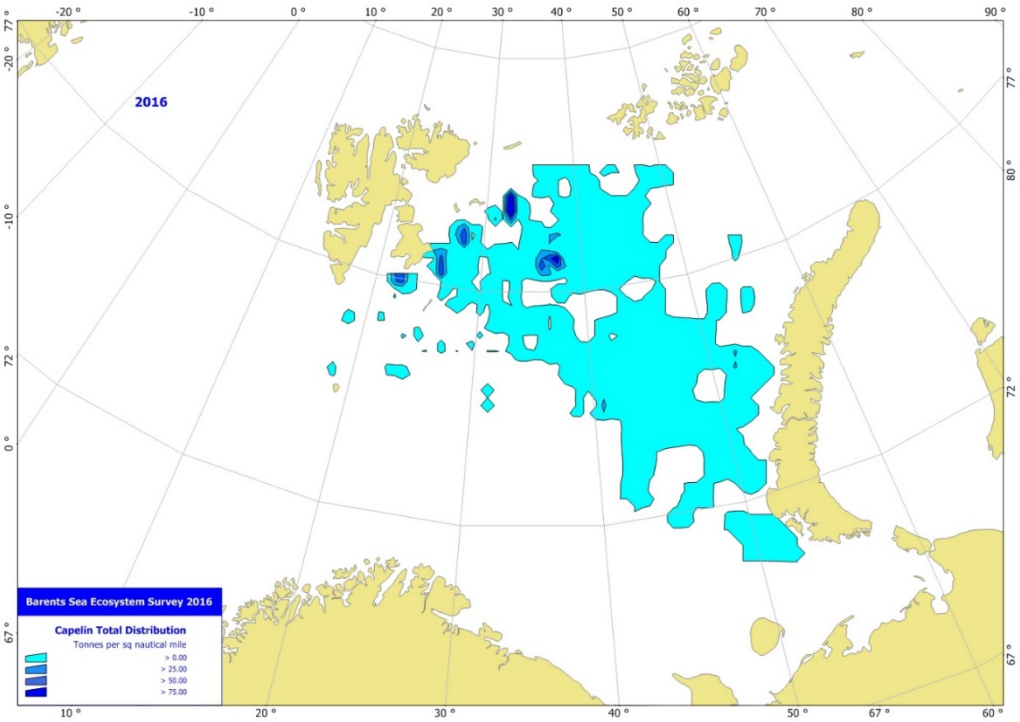


Figure 3.5.5. Estimated total acoustic density distribution of capelin (s_A-values), August-October 2016

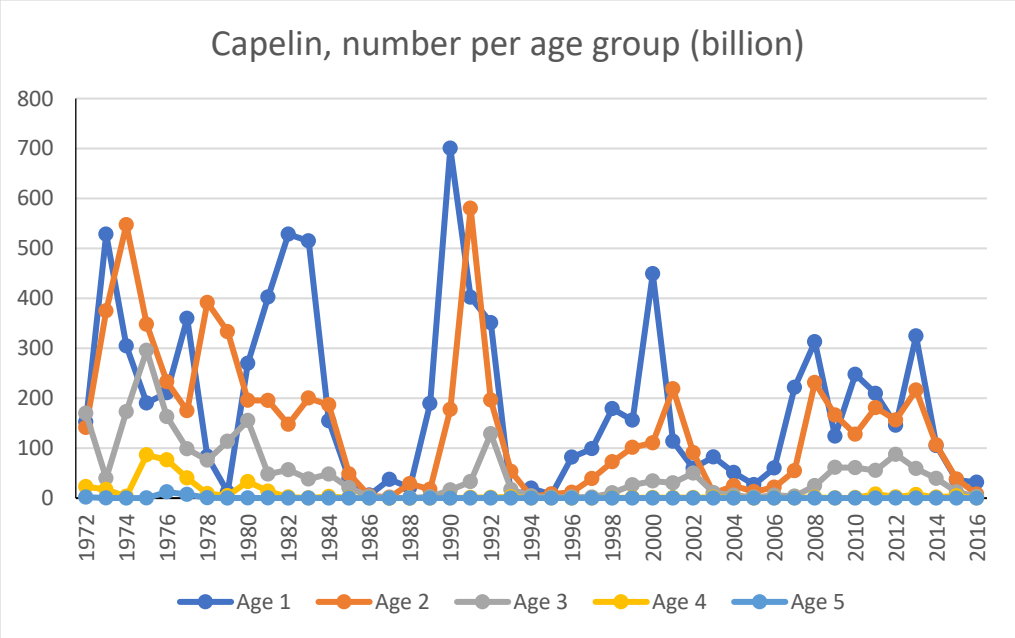


Figure 3.5.6. The capelin stock age composition during 1972-2016.

Herring
Young of the year

0-group herring were wider distributed than previous years and were found in the central, northern and eastern areas area and west of Svalbard/Spitsbergen in 2016. The main dense concentrations of herring were found in the central and eastern areas and west of Svalbard/Spitsbergen. The length of 0-group herring varied between 3.0 and 11.5 cm, and most of the fish (85%) were 7.0–9.5 cm long. In 2016 the mean length of 0-group herring was 8.4 cm and it was the highest since 2000. The 2016 year class of herring was below the long-term mean, and can be characterized as average (Figure 3.5.7).

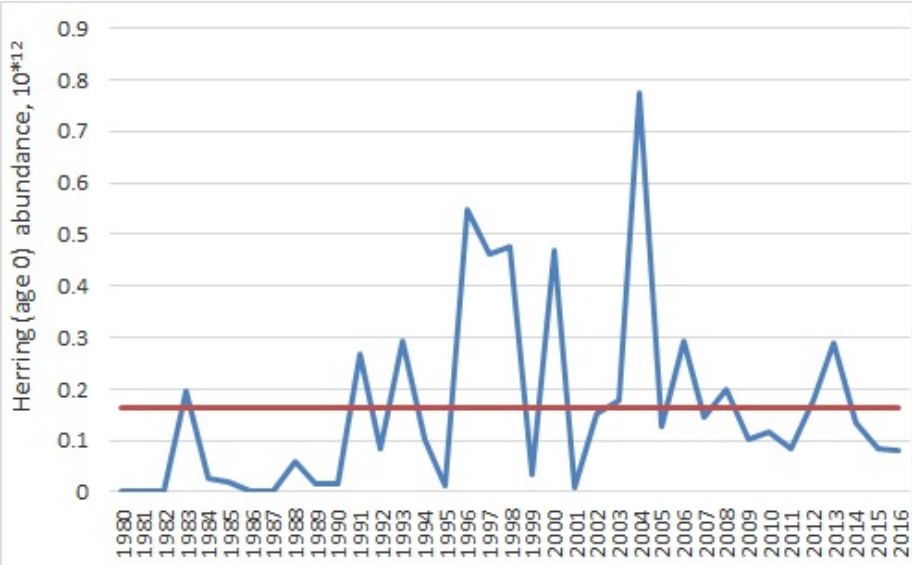


Figure 3.5.7. 0-group herring abundance in the Barents Sea 1980-2016. Orange line shows long-term mean for the period 1980-2016, while the blue line indicates 0-group abundance fluctuation.

Herring age 1, 2, and 3

From 2013-2016 the abundance of young herring found in the ecosystem survey has been relatively stable. Figure 3.5.8 shows the biomass of age 1 and 2 herring in the Barents Sea, calculated based on the last ICES assessment for age 2+ and assuming M=0.9 for age 1. In 2016 herring were found in patchy distributions in the southern Barents Sea (Figure 3.5.9).

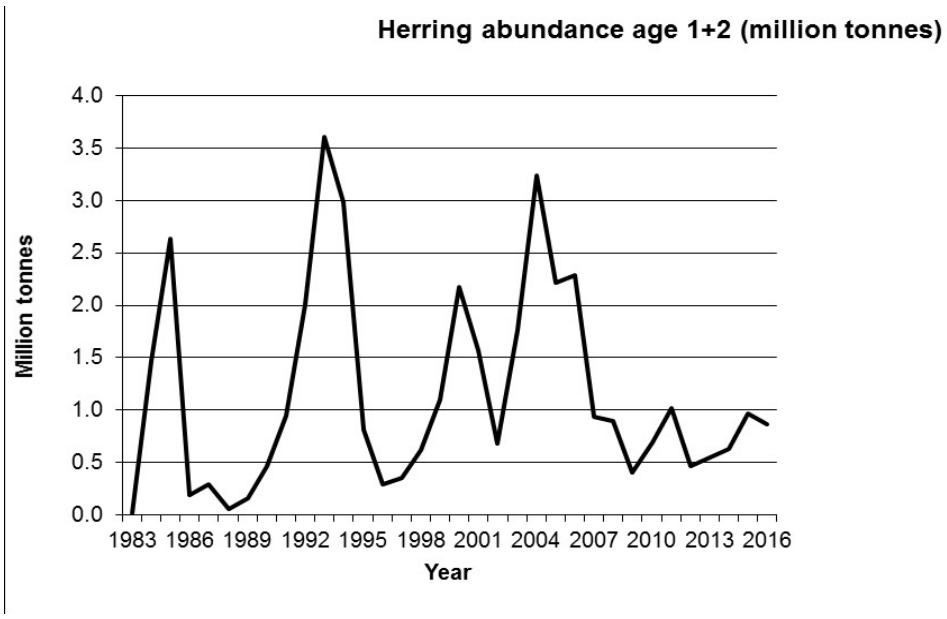


Figure 3.5.8. Age 1 and 2 herring in the Barents Sea – based on WGWIDE VPA estimates (ICES 2016b)

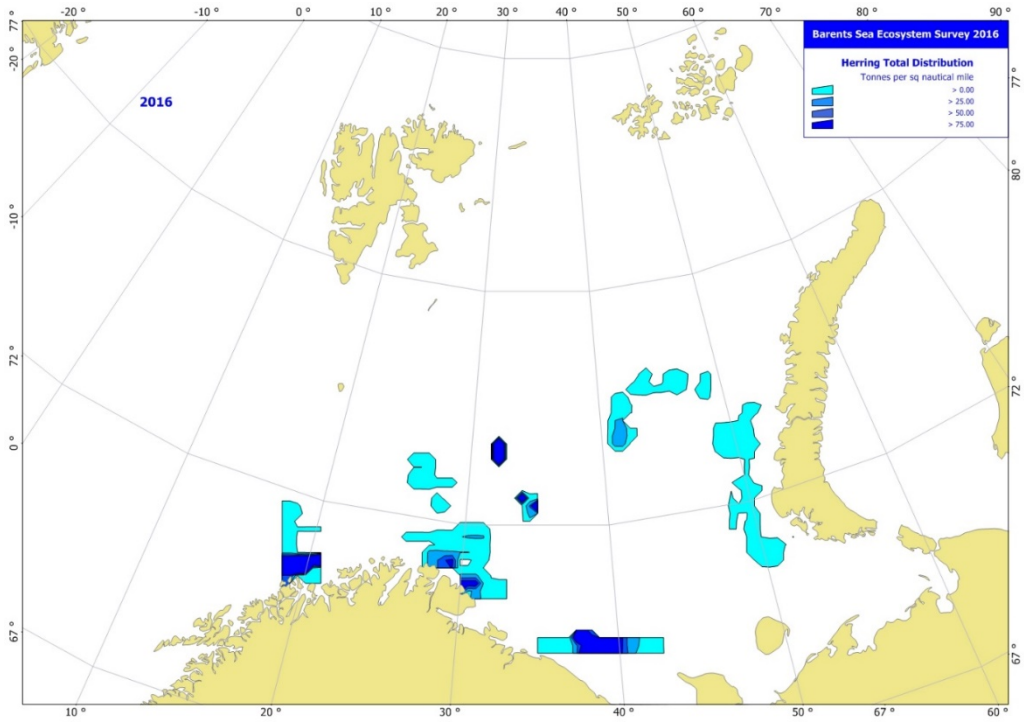


Figure 3.5.9. Estimated total density distribution of herring (t/nautical mile²). August-October 2016. Note that the survey coverage in the south central area was not complete.

Polar cod

Polar cod is a true Arctic species found in the whole circumpolar region. Traditionally, the world's largest population(s) of this species has been found in the Barents Sea.

Young of the year

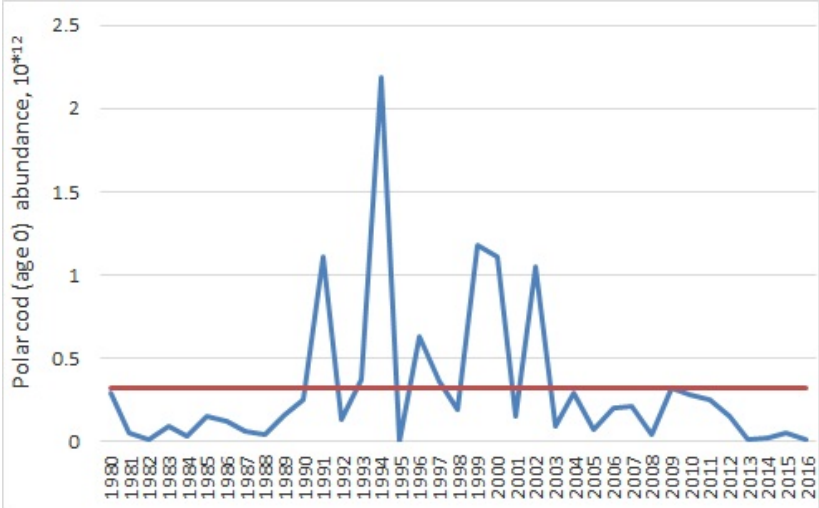


Figure 3.5.10. 0-group polar cod abundance in the Barents Sea 1980–2016. Red line shows long-term mean for the period 1980–2016, while the blue line indicates 0-group abundance fluctuation.

As in previous years, the distribution of 0-group polar cod in 2016 was split into two components: western (around the Svalbard/Spitsbergen Archipelago) and eastern (off the west coast of Novaya Zemlya). Polar cod of the eastern component distributes usually along the west coast of Novaya Zemlya, however in 2016 only few registrations were found there. The length of polar cod varied between 1.5 and 8.0 cm, and most of the fish were between 2.0 and 5.0 cm long. The mean length of 0-group polar cod (4.2 cm) was close to the long-term mean of 4.1 cm. The abundance of the western component was only approximately 1/7 of the long-term mean. The abundance index of the eastern component was very low and only 0.8% of the long-term mean. The 2016 year class of polar cod was very weak at 0-group stage. (Figure 3.5.10). The abundance indices of 0-group polar cod have been extremely low for several years, indicating lack of spawning success and/or that a large proportion of the polar cod 0-group are distributed outside the standard survey area.

Older polar cod

In 2016 there was a significant increase in polar cod biomass, and it was mainly driven by a very high abundance of 1-year-olds. The biomass level was the highest since 2010, and the abundance of 1-year-olds the second highest on record. This marks a break in a long lasting trend of decreasing abundance of polar cod in the Barents Sea. The distribution was concentrated in the northeast (Figure 3.5.12), and polar cod typically occurred in dense and large pelagic schools. The total stock in 2016 amounted to 0.9 million tonnes (Figure 3.5.11).

Two reason are possible for good recruitment of polar cod in 2016. A lot of the 0-group polar cod are distributed outside the standard survey area, so the indices are more uncertain than for other species. In addition, survival of 0-group is very fluctuating

and strongly depends from environment, cannibalism, consumption by other predators etc. Most probably from 2015 to 2016 there were very good conditions for survival of polar cod from age 0 to 1.

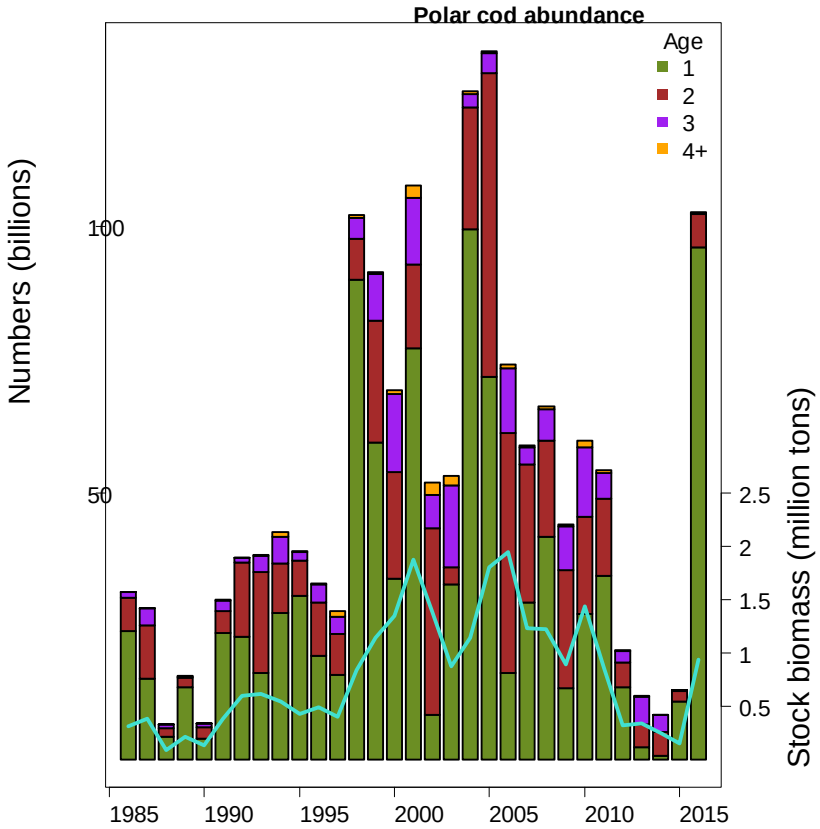


Figure 3.5.11. Total abundance in billions (coloured bars and left axis), and biomass (turquoise line and right axis) of polar cod in the Barents Sea (acoustic survey and BESS data), August-September 1986–2016. (2003 numbers based on VPA due to poor coverage in survey).

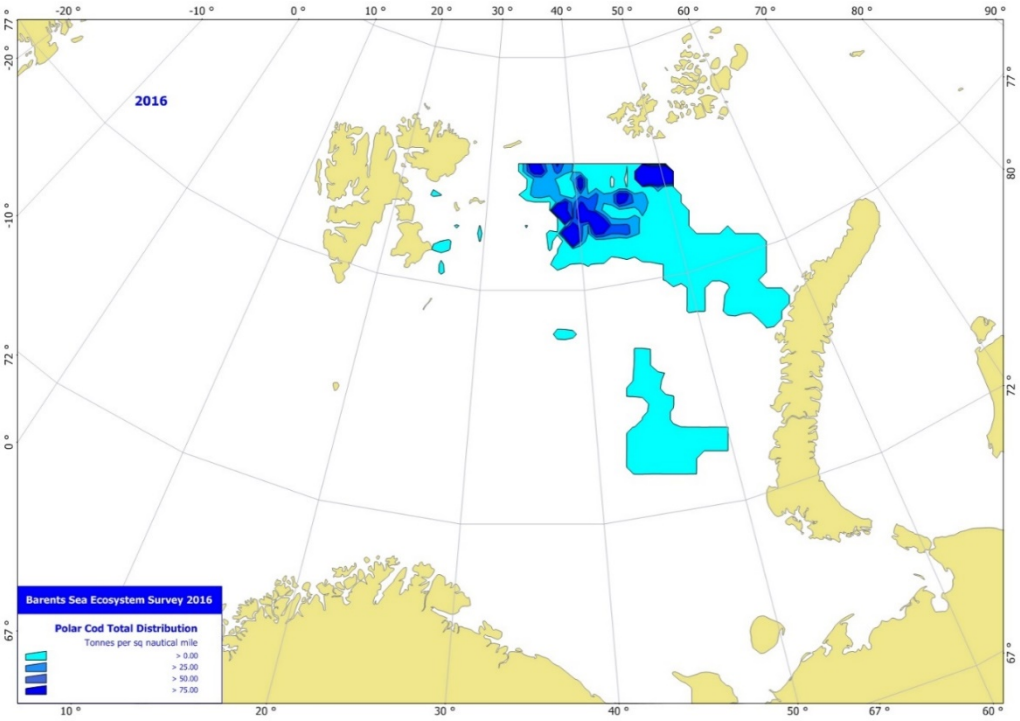


Figure 3.5.12. Estimated total density distribution of polar cod (t/sq nautical mile), August-October 2016.

Blue whiting

Acoustic estimates of blue whiting in the Barents Sea have been made since 2004. In 2004–2005 estimated biomass of blue whiting in the Barents Sea was higher than 1 million tonnes (Figure 3.5.13). The estimate dropped abruptly in 2008. In 2016 blue whiting biomass was about 397 000 tonnes which is a slight decrease from last year (Figure 3.5.13). Blue whiting migrate from the Norwegian Sea into the deeper parts of the Barents Sea (Figure 3.5.14) when the stock is large and when sea temperatures are high.

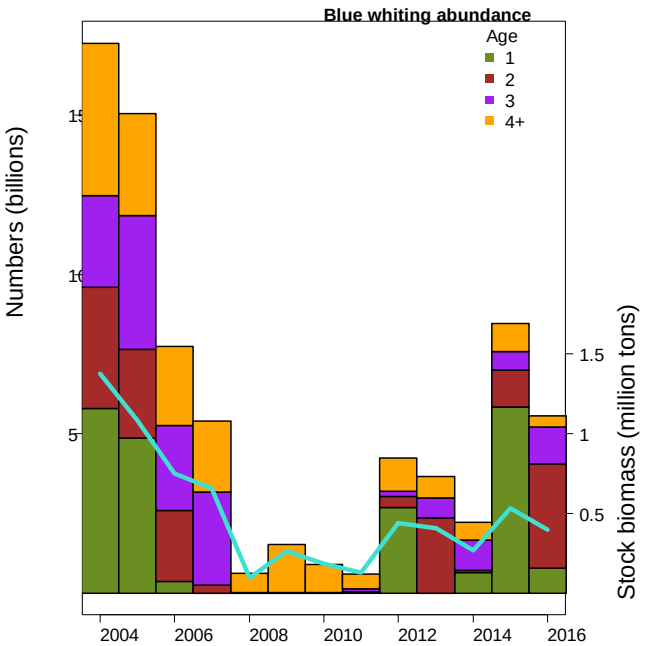


Figure 3.5.13. Total abundance in billions (coloured bars and left axis), and biomass (turquoise line and right axis) of blue whiting in the Barents Sea (BESS data), August-September 2004–2016.

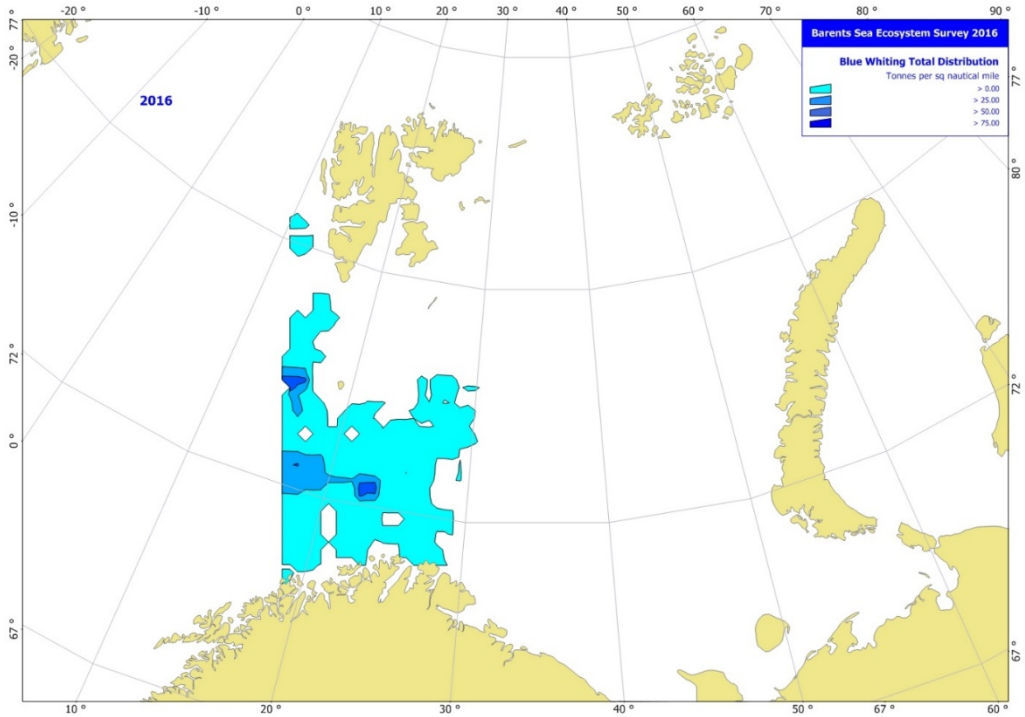


Figure 3.5.14. Estimated distribution of blue whiting (t/nautical mile2) based on acoustic recordings. August-October 2016.

3.6 Demersal fish

Most of the fish in the Barents Sea are demersal (Dolgov *et al.*, 2011). The demersal fish community consists of about 70–90 regularly occurring species. These have been classified into zoogeographical groups. About 25% are Arctic or mainly Arctic species. The commercial species are all boreal or mainly boreal (Andriashev and Chernova, 1995), except for Greenland halibut (*Reinhardtius hippoglossoides*) that is classified as either Arcto-boreal (Mecklenburg *et al.*, 2013) or mainly Arctic (Andriashev and Chernova, 1995).

Distribution maps for cod, haddock, long rough dab, Greenland halibut, redfish, and six other demersal fish species based on data from the ecosystem survey in August-September can be found at: http://www.imr.no/tokt/okosystemtokt_i_barentshavet/utbredelseskart/en

Abundance estimates are available for the commercial species that are assessed. Figure 3.6.1 shows the biomass of cod, haddock and saithe (*Pollachius virens*) from the ICES AFWG assessments made in 2016. Saithe is mainly found along the Norwegian coast and off the coast south of the Barents Sea – little in the Barents Sea itself. The total biomass of these three species is close to the highest recorded (time-series start in 1960). Greenland halibut and redfish, in particular *S. mentella,* are important commercial species with a large part of their distribution within the BS: Time-series of biomass estimates of *S. mentella* and Greenland halibut are much shorter than those of haddock, cod and saithe. Apart from these main commercial stocks, long rough dab is the demersal stock with the highest biomass. Overall, cod is the dominant demersal species.

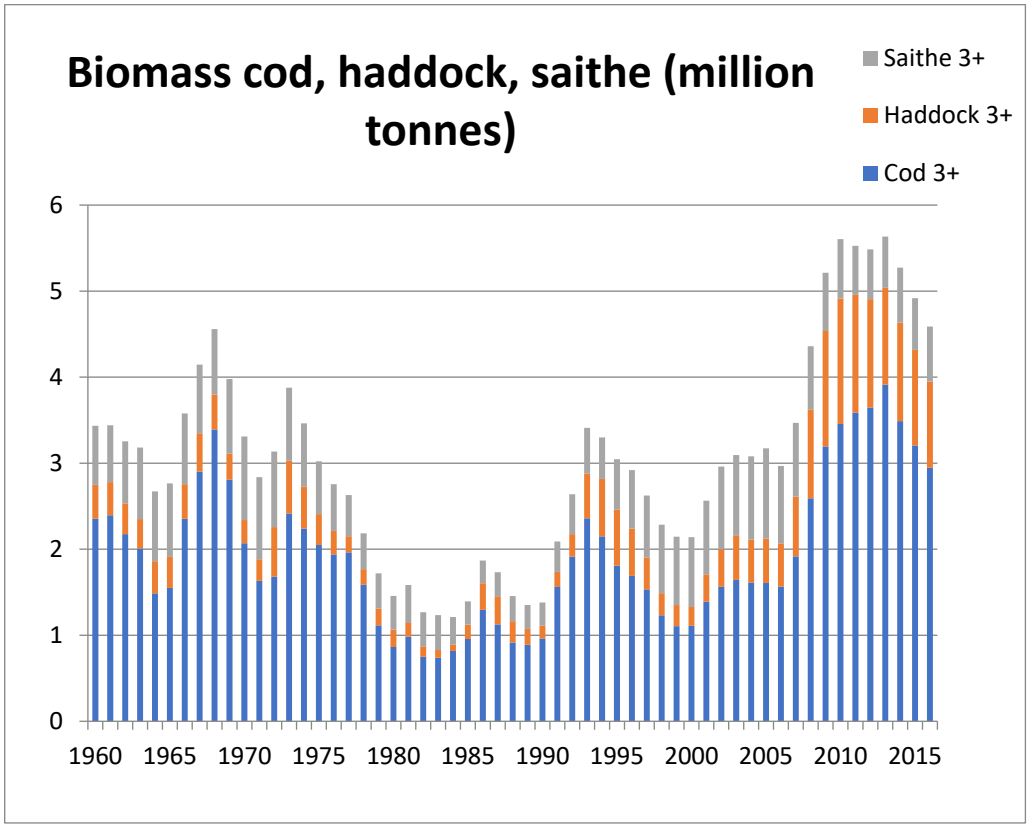


Figure 3.6.1 Biomass estimates of cod, haddock and saithe 1960–2016 from AFWG 2016 (ICES, 2016c). Please note that saithe is only partly distributed in the Barents Sea.

Cod

Young of the year

Cod were widely distributed in 2016, and the densest concentrations were found cod were found in the central, southern, eastern parts of the Barents Sea and northwest of Svalbard/Spitsbergen. The cod Archipelago were covered one month later than the main area and the southern Barents Sea was not completely covered. In 2016, the 0-group cod were also found in deeper water layer (100–200 m). The deeper layer was not regularly covered by trawl and only some catchers were taken to identify the acoustic registrations. Thus, the report present the standard coverage (0–60 m) only, and should be interpreted as minimum. The 0-group cod biomass (248 thousand tonnes) is 1.9 times higher than in 2015 (130 thousand tonnes) and 2.4 times lower than the long-term mean (603 thousand tonnes). The abundance index of 2016 year class is lower than long-term mean (Figure 3.6.2). The length of 0-group cod was between 2.9 and 13.5 cm. Most of the fish (69%) were between 7.5 and 9.5 cm, with a mean length of 8.9 cm, which is highest from 2007 and higher than the long-term mean of 7.6 cm.

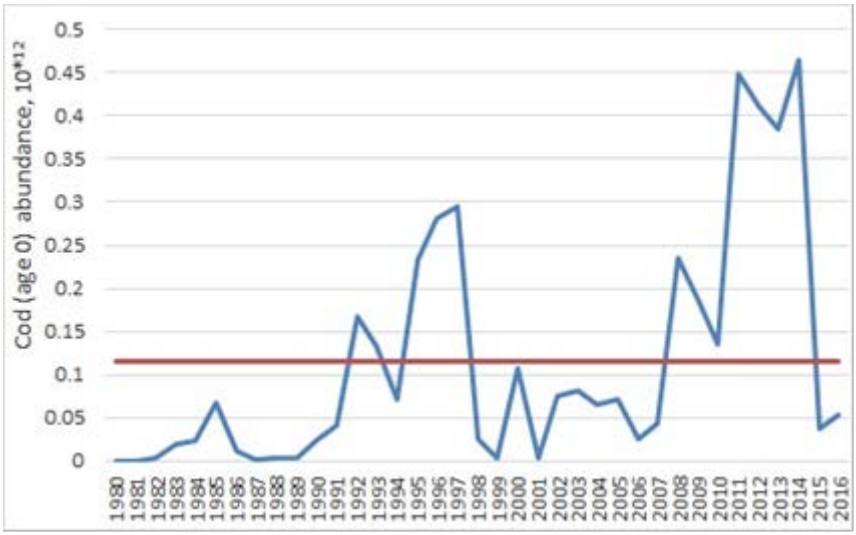


Figure 3.6.2. 0-group cod abundance in the Barents Sea 1980–2016. Red line shows long-term mean for the period 1980–2016, while the blue line indicates 0-group abundance fluctuation.

Older cod

The northeast Arctic cod stock is currently in a good shape, with high total stock size, and spawning-stock biomass (Figure 3.6.3). The 2004 and 2005 year classes were very strong, but after that recruitment-at-age 3 has returned to an average level (Figure 3.6.4). 0-group abundance has been very high in recent years (2011–2014), but this does so far not seem to result in strong year classes later on.

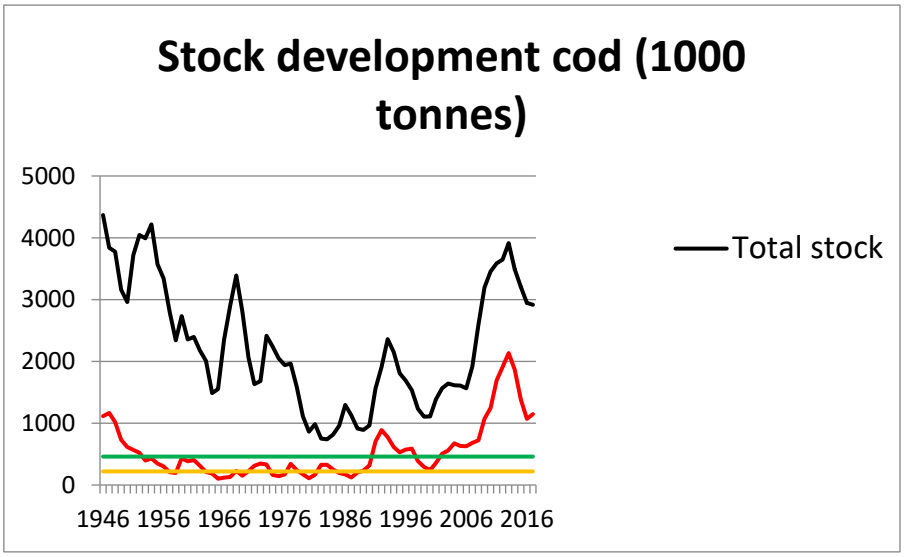


Figure 3.6.3. Cod total stock and spawning stock development – from AFWG 2016 (ICES 2016c)

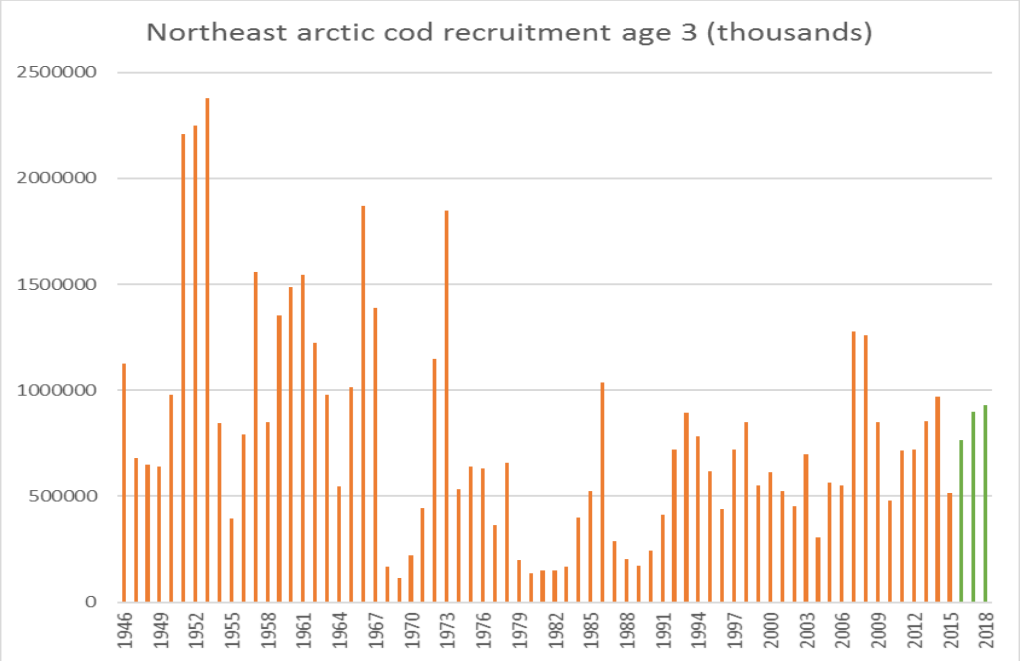


Figure 3.6.4. Cod recruitment-at-age 3 from AFWG 2016 (ICES 2016c).

The strong 2004 and 2005 year classes have, together with a low fishing mortality, led to a rebuilding of the cod age structure to that seen in the late 1940s (Figure 3.6.5).

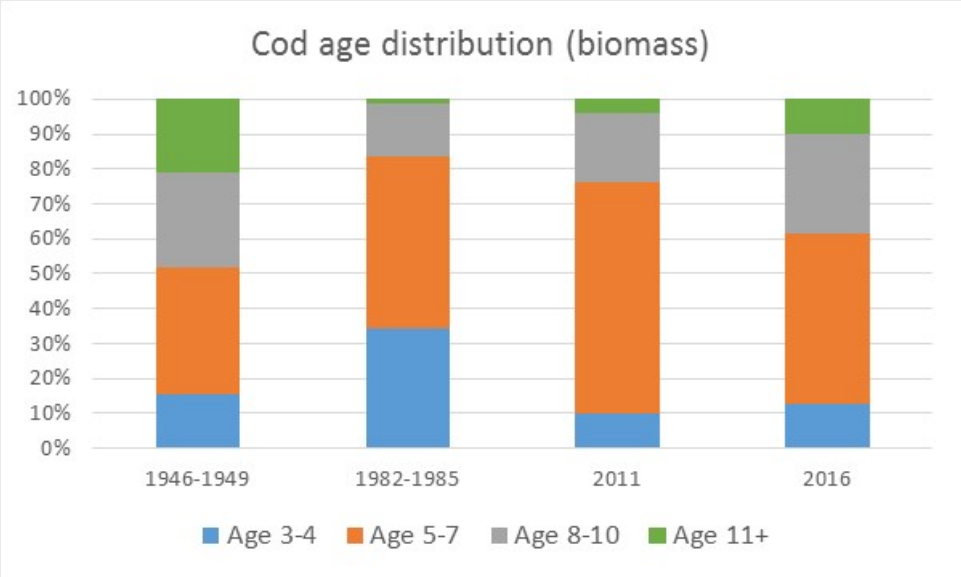


Figure 3.6.5. Cod age-groups distribution (biomass). From data in ICES 2016c.

NEA haddock
Young of the year

Haddock was relatively widely distributed in the western, central areas and north, west and east of Svalbard/Spitsbergen in 2016. The haddock biomass was 264 thousand tonnes and it is higher than in 2015 (178 thousand tonnes) and the long-term mean (164 thousand tonnes, for period 1993–2016). The number of fish belonging to the 0-group is lower than in 2015 and close to the long-term mean and thus can be characterized as average year class (Figure 3.6.6). The length of 0-group haddock varied between 3.0 and 16.9 cm, with mean length of 13.4 cm, and it is higher than long-term mean of 9.2

cm and is record high. The large 0-group haddock length may indicate suitable living conditions for young haddock in 2016.

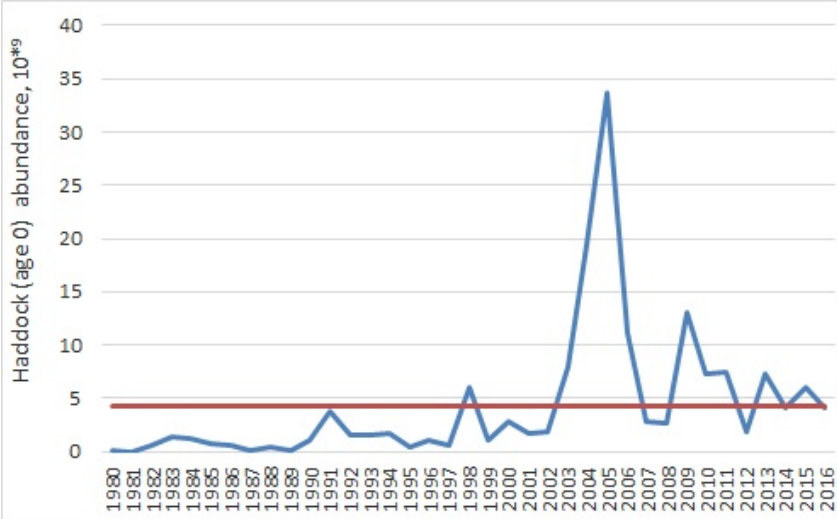


Figure 3.6.6. 0-group haddock abundance in the Barents Sea 1980–2016. Red line shows long-term mean for the period 1980–2016, while the blue line indicates 0-group abundance fluctuation.

Older haddock

The Northeast Arctic haddock stock reached record levels in 2009–2013, due to the very strong 2004–2006 year classes. After that, recruitment has normalized, and the stock has declined in recent years but is still at a high level (Figures 3.6.7 and 3.6.8).

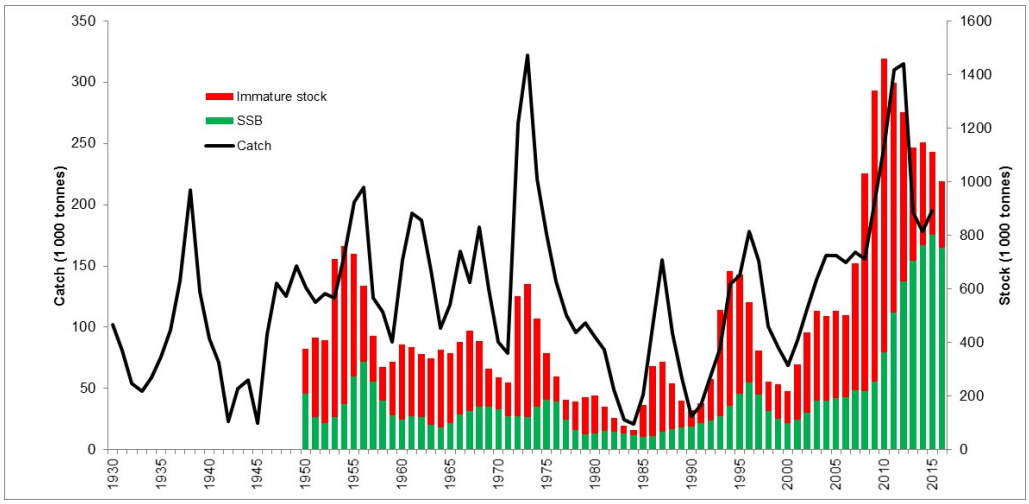


Figure 3.6.7. Catches and biomass of haddock 1930–2016 (ICES 2016c)

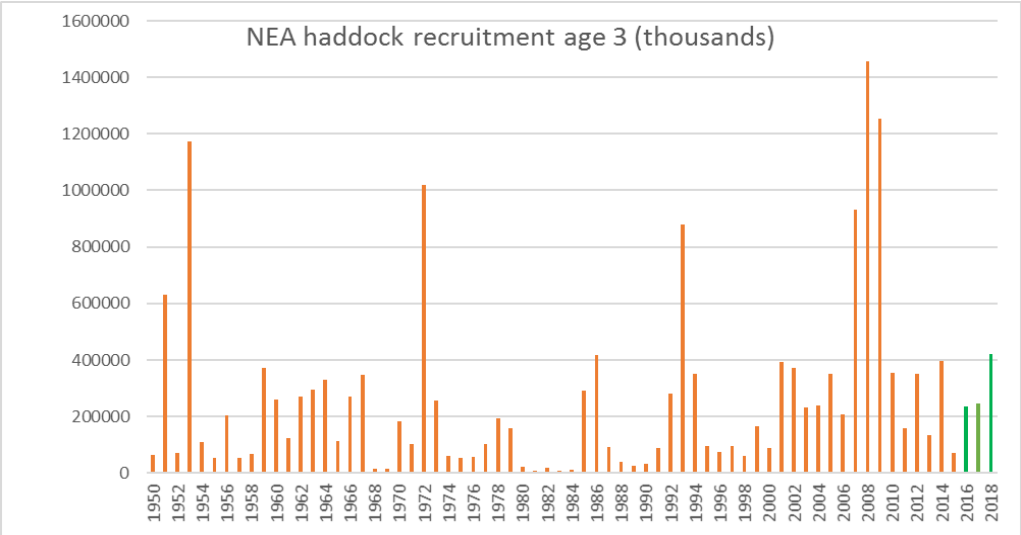


Figure 3.6.8 Recruitment of haddock (ICES 2016c)

Long rough dab
Young of the year

Long rough dab in 2016 were distributed mainly in the northern part of the Barents Sea. 0-group of long rough dab was observed both in pelagic and bottom catches indicating start of settlement to the bottom. Thus, the abundance indices were likely underestimated in 2016. The long rough dab index (526 million) in 2016 was the highest since 2009 and close to the long-term mean (Figure 3.6.9). Fish length varied between 1.0 and 5.0 cm with a mean length of 2.9 cm, and this is lower than the long-term average (3.3 cm).

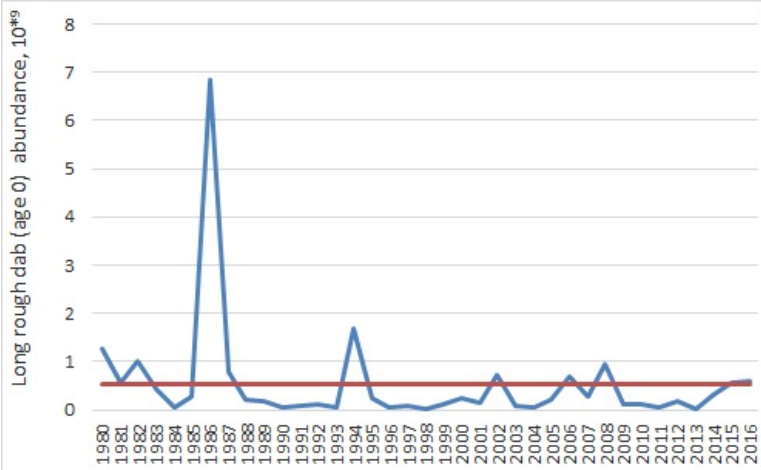
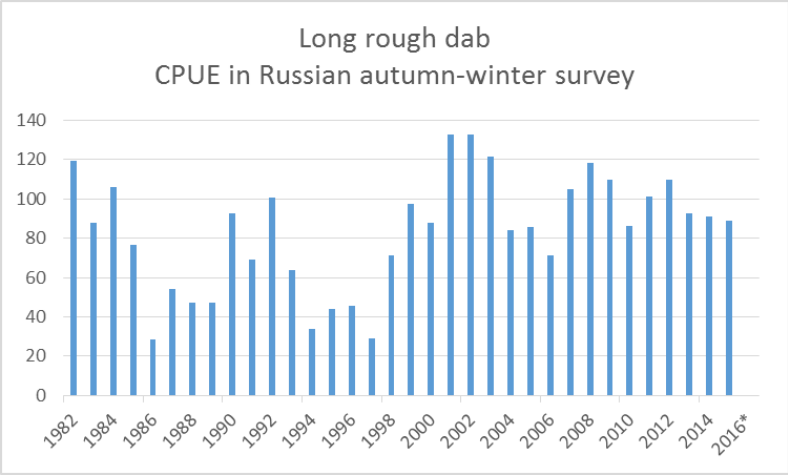


Figure 3.6.9. 0-group long rough dab abundance in the Barents Sea 1980–2016. Red line shows long-term mean for the period 1980–2016, while the blue line indicates 0-group abundance fluctuation.

Older long rough dab

Older long rough dab (age 1+) are widely distributed in the Barents Sea. During the Russian autumn-winter survey in October-December and ecosystem survey in August-September main concentrations of long rough dab were observed in the central-northern and eastern areas and were dominant by numbers in the bottom-trawl catches in surveys. Many small fish were observed in trawl catches especially in the eastern areas at the ecosystem survey in 2015–2016. In 2013–2015, long rough dab catch per unit of

effort in Russian survey (Figure 3.6.10) and the biomass of long rough dab in the ecosystem survey in 2014–2016 (Figure 3.6.11) has been relatively stable.



***2016 – no survey**

Figure 3.6.10. Catch per unit of effort of long rough dab at the Russian autumn-winter survey 1982–2016 (October-December).

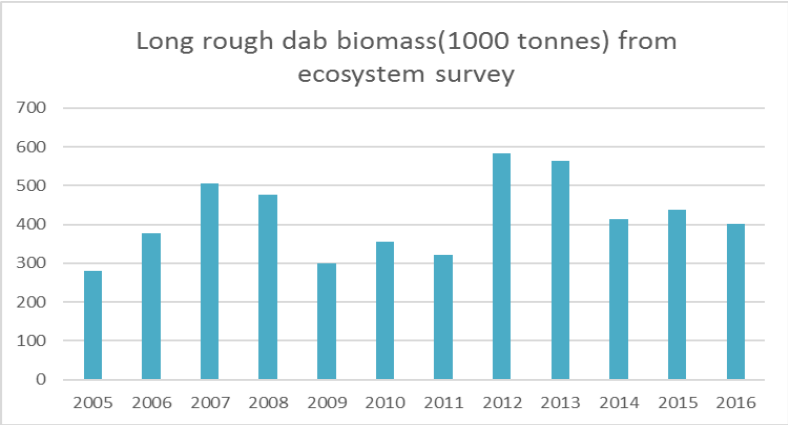


Figure 3.6.11. Stock biomass of long rough dab during the ecosystem survey 2005–2016, calculated using bottom-trawl estimates (swept-area).

Greenland halibut
Young of the year

Since 2005 only low concentrations of 0-group Greenland halibut were found. Greenland halibut were mostly observed around Svalbard/Spitsbergen, however in 2016, only north and south and southeast of Svalbard/Spitsbergen. The survey did not cover the numerous Svalbard/Spitsbergen fjords, where 0-group Greenland halibut are abundant, and therefore this index does not give the real recruitment (at age 0) to the stock, although it may reflect the minimum abundance index of the year-class strength in the standard long-term surveyed area. In 2012–2016 the abundance of Greenland halibut continuously decreased, and the 2016 year-class index is also low. Most of the fish (69%) were between 6.0 and 8.0 cm. The mean length of fish was 7.5 cm, which is at the same level as in 2015 and is the highest recorded.

Older Greenland halibut

The adult part of the stock was, as usual, mainly distributed outside the survey area. On the other hand, in recent years an increasing number of large Greenland halibut

has been captured in the deeper waters in the surveyed area (Figure 3.6.12). The northern and northeastern areas of the sea serve as nursery area for the stock. Greenland halibut are also relatively abundant in deep channels running between the shallowest fishing banks. Figure 3.6.13 shows an index for Greenland halibut at the nursery area, based on the Ecosystem survey north of 76.5°N from northwest of Svalbard and east to Franz Josef Land.

The fishable population (length ≥45 cm) has increased from 1992 to 2012, and has been stable since then (Figure 3.6.14). The harvest rate has been relatively stable since 1992.

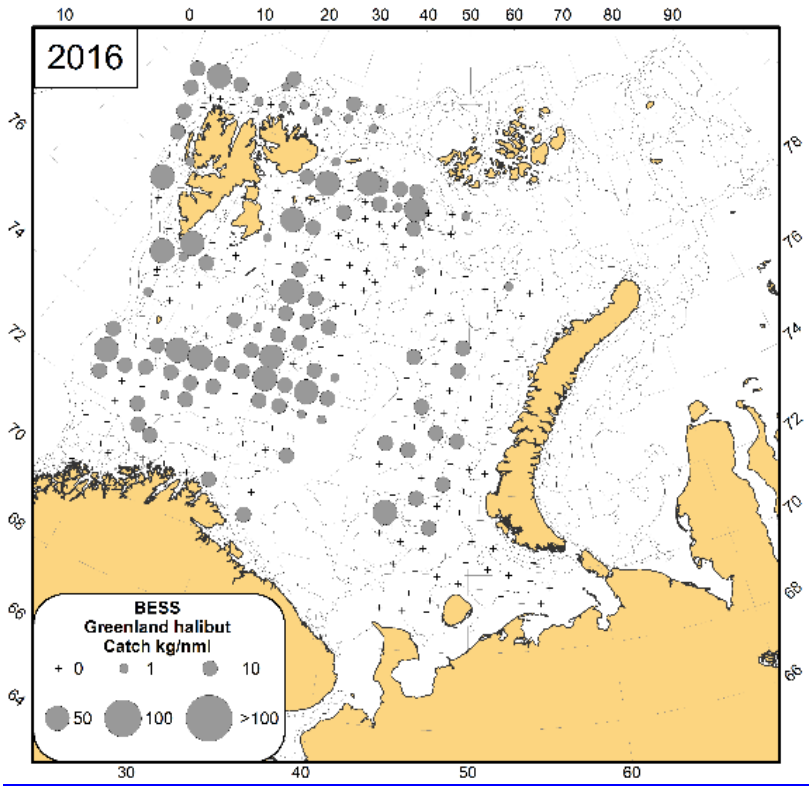


Figure 3.6.12 Greenland halibut distribution (specimens/nautical mile) during August- September 2016 based on the Joint Ecosystem Survey data.

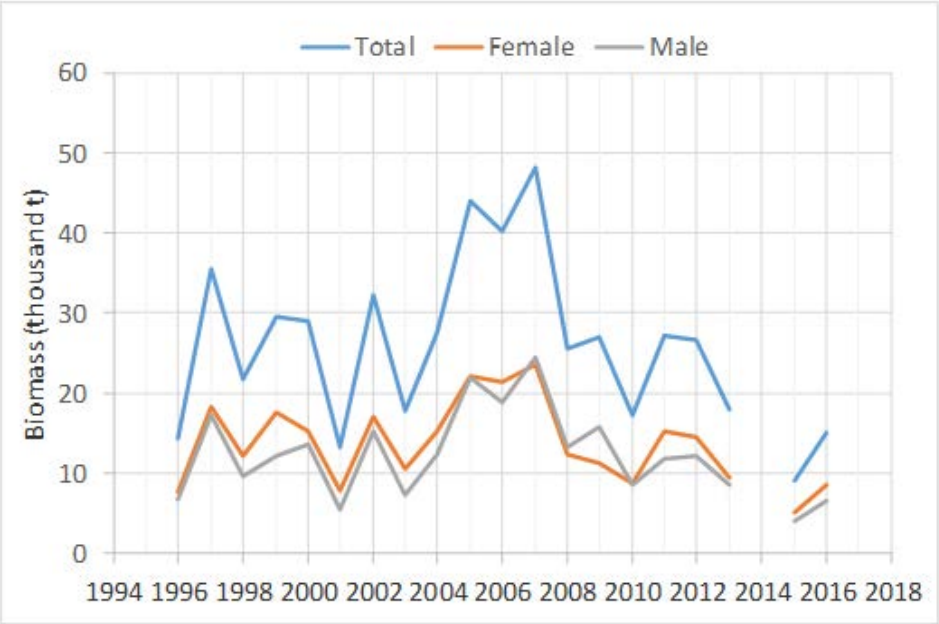


Figure 3.6.13. Biomass index for Greenland halibut at the nursery areas, 2014 excluded due to poor area coverage.

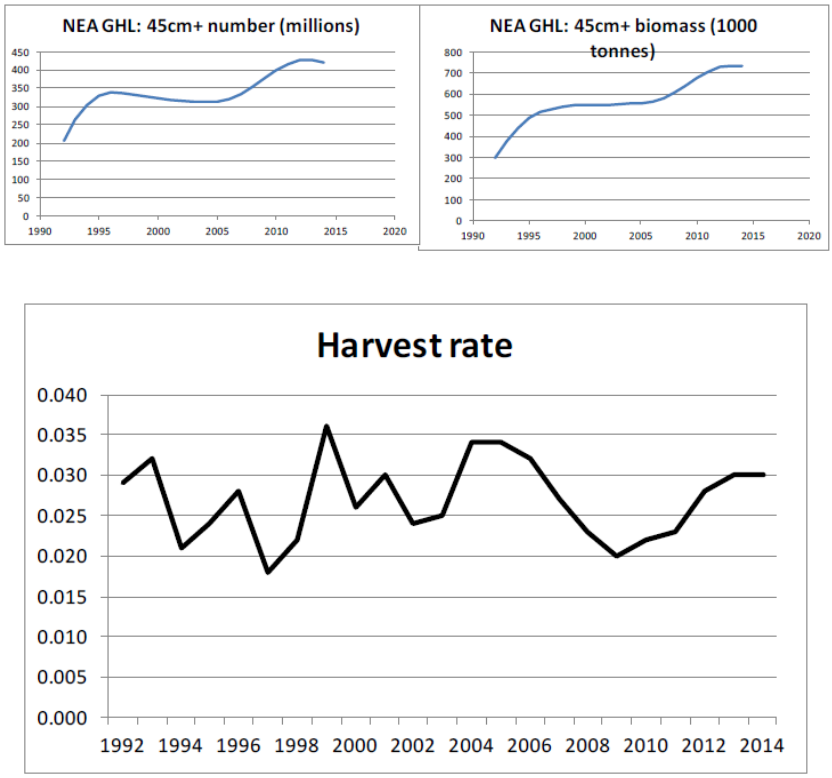


Figure 3.6.14 Northeast Arctic Greenland halibut. Numbers (upper left) and biomass (upper right) 1992–2014 for 45+ cm Greenland halibut as estimated by the GADGET model, and estimated exploitation rates (be-low) (ICES 2016c).

Deep-water redfish

Young of the year

Redfish, mostly *Sebastes mentella*, are distributed in the western part of the Barents Sea and north of Svalbard/Spitsbergen. The 0-group redfish biomass in 2016 (58 thousand tonnes) was lower than in 2015 (231 thousand tonnes) and 3 times lower than the long-term mean. The abundance of 0-group redfish is 7.9 times lower than in 2015 and 4.6 times lower than the long-term mean. Thus the 2016 year class can be characterized as weak. The index of 0-group redfish in the Barents Sea is an unknown proportion of the total 0-group abundance, and therefore representative only for the shelf area of the Barents Sea.

Older redfish

Deep-water redfish were widely distributed in the Barents Sea. At the ecosystem survey and the winter survey, the main concentrations of deep-water redfish were found, as usual, in the western and northwestern parts of the Barents Sea. The biomass of deep-water redfish in the Barents Sea has been at a higher level in 2013-2016 than in the preceding years. The geographical distribution of deep-water redfish during the ecosystem survey in 2016 is shown in Figure 3.6.15. Most of the adult fish is found in the Norwegian Sea. The stock development of redfish from the latest ICES AFWG assessment is shown in Figure 3.6.16.

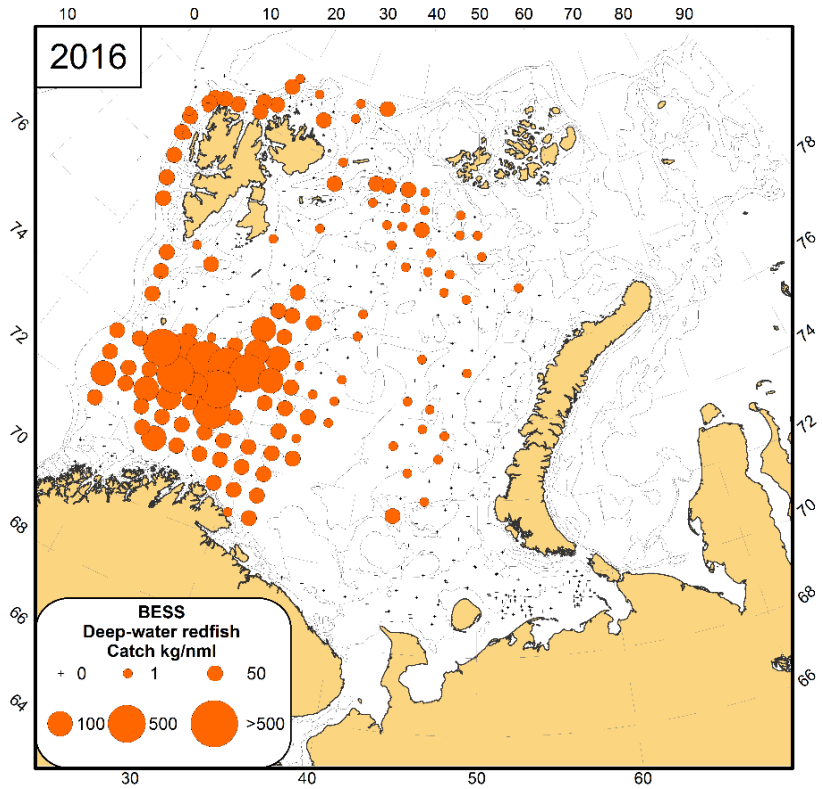


Figure 3.6.15. Geographical distribution of deep-water redfish during the ecosystem survey in 2016.

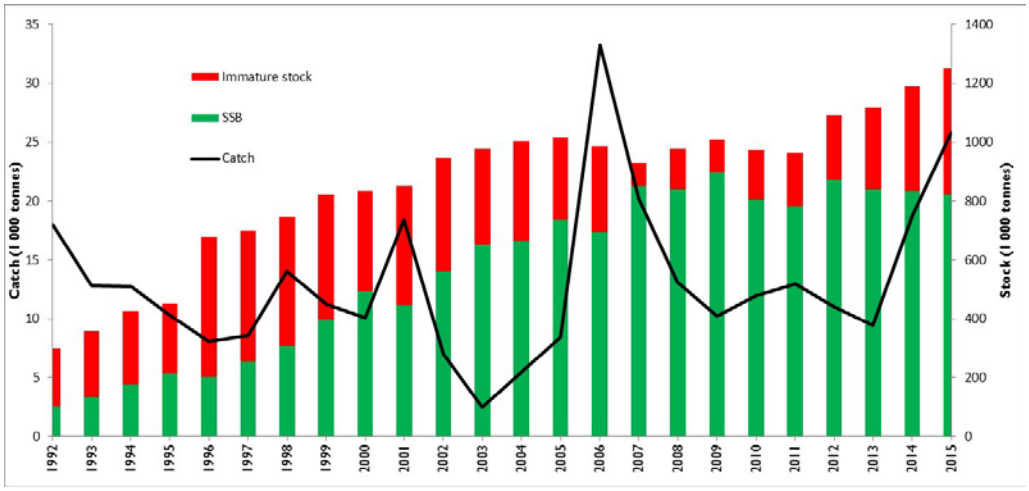


Figure 3.6.16 Results from the statistical catch-at-age model showing the development of total biomass ('000s), spawning-stock biomass and recruitment-at-age 2 for the period 1992–2015, for S. *mentella* in Subareas 1 and 2. (ICES 2016c)

3.7 Zoogeographical groups of non-commercial fish

During the 2016 Barents Sea Ecosystem Survey (BESS) 96 fish species from 33 families were recorded in the both pelagic and bottom catches, some taxa were recorded at genus or family level only (Prokhorova *et al.,* 2017). In the period 2004–2015 a total of 106 species were caught in demersal trawls during the BESS (Johannesen *et al.,* 2017).

All recorded species belonged to the 7 zoogeographic groups: **widely distributed, south boreal, boreal, mainly boreal, arctic-boreal, mainly arctic** and **arctic**. Definitions of zoogeographic patterns follow Andriashev and Chernova (1995), with slight modifications by Mecklenburg *et al.* (2010). Here only bottom-trawl catches of non-commercial fish were used. Both demersal (including bentho-pelagic) and pelagic (neritopelagic, epipelagic, bathypelagic) species were included (Andriashev and Chernova, 1994; Parin, 1968, 1988).

Widely distributed (only ribbon barracudina *Arctozenus risso* represents this group), south boreal (e.g. whiting *Merlangius merlangus*, silvery pout *Gadiculus argenteus*, grey gurnard *Eutrigla gurnardus*) and boreal (e.g. round skate *Rajella fyllae*, silvery lightfish *Maurolicus muelleri*, moustache sculpin *Triglops murrayi*) species were mostly found in the south western and western part of the survey area where warm Atlantic and Coastal Waters dominates (Figure 3.7.1). The median catch of species from the south boreal and the boreal groups in 2016 (was higher than in 2015 (Table 3.7.1).

Mainly boreal species (e.g. Vahl's eelpout *Lycodes gracilis*, snakeblenny *Lumpenus lampretaeformis*, lesser sandeel *Ammodytes marinus*) were as usual widely distributed over the entire survey area (Figure 3.7.1). The south boreal, boreal and mainly boreal species were widely distributed, most likely due to higher temperature near the bottom throughout the Barents Sea in 2016 compared to 2013–2015. The median catch of species from the mainly boreal group in 2016 was somewhat higher than in 2015) (Table 3.7.1).

Arctic-boreal (e.g. ribbed sculpin *Triglops pingelii*, Atlantic poacher *Leptagonus decagonus*), mainly Arctic (e.g. slender eelblenny *Lumpenus fabricii*, Arctic staghorn sculpin *Gymnocanthus tricuspis*, variegated snailfish *Liparis bathyarcticus*) and Arctic (e.g. bigeye sculpin *Triglops nybelini*, Arctic alligatorfish *Aspidophoroides olrikii*, pale eelpout *Lycodes pallidus)* species were distributed west and north off Svalbard/ Spitsbergen, west off Novaya Zemlya Archipelago, in the Pechora Sea area and in the northern part

of the survey area (Figure 3.7.1). Species of these groups mostly occur in areas influenced by cold Arctic Water, Spitsbergen Bank Water, Novaya Zemlya Coastal Water and Pechora Coastal Water. The median catch of species from the Arctic-boreal and Arctic group in 2016 were less than in 2015, while the median catch of species from the mainly Arctic group in 2016 was higher than in 2015 (Table 3.7.1).

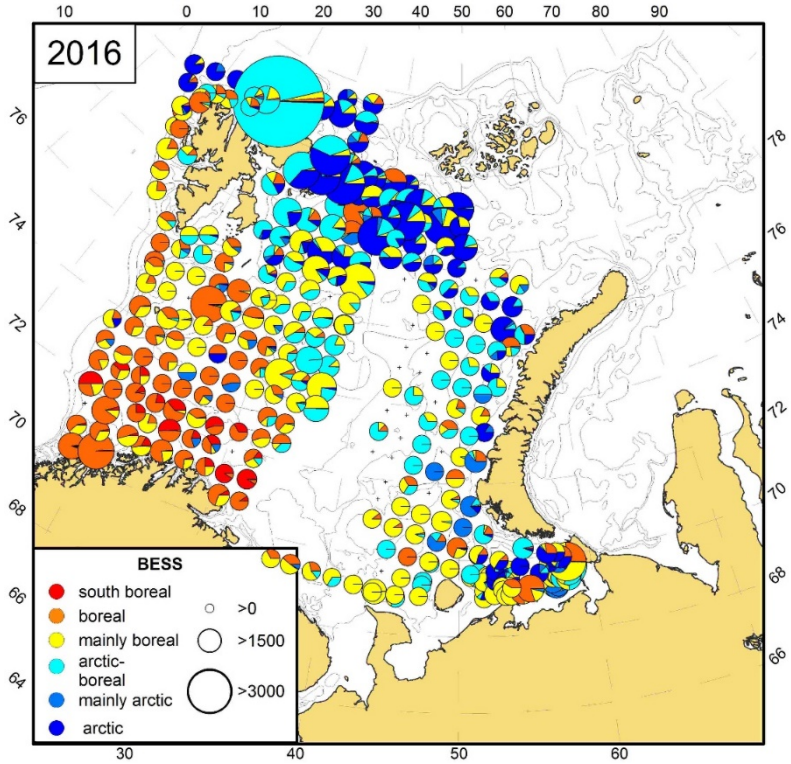


Figure 3.7.1. Distribution of non-commercial fish species from different zoogeographic groups during the ecosystem survey 2016. Size of circle corresponds to abundance (individuals per nautical mile, only bottom-trawl stations were used, both pelagic and demersal species are included)

Table 3.7.1. Median catch (individuals per nautical mile) of non-commercial fish from different zoogeographic groups (only bottom-trawl data were used, both pelagic and demersal species are included).

Zoogeographic group	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	LTM
Widely distributed	0.3	0.3	0.4	0.5	0.3	0.1	0.2	0.1	0.2	0.2	0.1	0.1	0.5	0.25
South boreal	0.3	0.2	1.4	2.3	1.4	2.2	0.4	0.6	0.3	0.8	0.9	1.2	1.4	1.01
Boreal	7.4	13.0	12.3	13.4	11.9	9.2	5.8	4.6	7.7	7.1	8.7	8.7	18.3	9.86
Mainly boreal	32.9	24.9	28.1	25.9	26.5	18.3	13.4	30.3	66.1	32.9	19.1	30.0	32.5	29.30
Arctic-boreal	27.4	19.1	36.4	23.7	24.7	17.8	7. 2	29.3	40.1	39.3	24.5	54.4	30.5	28.81
Mainly Arctic	7.7	8.8	7.4	6.8	5.4	2.8	1.6	2.1	5.5	10.2	1.7	1.9	3.3	5.02
Arctic	68.9	74.1	50.5	46.0	51.9	34.7	51.6	93.2	166.5	70.7	7.2	31.4	28.9	69.08

Temporal development

Since the onset of BESS in2004 we observed a decrease of the area of species from boreal, Arctic-boreal, mainly Arctic and Arctic groups (Figure 3.7.2). Moreover, the median catch of species from mainly Arctic and Arctic groups in the last three years is below the long-term median (Table 3.7.1).

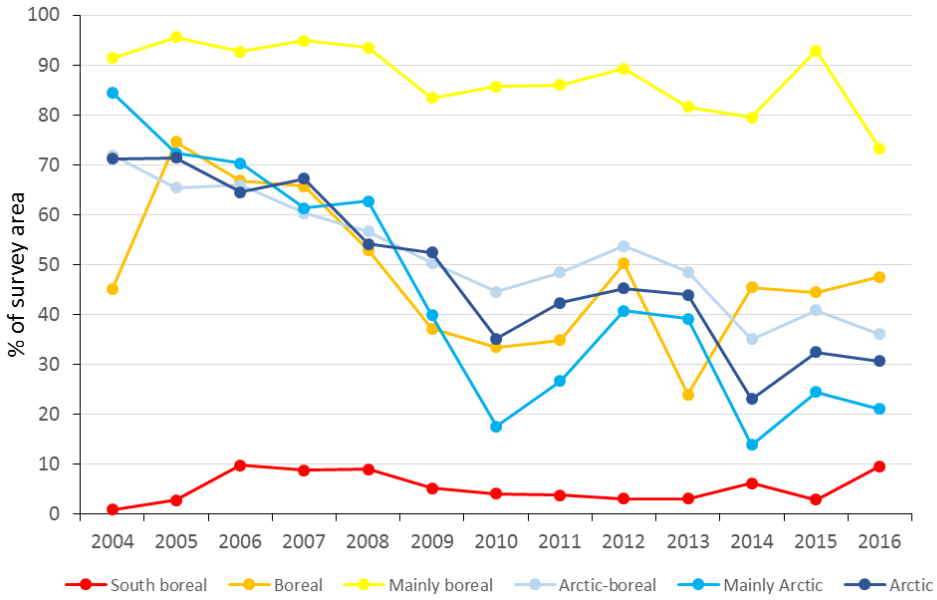


Figure 3.7.2. The area occupied by species of different zoogeographical groups (% of total survey area calculated for each year). Only bottom-trawl catches of non-commercial fish were used, both demersal and pelagic species are included

The Arctic group of fish is dominated by polar cod (Figure 3.7.3). Excluding polar cod still results in a significant decrease from 2004–2015 in both the number of Arctic fish species per station and the proportion of stations including Arctic fish (Johannesen *et al.*, 2017). The decline was highest in the area around central bank where the proportion of stations with catches of Arctic fish (excluding polar cod) declined from 80% to 40% over the period (Johannesen *et al.,* 2015). There was a significant decline in the proportion of stations with Arctic species over time and the number of Arctic species caught per station.

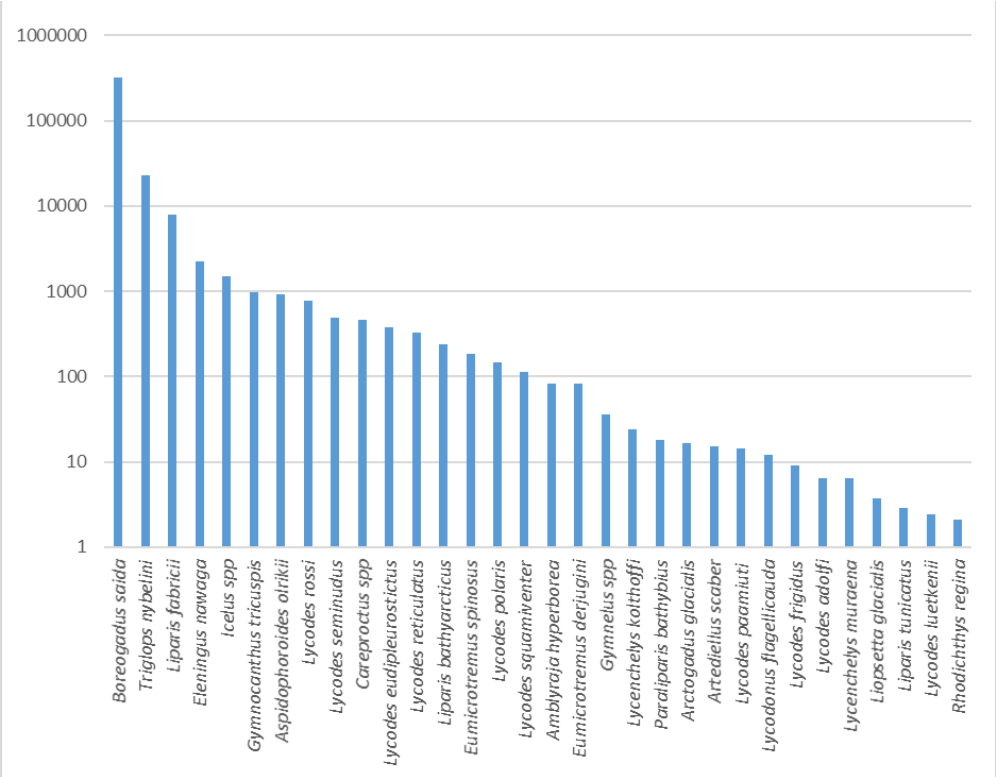


Figure 3.7.3. Species rank plotted against log abundance of Arctic fish caught at BESS 2004-2015 (from Johannesen *et al.*, 2017).

Median catch of species from the south boreal, boreal, mainly boreal and mainly Arctic group in 2016 were higher than in 2015. Catch of species from the Arctic-boreal and Arctic group were less than in 2015 but this might be due to lack of the coverage of the northeastern part of the Barents Sea in 2016.

Overall there has been a decline in the Arctic fish in the Barents Sea since 2004.

Median catch of species from the mainly Arctic and Arctic groups in the last three years was below the mean from 2004–2016 and the area where species from the Arctic-boreal, mainly Arctic and Arctic groups were found decreased. The likely reason for this is the decrease in ice cover and associated Arctic water masses in the Barents Sea.

The area where species from the mainly boreal and south boreal groups were found did not show any trend but the area with boreal species decreased from 2004–2015. We cannot provide any explanation at this point.

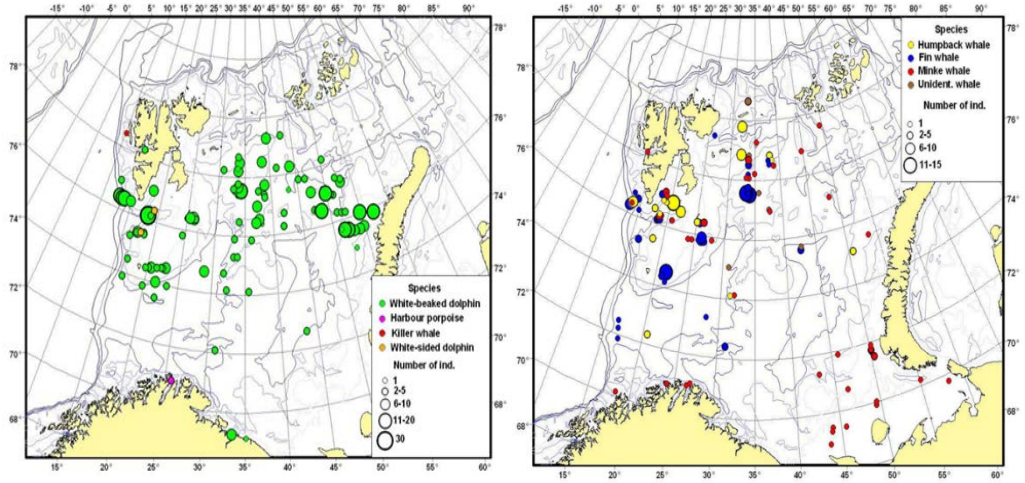
3.8 Marine mammals

There were no special researchers on marine mammals on board of Norwegian vessels during ecosystem survey. However, the Norwegian observers of seabirds on boards «Eros», «Johan Hjort», and «Helmer Hansen», as far as possible in parallel also did observations of marine mammals.

8 species of marine mammals were observed during the observation period in the research area, reaching a total of 899 individuals.

The most observed species was white-beaked dolphin (*Lagenorhynchus albirostris*) (68.4% of all recordings). This species had a wide distribution in the research area (Figure 3.8.1). The most frequent observations of this dolphins were in areas close to obser-

vations of capelin, polar cod and Northeast Arctic cod aggregations with different densities, and this were in the western, central and eastern parts of the Barents Sea between 74°–80°N.



a b

Figure 3.8.1 Distribution of toothed whales (a) and baleen whales (b) observed in August- September 2016.

Other observations toothed whales, besides white-beaked dolphin, consisted of two groups of Atlantic white-sided dolphin (*Lagenorhynchus acutus*) to the south of Spitsbergen. Previous years, this dolphin was not recorded in the Barents Sea during the research period. Also, one killer whale (*Orcinus orca*) and two harbour porpoise (*Phocoena phocoena*) were observed.

Out of the baleen whales of research area, minke whale (*Balaenoptera acutorostrata*), humpback whale (*Megaptera novaeangliae*) and fin whale (*Balaenoptera physalus*) (in total about 28.5% of all animals) were observed (Figure3.8.1). Minke whale were recorded mainly in the western, northern and southeastern parts of the research area. The densest concentrations of this species was seen on the southern ridge of Novaya Zemlya Archipelago coast in the herring aggregations that were observed, as well as on the southern tip of Spitsbergen and in the Great Bank area in capelin aggregations. In the northeastern parts of the Barents Sea minke whale were found in aggregations of juvenile polar cod and capelin, and in the southeast part of the Barents Sea it was in aggregations of juvenile cod, herring and other fish.

Recordings of the main groups of humpback whale were in the areas adjacent to the southern tip of Spitsbergen and in the Great Bank area, in capelin aggregations. Fin whale observed in the northern and western regions of the research area together with humpback whale and minke whale.

As a result of conducted study, main points of marine mammal research during Barents Sea ecosystem survey in August-September 2016 can be condensed to following:

- the main groups of humpback and fin whales were feeding at concentrations of capelin, primarily in areas south of Spitsbergen and on the Great Bank;
- other marine mammals in the Barents Sea were observed at concentrations of polar cod, capelin, herring, and cod fish;
- when compared with the last year, there was a decrease in the number of registered humpback whales by almost sevenfold;

- the Russian vessel «Fridtjof Nansen» did not fully cover the southern regions of the Barents Sea, and thus, data on the occurrence of the harbour porpoise was not received;
- total expert estimate of the number of main species of cetaceans in the whole area of the Barents Sea in August-September 2016 was estimated at 82.5 thousand individuals.

3.9 Anthropogenic impact

3.9.1 Fisheries

Total catches

Fishing is the largest human impact on the fish stocks in the Barents Sea, and thereby on the functioning of the whole ecosystem. However, the observed variation in both fish species and ecosystem is also strongly affected by as climate and trophic interactions. During the last decade catches of most important commercial species in the Barents Sea and adjacent waters of Norwegian and Greenland Sea varied around 1.5–3 mill. tonnes and has decrease in the last years (Figure 3.9.1.1.).

Variation of catches in the region depends both on stock dynamics of species and management considerations. For all main species harvesting strategies are applied when setting TACs and also actual catches are very close to the agreed TACs.

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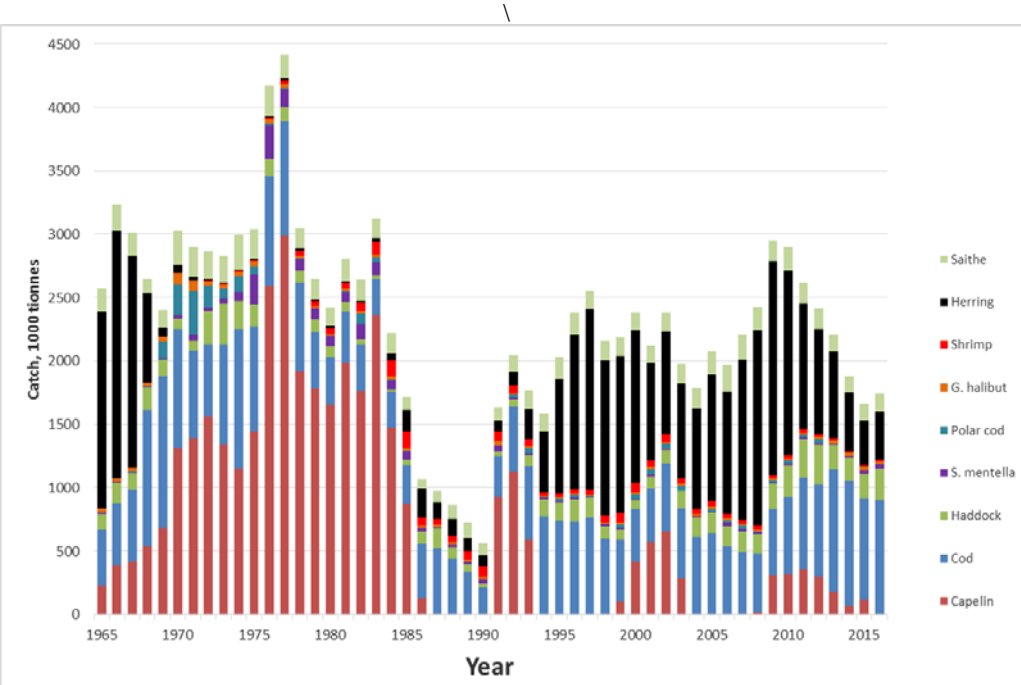


*** 2016 preliminary data**

Figure 3.9.1.1. Total catches of the most important stocks in the Barents Sea and adjacent waters of Norwegian and Greenland Sea (including catches in all of ICES area 2a, i.e. along the Norwegian coast south to 62N) from 1965 to 2016. Catches of Norwegian spring-spawning herring outside ICES area 2a are also included. Also minor catches of other stocks are taken in the Barents Sea (see ICES website).

Fishing mortalities and harvesting strategies

Fisheries influence the ecosystem by removing sustainable quantities of fish as food for humans and other purposes. The fishery is not considered sustainable if it impairs the

recruitment of the fish stocks. Single species management often focuses on measuring the status of the fishery in relation to benchmarks called biological reference points (BRPs). BRPs for single species management are usually defined in terms of fishing mortality rate (F) and total or spawning-stock biomass (TSB or SSB) and in terms of target and limit reference points. Limit BRPs suggest maximum levels of F and minimum levels of B that should not be exceeded. These BRPs are then compared to estimates of F and B from stock assessments to determine the state of the fishery and suggest management actions.

The limit reference point for fishing mortality, F_{lim}, will eventually bring the spawning stock down to B_{lim}, below which the recruitment will be impaired. F_{lim} may hence be used as an indicator for unsustainable exploitation and negative influence on the stock and the ecosystem. Keeping F below F_{lim} and the stock above B_{lim} may, however, not be considered as sufficient protection. Smaller and younger adults resulting from high fishing pressure have a lower reproductive potential than adults of a wider range of sizes and ages. The harvest rate and fishing pattern should hence fit with these biological requirements.

Recently the Maximum Sustainable Yield (MSY) concept was implemented in ICES work. The ICES approach to fisheries advice integrates the precautionary approach, maximum sustainable yield, and an ecosystem approach into one advisory framework. The aim is, in accordance with the aggregate of international guidelines, to inform policies on yields that can be taken out in the fisheries while maintaining productive fish stocks within healthy marine ecosystems. Maximum sustainable yield is a broad conceptual objective aimed at achieving the highest possible yield in the long term (an infinitely long period of time). For several stocks, MSY reference points have been identified and implemented in fishery management strategy.

Furthermore, a fishery may not be considered optimal if the fish are caught too early, i.e. if the net natural growth potential is not utilized. This is called growth overfishing and makes the total yield less than it would be if the fish were allowed to grow to a reasonable size. Introduction of minimum catch size and selective gears are the most common management measures to avoid growth overfishing.

Larvae and juveniles of all groundfish species are important predators on zooplankton. It is hence important for a sound ecosystem that there are sufficient plankton eaters present to utilize the plankton production and convert this into production of fish, both as food for humans, but also as food for other fish, marine mammals and seabirds that depend on fish prey. It is therefore not sufficient to manage the fish stocks to the extent that the recruitment is not impaired as seen from a single species point of view, but rather to maximize the larvae production as a valuable food contribution to the ecosystem as a whole.

Cod, haddock, and saithe

These stocks have F-based management plans which are largely followed by managers when setting TACs. All of these stocks are currently harvested close to or below MSY (Figure 3.8.1.2), and all of them are above B_{pa} at present. Several variants of harvest control rules for cod and haddock were tested by ICES in 2016. A new harvest control rule for cod, with increasing F at high stock sizes, was adopted by the joint Russian-Norwegian Fisheries commission in autumn 2016. The HCR for haddock was not changed. The current HCR for saithe was set by Norway in 2013.

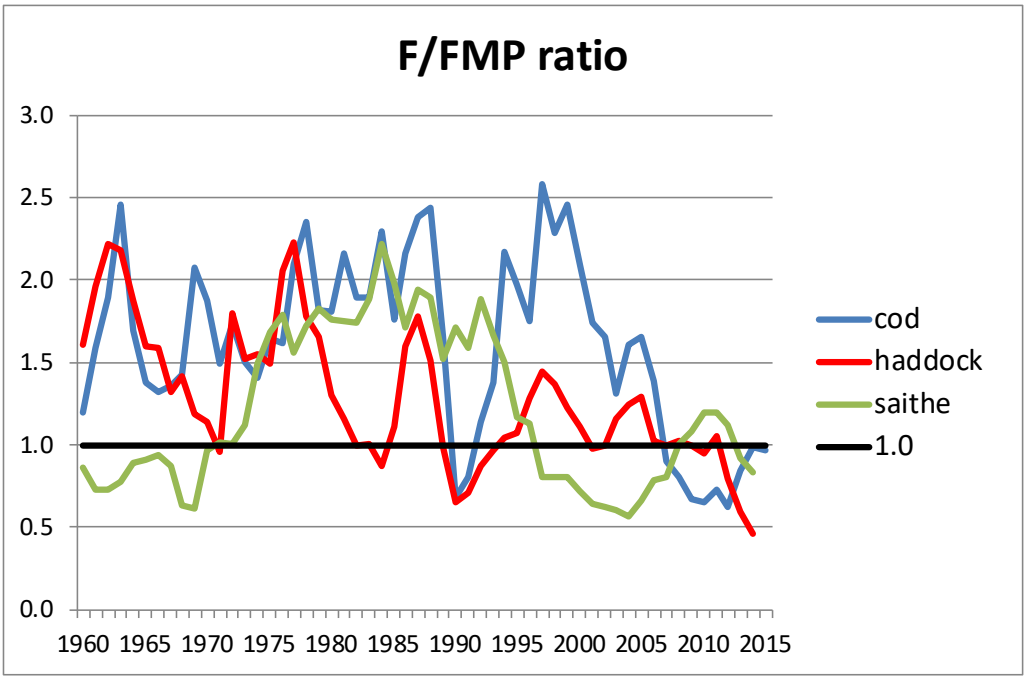


Figure 3.9.1.2. Annual fishing mortalities of the northeast Arctic cod, haddock and saithe stocks relative to fisheries management plan (FMP), i.e. the level used in the management plans for these stocks when SSB > B_{pa} (ICES 2016). Note that saithe is mainly found along the Norwegian coast and off the coast south of the Barents Sea – little in the Barents Sea itself.

The exploitation rate has in some periods been critically high. Because of the harvest control rule and better control and enforcement, this problem seems to have been reduced in recent years. The recent increased exploitation rate of cod needs careful monitoring. Although the exploitation rate may have been too high to fully utilize the production potential in the stocks, it may be concluded that the exploitation of these three stocks since 2005 have been sustainable.

The current large cod stock has caused some concerns about it being 'too large' as compared to food availability / carrying capacity. So far the cod population dynamics has been little affected by the stock size, but the question is certainly valid, and the introduction of a harvest control rule with increased fishing mortality at high stock sizes is a step towards taking such concerns into account. However, the concept of a stock being 'too large' is not at present incorporated in the ICES advice framework, although such issues are well known e.g. in management of freshwater fisheries and wildlife.

Capelin

Capelin is managed by a target escapement strategy. MSY for capelin will depend strongly on the cod stock and gives little meaning in a single-species context. There was no fishery for capelin in the area during 2004–2008 due to poor stock condition. During 2009–2013 the stock was sufficiently sound to support a quota between 200 000 and 400 000 metric tonnes. After that, the stock collapsed again, and there was no fishery in 2016, and an agreement of no fishery for 2017. Since 1979, the capelin fishery has been regulated through quotas set using a harvest control rule enforced by the Norwegian-Russian Fishery Commission. The harvest control rule is considered by ICES to be in accordance with the precautionary and ecosystem approaches to fisheries management. Being a forage fish in an ecosystem where two of its predators, cod and haddock, are currently at high levels, the capelin stock is now under heavy predation pressure. The fishery is restricted to the prespawning period (mainly February-March) and

the exploitation level is regulated based on a model that incorporates natural mortality, including predation from cod. A minimum landing size of 11 cm has been in force since 1979. The management plan's harvest control rule is designed to ensure that SSB remains above the proposed B_{lim} of 200 000 metric tonnes (with 95% probability).

Greenland halibut

For Greenland halibut no limit reference points have been suggested or adopted. The assessment is still considered to be uncertain due to problems with the age-reading and input data quality. The exploratory assessment may nevertheless be accepted as indicative for stock trends. Although many aspects of the assessment remain uncertain, fishery-independent indices of stock size from research surveys indicate positive trends in recent years. After many years of overexploitation of the stock, the recent exploitation rates at F = 0.027 (average over recent 5 or 10 years) have been consistent with a rise in fishable biomass (length ≥45 cm) over the same periods, and hence seems to be sustainable and will not influence the ecosystem negatively (Figure 3.6.14). Reconstruction of historical (pre-1992) stock and exploitation levels is needed to provide a better basis for reference points and evaluation of harvest control rules.

Beaked redfish (*Sebastes mentella*)

The analytical assessment and advice are provided for ICES Areas 1 and 2 combined. The fishery for *S. mentella* operates in national and international waters, which are managed under different schemes and by different management organizations. A pelagic fishery for *S. mentella* developed in the Norwegian Sea outside EEZs since 2004. This fishery is managed by the Northeast Atlantic Fisheries Commission (NEAFC). A new directed demersal and pelagic fishery has been permitted in the Norwegian Economic Zone, since 2014. In 2015 all catches of *S. mentella* from the Russian and Norwegian fisheries (Figure 3.9.1.4) were taken in the Norwegian Exclusive Economic Zone or as bycatch in the Fisheries Protection Zone around Svalbard, while catches in international waters have mostly been taken by EU countries.

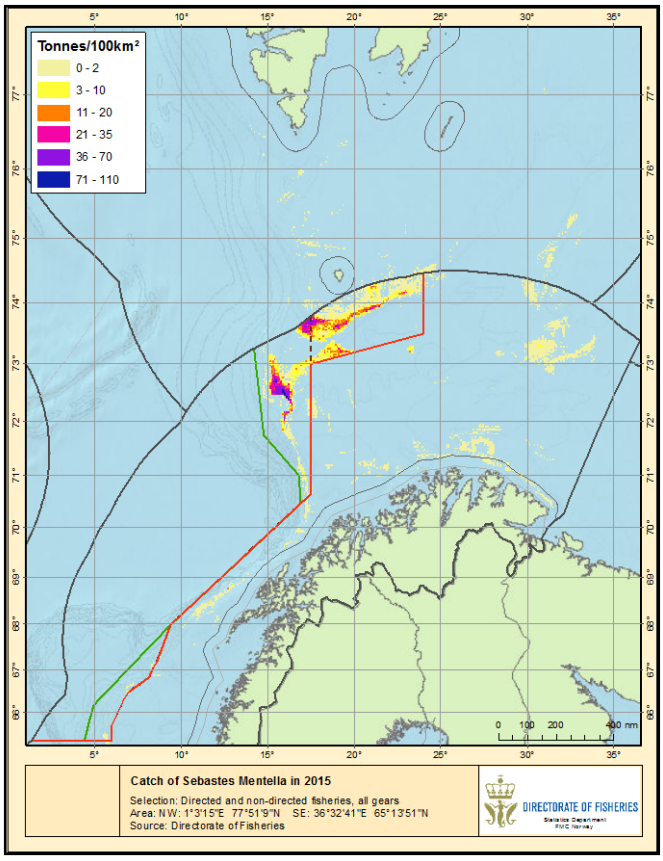


Figure 3.9.1.4. ***Sebastes mentella*** **in Areas 1 and 2. Location of** ***S. mentella*** **catches by Norwegian fishing vessels in 2015, both in a directed fishery and as bycatch.**

At present, no fishing mortality or biomass reference points are defined for this stock. $F_{0.1}$ = 0.039 is considered as a good candidate for F_{MSY} proxy when the stock has been re-built. A biomass trigger of 600 kt is a good starting point for management.

The current estimate of fishing mortality is below the assumed natural mortality (0.05) and F_{MSY} proxy ($F_{0.1}$ = 0.039). Fishing at $F_{0.1}$, which is close to the assumed value of natural mortality is not considered to be detrimental to the stock, but the historical (1996–2003) failure in recruitment indicates that catches based on the long-term average FMSY may be inappropriate in the short term.

The Joint Norwegian-Russian Fisheries Commission has not yet decided on a management plan for this stock, nor the elements that should be incorporated in such a future management plan. Until then, ICES only advises on the basis of precautionary considerations that an annual catch in 2015, 2016, and 2017 should be set at no more than 30 000 t (below the catch level corresponding to MSY), and that the measures currently in place to protect juveniles should be maintained. Accordingly, Norway and Russia set a quota of 30 000 t for those years.

Golden redfish (*Sebastes norvegicus*)

For golden redfish no limit reference points have been suggested or adopted. Golden redfish SSB has been decreasing since the 1990s and is currently at the lowest level in the time-series. Fishing mortality has been increasing since 2005 and is currently at the highest level in the time-series (Figure 3.9.1.5). Recruitment is very low. ICES advises that there should be no fishing on this stock, given the very low SSB (below any possible reference points) and poor recruitment.

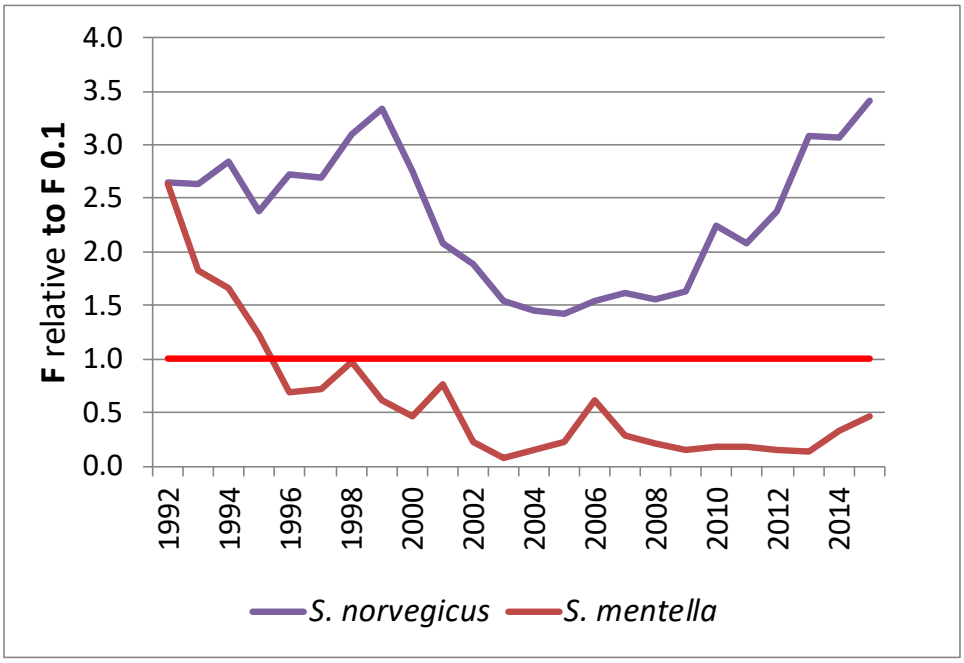


Figure 3.9.1.5. Annual fishing mortalities of Golden redfish (*Sebastes norvegicus*) and Beaked redfish (*S. mentella*) relative to the target levels ($F_{0.1}$) as a precautious proxy to F_{MSY} at which the stocks are supposed to give the highest long-term sustainable yields (ICES 2016c).

Experience from other Sebastes stocks, e.g. in the Pacific and in the Irminger Sea, suggests that annual harvest rates of such slow growing and long-lived species should not exceed 5% if the stock is recruiting normally. At a time when this stock is not recruiting normally, even an annual exploitation rate of 5% may be too high. It can thus be concluded that the current fishery of golden redfish is too intensive and may have a negative influence on the stock itself. $F_{0.1}$ (a typical precautionary proxy for F_{MSY}) is around $F_{0.1} = 0.08$. For $F_{0.1} = 0.08$ the sustainable yield at current recruitment is 1400 tonnes per year.

Even if the regulations have succeeded in reducing the landings in recent years, if catches are maintained at the current level (3600 tonnes annually) and recruitment is similar to the average recruitment for recent years (2001–2015), the stock size is projected to be very low by 2020.

Polar cod (*Boreogadus saida*)

For economic reasons, there has been little interest in developing a fishery for polar cod. No fishery at all has been carried in recent years, and the stock size as measured in the Barents Sea in autumn, has also been at very low levels. The historical fishery which has taken place, mainly by Russia, was conducted in late autumn when concentrations of polar cod were targeted during southward spawning migrations along the coast of Novaya Zemlya.

Wolffish (Catfish)

Three species of wolffish: Atlantic wolffish (*Anarhichas lupus*), Spotted wolffish (*Anarhichas minor*), and Northern wolffish (*Anarhichas denticulatus*) are taken mostly as bycatch in fisheries for gadoids in the Barents Sea, but also in a directed longline fishery. From 1905 to 1950, international catches of wolffish in the Barents Sea and along the northern Norwegian coast increased from 100 to 14 000 tonnes. Until 1998 the annual landings were between 6000 and 44 500 tonnes. The high quantity in 1997–2001 was

primarily caused by an intensive fishing for northern wolffish because of the bycatch regulations of other valuable species (e.g. Greenland halibut) and a growing Russian market. After 2001, the total wolffish catches north of 62°N decreased, but have improved slightly again in recent years (24 567 tonnes in 2016). The Russian catches increased from a stable level of about 13 000 tonnes in several years, to 18 000 tonnes in the past two years, while Norwegian catches have been about 6000 tonnes in recent years (Figure 3.9.1.6). Northern and Spotted wolffish comprise more than 90% of the total wolffish catch in the Barents Sea region. The Atlantic wolffish are mainly caught in the coastal zone, also outside this region

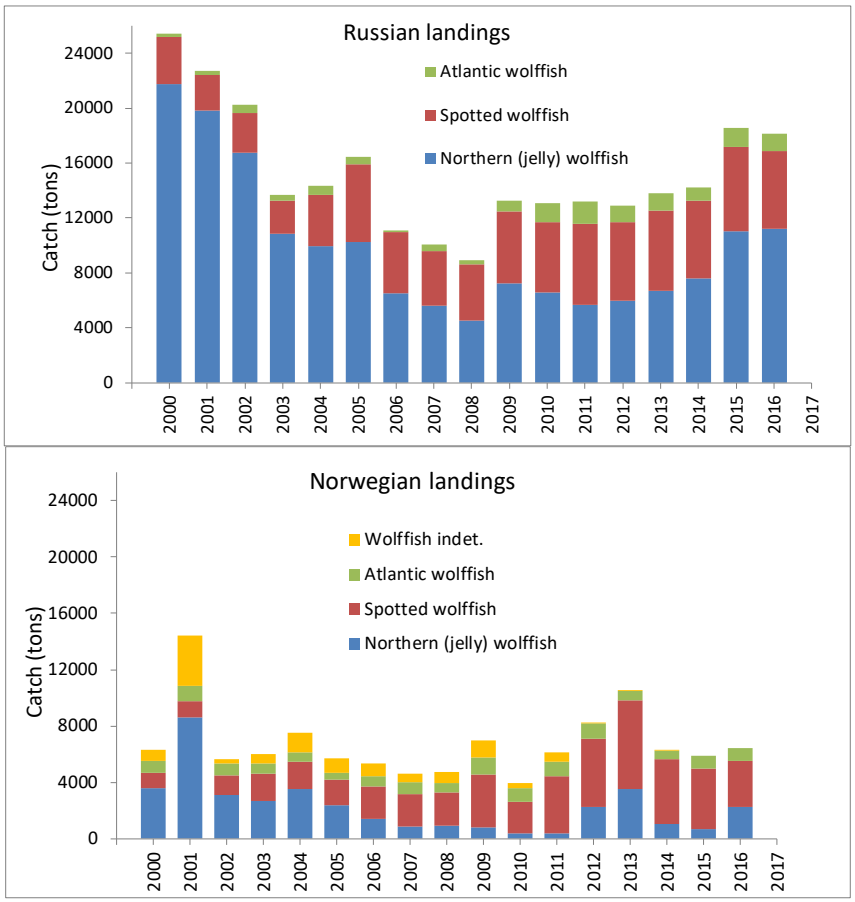


Figure 3.9.1.6. Russian (above) and Norwegian (below) official landings of the different wolffish species north of 62°N in 2000–2016.

Other fish species

Information about the species composition in the Norwegian fisheries north of 67°N is available from the Norwegian Reference fleet (NRF), i.e. 15 high seas and 24 coastal fishing vessels contracted by the Institute of Marine Research. Such data are now routinely being collected from these vessels' fishery every day or every second day. What affect the fishery may have on all the non-regulated species and the ecosystem will be a subject for further research.

Gullestad *et al.* (2017) presents the practical implementation of the Ecosystem Approach to Fisheries Management (EAFM) in Norway. This involves defining management objectives and developing simple and efficient tools to achieve an overview of management needs and prioritize among these, while integrating broader conservation issues and ensuring stakeholder involvement.

Species of economic interest not mentioned in this chapter are tusk and ling, and relatively small landings of grenadiers, Atlantic halibut, other flatfish, lumpsucker, hake, pollack, whiting, Norway pout, argentines, salmon, dogfish, skates, and molluscs.

3.9.2 Catches of shellfish

Northern shrimp (*Pandalus borealis*)

Norwegian and Russian vessels harvest northern shrimp in the Barents Sea over the stock's entire area of distribution. Vessels from other nations are restricted to fish only in the Svalbard zone and the loophole. No overall TAC has been set for northern shrimp, and the fishery is regulated through effort control, licensing, and a partial TAC in the Russian zone only. The regulated minimum mesh size is 35 mm. Bycatch is constrained by mandatory sorting grids, and by temporary closures in areas with high bycatch of juvenile cod, haddock, Greenland halibut, redfish, or shrimp (<15 mm carapax length or <6 cm total length). Catches have varied between 19 000 and 128 000 tonnes/year since 1977. Since the mid-1990s, a major restructuring of the fleet toward fewer and larger vessels has taken place. Since 1995, average engine size of a shrimp vessel in ICES Subareas 1 and 2 increased from 1000 HP (horse power) to more than 6000 HP in the early 2010s, and the number of fishing vessels has declined markedly. Overall catch decreased from approximately 83 000 tonnes since 2000, reflecting reduced economic profitability in the fishery. After a low of about 20 000 tonnes in 2013, catches have again started to increase and is expected to reach about 36 000 tonnes in 2016. The 2016 stock assessment indicated that the stock has been exploited in a sustainable manner, and has remained well above precautionary reference limits throughout the history of the fishery. Accordingly, ICES advised per the MSY-approach a 2017 TAC of 70 000 metric tonnes (ICES 2016a).

The geographical distribution of the stock in 2009–2015 was more easterly compared to that of the previous years (Figure 3.9.2.1). Therefore, catch levels from some of the more traditional western fishing grounds have declined. Recent reports indicate lower catch rates than would be expected given the overall good stock condition. This may be related to operation costs for a relatively small fleet to move from more traditional fishing grounds, and to find new grounds with commercially viable shrimp concentrations.

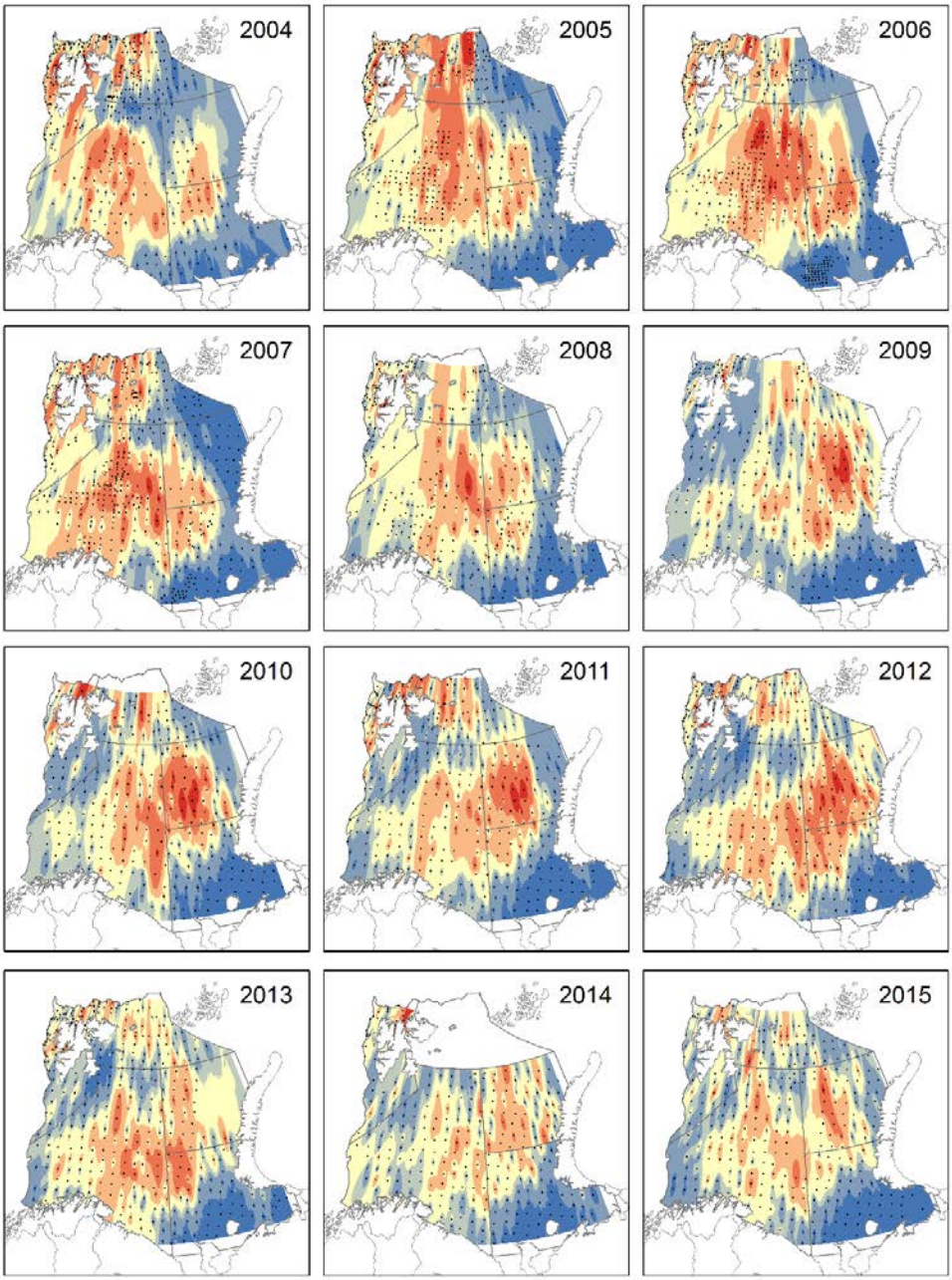


Figure 3.9.2.1. Shrimp density by year from inverse distance weighted interpolation (e.g. Fisher *et al.*, 1987) between trawl stations (black dots) for the Joint Russian-Norwegian Ecosystem survey (Europe Albers Equal Area Conic projection). No map for 2016 available.

Red king crab (*Paralithodes camtschaticus*)

In the area east of 26°E and south of 71°30′N, and in Russian waters of the Barents Sea, the commercial crab fishery is managed to achieve long-term sustainability by setting annual quotas for this area. Outside this area (west of 26°E), the red king crab fishery is regarded as undesirable; a free non-legislated fishery is permitted, and release of viable crabs back into the sea is prohibited. In the Norwegian waters of the Barents Sea, the harvest rate of this species in the quota-regulated area is high; this is intended to keep the standing stock as low as possible to limit further spread of the crab. Male crabs above a minimum legal size of 130 mm, and females above 120 mm carapace length are taken in the quota-regulated fishery, and there are no seasonal catch restrictions.

Hence, Norwegian management of this fishery contradicts management regimes applied in both the Bering Sea (Alaska) and in the Russian part of the Barents Sea.

The current management of red king crab was evaluated in 2015. In 2016, 616 vessels participated in the regulated Norwegian king crab fishery while approximately 80 vessels participated in the free fishery. The Norwegian quota for 2017 are set to 2000 tonnes of male crabs and 150 tonnes of females. This corresponds to an extremely high exploitation rate in Norwegian waters. The Russian quota for 2016 was 8000 tonnes red king crab.

Snow crab (*Chionoecetes opilio*)

The fishery for snow crab started at a low scale in 2012. That year, 2500 tonnes was landed and since then the fishery intensity has increased and the number of boats from different countries participating has increased as well. Available data on landings reveals a steady increase in effort and catch. In 2016, 10 000 tonnes of snow crab was landed in Norway, and most of the crabs were fished in the Loophole. Also, the number of vessels participating in the fishery has increased from one vessel in 2012 to 33 boats in 2016.

Russian and Norwegian authorities have now defined the snow crab as a sedentary species which means that there are no obligations for the two nations to cooperate on the management framework. The management regime for the snow crab in the Barents Sea is under development and is expected to be finished during 2017.

3.9.3 Whaling and seal hunting

Minke whale (*Balaenoptera acutorostrata*)

The management of this species is based on the Revised Management Procedure (RMP) developed by the Scientific Committee of the International Whaling Commission. The inputs to this procedure are catch statistics and absolute abundance estimates. The present quotas are based on abundance estimates calculated from surveys conducted in 1989, 1995, 1996–2001, 2002–2007 and 2008–2013. The most recent estimates (2008–2013) are 89 600 minke whales for the Northeastern stock, and 11 000 animals for the Jan Mayen area, which is also exploited by Norwegian whalers. The present (2016-2021) basic RMP quota of 880 animals annually is considered precautious, conservative and protective for the minke whale population in the Northeast Atlantic. At present only Norway utilizes this quota.

Harp seals (*Pagophilus groenlandicus*)

The Northeast Atlantic stocks of harp seals are assessed every second year by the ICES Working Group on Harp and Hooded Seals (WGHARP). The assessments are based on modelling, which provides ICES with sufficient information to give advice on both status and catch potential of the stocks. The population model applied estimates the current total population size, incorporating historical catch data, estimates of pup production and historical values of reproductive rates. The modelled abundance is projected into the future to provide a future population size for which statistical uncertainty is provided for various sets of catch options. Russian aerial surveys of White Sea harp seal pup production conducted in the period 1998–2013 indicate a severe reduction in pup production after 2003. According to ICES, this could be due to changes in fecundity and/or changes in survival. The Barents Sea/White Sea population of harp seals is now considered data poor (available data for stock assessment older than 5 years). Nevertheless, and despite that the population model provided a poor fit to the

pup production survey data, primarily due to the abrupt reduction after 2003, ICES decided to use it to provide advice in 2017 (ICES 2016d). The total size of the population was estimated as 1 408 200 (95% C.I. 1 251 680–1 564 320). A catch of 10 090 1+ animals, or an equivalent number of pups (where one 1+ seal is balanced by 2 pups), per year would sustain the 1+ population at present level over the 15 years' period 2017–2032. The catches in recent years have been much lower than the quotas, in particular after 2008 which was the last year with Russian hunt on this population.

3.9.4 Fishing activity

The fishing activity in the Barents Sea is among other monitored by Vessel Monitoring System (VMS) data. Figures 3.9.4.1-3.9.4.2 show fishing activity in 2016 from Russian and Norwegian data. VMS data might give us valuable information about temporal and spatial changes in fishing activity. The most widespread gear used in the Barents Sea is bottom trawl, but also longline, gillnets, Danish seine and handline are used in the demersal fisheries. The pelagic fisheries use purse-seine and pelagic trawl, shrimp fishery used special bottom trawls.

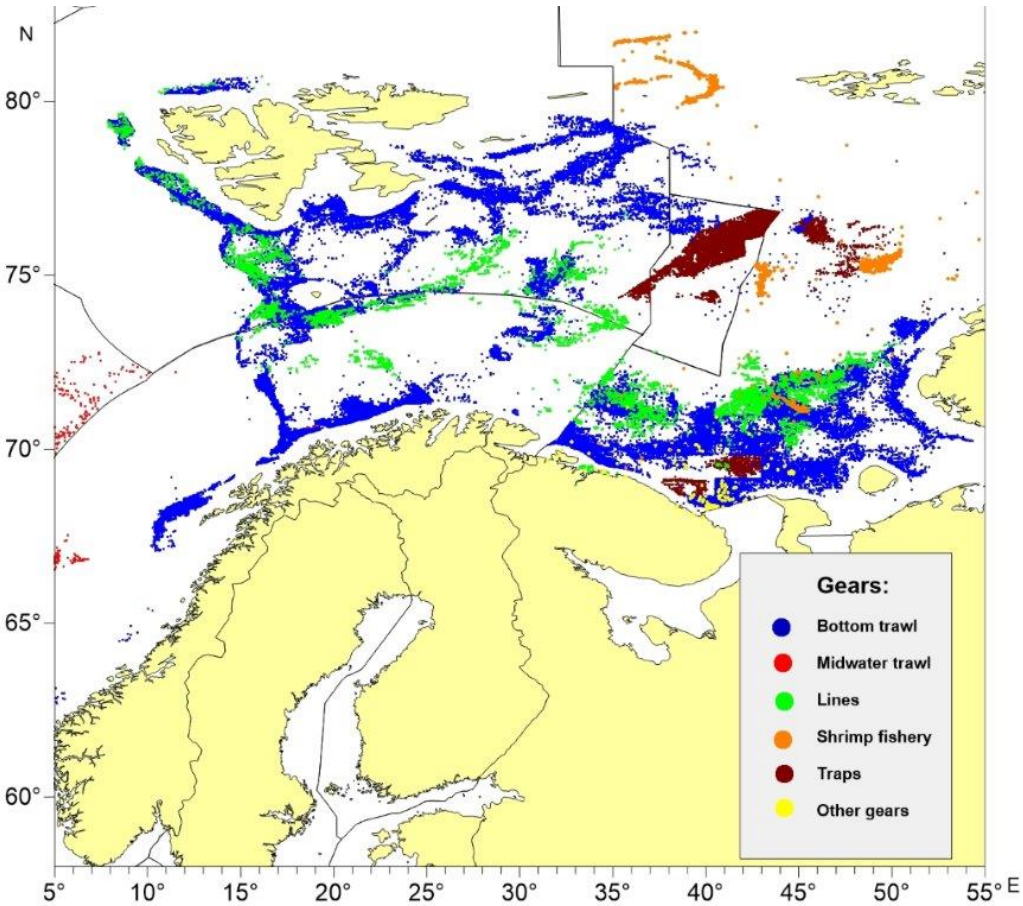


Figure 3.9.4.1. Location of Russian and foreign fishing activity from commercial fleets and fishing vessels used for research purposes in 2016 as reported (VMS) to Russian authorities. This is VMS data linked with logbook data (source: PINRO Fishery statistics database).

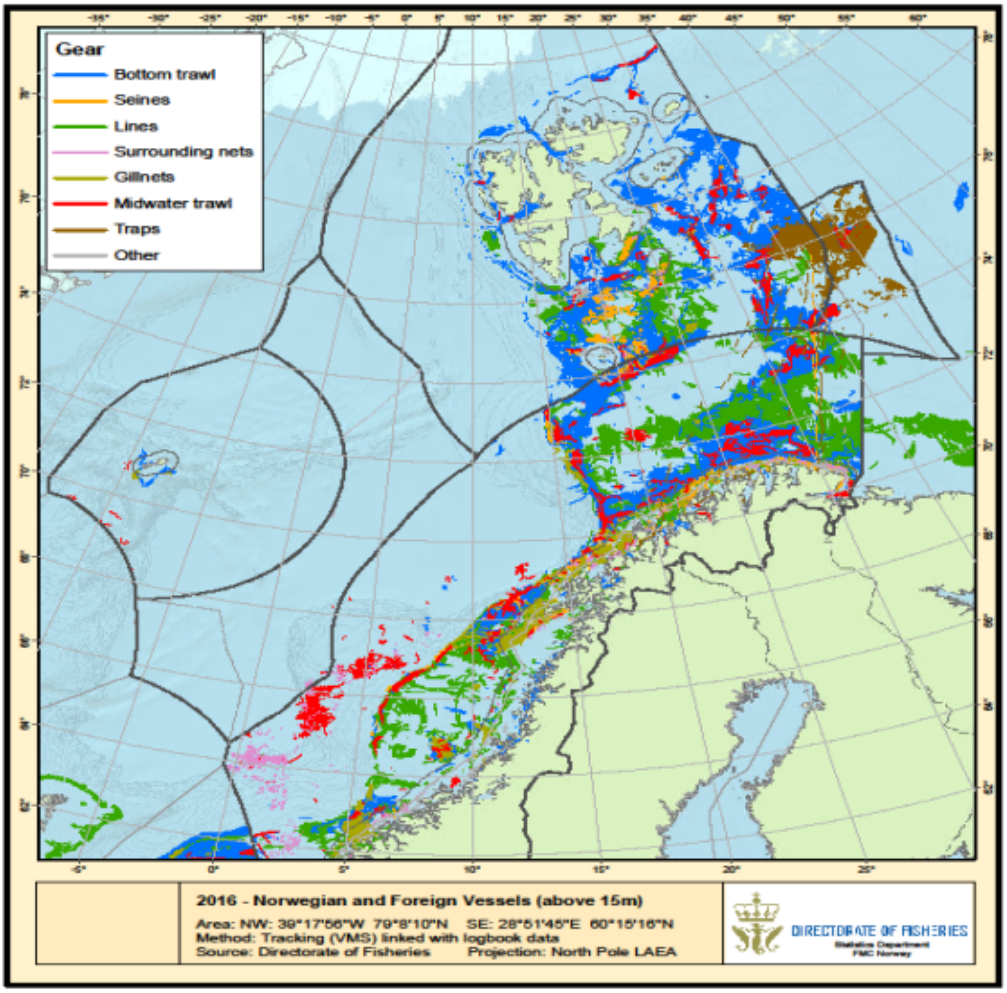


Figure 3.9.4.2 Location of Norwegian and foreign fishing activity from commercial fleets (larger than 15m) and fishing vessels used for research purposes in 2016 as reported (VMS) to Norwegian authorities. This is VMS data linked with logbook data. Surrounding nets = Danish seine (source: Norwegian Directorate of Fisheries).

From 2011 onwards, the minimum mesh size for bottom-trawl fisheries for cod and haddock is 130 mm for the entire Barents Sea (previously the minimum mesh size was 135 mm in the Norwegian EEZ and 125 mm in the Russian EEZ). It is still mandatory to use sorting grids. The minimum legal catch size was harmonized at the same time: for cod from 47 cm (Norway) and 42 cm (Russia) to 44 cm for all, and for haddock from 44 cm (Norway) and 39 cm (Russia) to 40 cm for all.

3.9.5 Discards

The level of discarding in the fisheries is not known, and no discards are accounted for in the assessments. Both undersized fish and bycatch of other species can lead to discarding, and also low-paid fish just above the minimum size has been subject to discarding in order to fill the quota with larger and better paid fish (known as highgrading).

Discarding is known to be a (varying) problem, e.g. in the haddock fisheries where discards are highly related to the abundance of haddock close to, but below the minimum legal catch size. Dingsør (2001) estimated discards in the commercial trawl fishery for northeast Arctic cod during 1946–1998 and the effects on the assessment. Sokolov (2004) estimated cod discard in the Russian bottom-trawl fishery in the Barents

Sea in 1983–2002. The lack of discard estimates leads to less precise and accurate stock assessments. The influence of the fishery on the ecosystem is hence not fully understood. A possible way to estimate values of discarded fish is analysis of landing information (size/weight composition of landings in relation to observe on board fishing vessels). Norway is conducting a pilot project to estimate the discards in some selected fisheries to test and establish methods for estimating discards in all Norwegian fisheries on a routine basis in near future.

Registration of redfish (dominated by *S. mentella*) taken as bycatch and discarded in the Norwegian shrimp fishery in the Barents Sea since 1984 show that shrimp trawlers removed significant numbers of juvenile redfish during the beginning of the 1980s. This peaked in 1984, when bycatches amounted to about 640 million individuals, a number similar to a good year class of this stock (Figure 3.9.5.1). As sorting grid became mandatory in 1993, bycatches of redfish were reduced drastically during the 1990s. The results also show that closure of areas is necessary to protect the smallest redfish juveniles since these are not sufficiently protected by the sorting grid. The bycatch and discard of cod consists mainly of 1- and 2-year-olds, but is generally small compared to other reported sources of mortality like catches, discards in the groundfish fisheries and cannibalism.

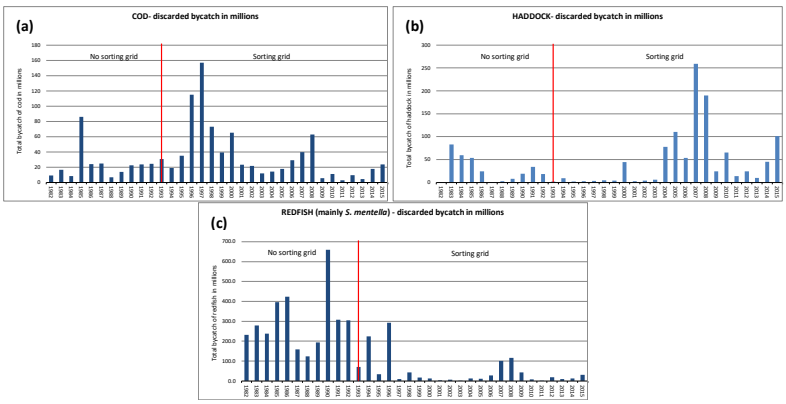


Figure 3.9.5.1. Revised bycatch (discards) estimates of small a) cod, b) haddock and c) redfish during the Barents Sea shrimp fishery 1982–2015 (ICES 2016c).

Noticeable discards of cod in the shrimp fishery occurred in 1985, 1996–1998. The highest recorded numbers of cod was in 1997 (157 millions). The cod bycatches have declined in recent years (<20 millions). Discards of haddock in the Barents Sea shrimp fishery have been estimated for the period 2000–2005, and show the highest discard in 2007–2008 (about 200 millions). Discards of Greenland halibut in the Barents Sea shrimp fishery have been estimated for the period 2000–2005, and show the highest discard in 2002 and 2000 of about 13 million specimens.

Even if the sorting grid prevents discarding of fish larger than about 18 cm, it becomes obvious that only an effective surveillance and closure of areas for shrimp fishing that can prevent bycatch and discarding of smaller specimens.

3.9.6 Pollution

According to the national monitoring program, every year PINRO conducts research of pollution level in the Barents Sea. The objective of the research is to collect data on the potential anthropogenic impact on bioresources and on the ecosystem of the Barents Sea in general, to obtain data, filling the gaps in quality assessment of the Barents Sea environment, and to develop an infobase for future monitoring. The report given

represents some information on the current level of pollution in certain elements of the Barents Sea ecosystem. Samples were collected during a cruise of RV "Fridtjof Nansen" in February 2016. Preparation and analysis of samples were carried out in accordance with ICES guidelines. In the present report, we present cruise data collected in different fishing areas of the central and the southern parts of the Barents Sea. The objects analysed are the following: water (surface and bottom layers), bottom sediments (upper layer), and commercial fish species (muscles and liver). PINROs sampling stations for sediment, seawater and fish are shown in Figure 3.9.6.1a and b.

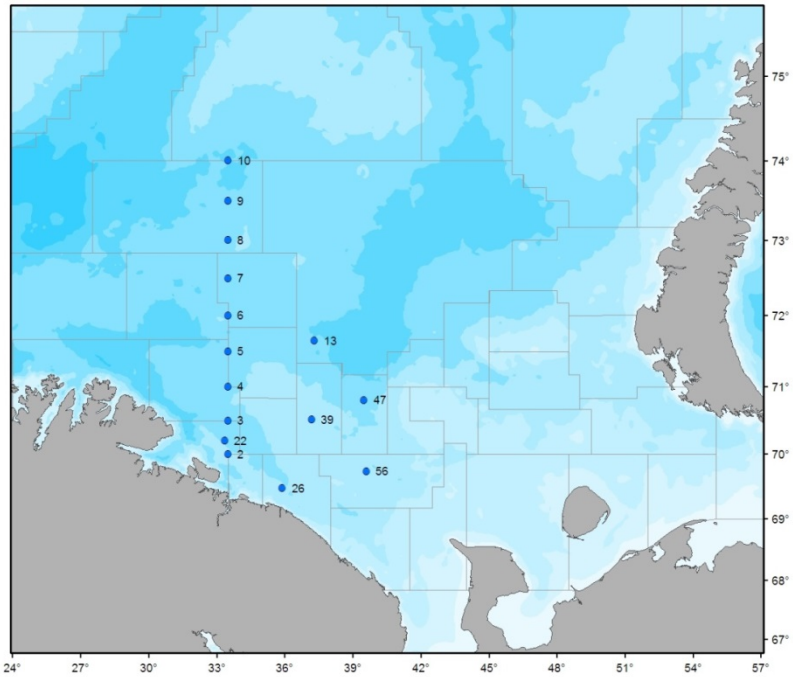


Figure 3.9.6.1a. PINROs sampling stations for sediment and seawater in 2016.

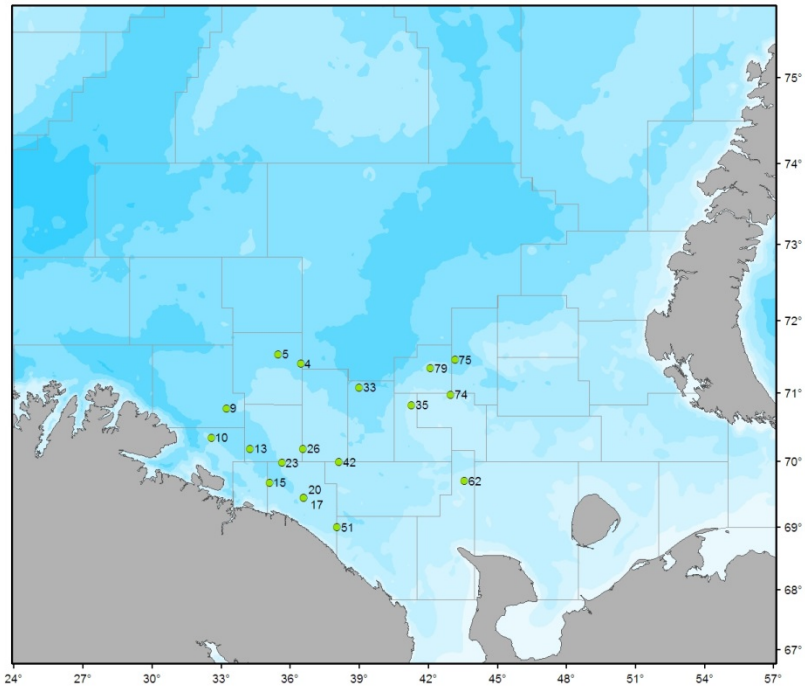


Figure 3.9.6.1b. PINROs sampling stations for fish in 2016.

IMR carries out sample collection for thorough investigations of the levels of contaminants in seawater, sediments and marine biota in the Barents Sea every third year. The last time was in 2015, when samples were collected from RV "Johan Hjort" and RV "G. O. Sars" in August and September. The sampling stations are shown in Figure 3.9.6.2. The analysis includes different hydrocarbons, persistent organic pollutants (POPs) (PCB, DDT, HCH, HCB) and radionuclides. Monitoring of radionuclides focuses on the most abundant anthropogenic (man-made) gamma-emitting radionuclide cesium-137 (Cs-137), but the levels of other anthropogenic radionuclides like strontium-90 (Sr-90), plutonium-238 (Pu-238), plutonium-239,249 (Pu-239,240) and americium-241 (Am-241) are also determined in a selection of samples. Monitoring of radionuclides is performed in close cooperation with the Norwegian Radiation Protection Authority (NRPA) within the national monitoring programme "Radioactivity in the Marine Environment" (RAME). Monitoring of organic contaminants is performed in close cooperation with NGU (The Geological Survey of Norway) and National Institute of Nutrition and Seafood Research (NIFES).

In addition to the triennial sampling cycle, samples of cod are caught along the coast of Finnmark and in the Bear Island area twice a year, in order to monitor the levels of Cs-137 in muscle tissue of this important commercial species. The results are part of a time-series from around 1990. Further, IMR investigate once a year the levels of radioactive contamination near the wreck of the Russian nuclear submarine "Komsomolets", which sank in 1989 in international waters in the Norwegian Sea 180–190 km south-southwest of Bear Island at 73°43′16′′N and 13°16′52′′ E. Samples of surface seawater (approximately 500 L) and bottom seawater (approximately 500 L) are collected with a CTD-rosette multi bottle sampler with large (10 L) water samplers. Sediment samples are collected with a sediment sampler of the type "Smøgen Boxcorer". The samples are analysed for a range of radionuclides (e.g. plutonium-238, plutonium-239,240, cesium-137 and strontium-90) at IMR and NRPA.

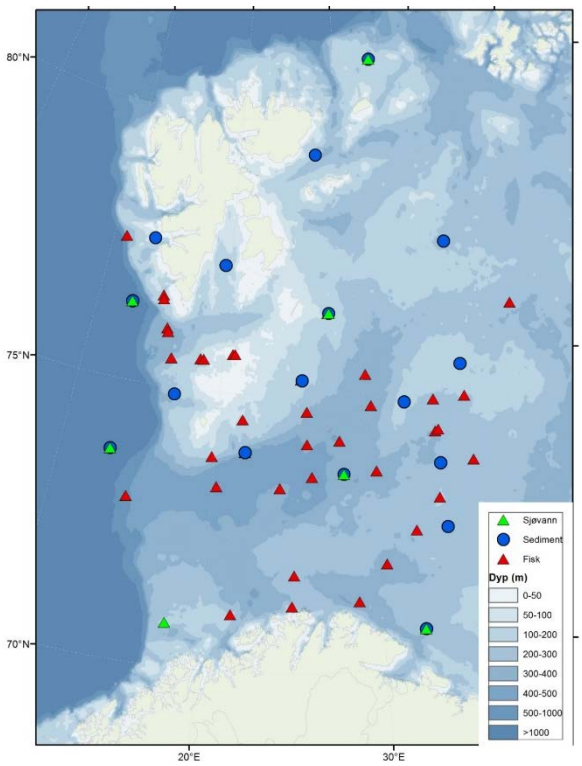


Figure 3.9.6.2. IMRs sampling stations in 2015 for sediment (blue circles), seawater (green triangles) and fish and other biota (red triangles).

Organic pollutants and metals

Average PAH concentration in clean areas of the Antarctic (20 ng/l) could be used as a global background level for assessment. In surface layer of the Barents Sea, total PAH content fluctuated in the range of 8–51 ng/l with the average concentration of 21 ng/l and in the near bottom layer – in the range of 8–47 ng/l with the average concentration of 22 ng/l (Figure 3.9.6.3a).

The highest total PAH concentrations are revealed in the surface layer at the Stations 8 and 13 and in the near bottom layer – at the Station 9. Compared to the data obtained during the same period in 2013, 2014, and 2015, current data shows reduction in median and extreme values of PAH content in seawater. Based on a classification given by the Norwegian Environment Agency (MD), PAH concentrations in surface and near bottom layers of the examined fishing areas of the Barents Sea fall into the category "slightly polluted".

Analysis of upper sediment layer samples showed the highest polycyclic aromatic hydrocarbons (PAH) content in sediments at the Station 8 of the Kola Section, which amounts to 285 ng/g dry weight (Figure 3.9.6.3b). Content of PAH in sediments of the explored Barents Sea areas, as well as content of the most famous carcinogenic PAH component – benzo[a]pyrene, did not exceed background levels of <300 and <10 ng/g dry weight respectively.

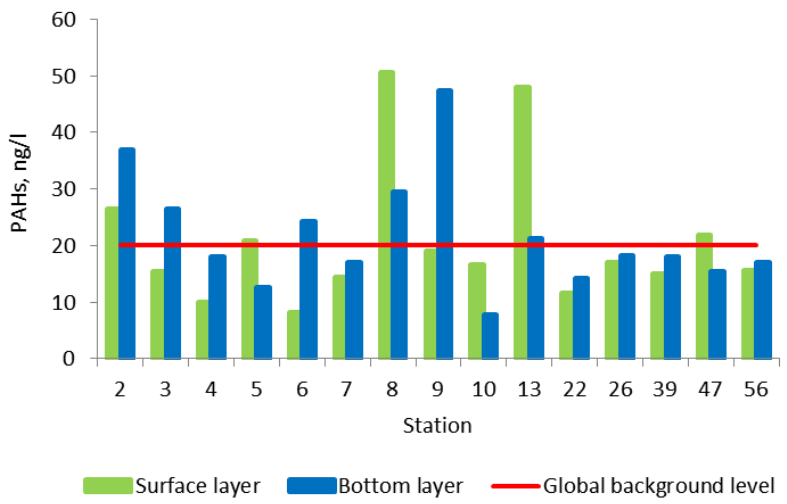


Figure 3.9.6.3a. Concentration of polycyclic aromatic hydrocarbons (PAHs) in seawater analysed by PINRO.

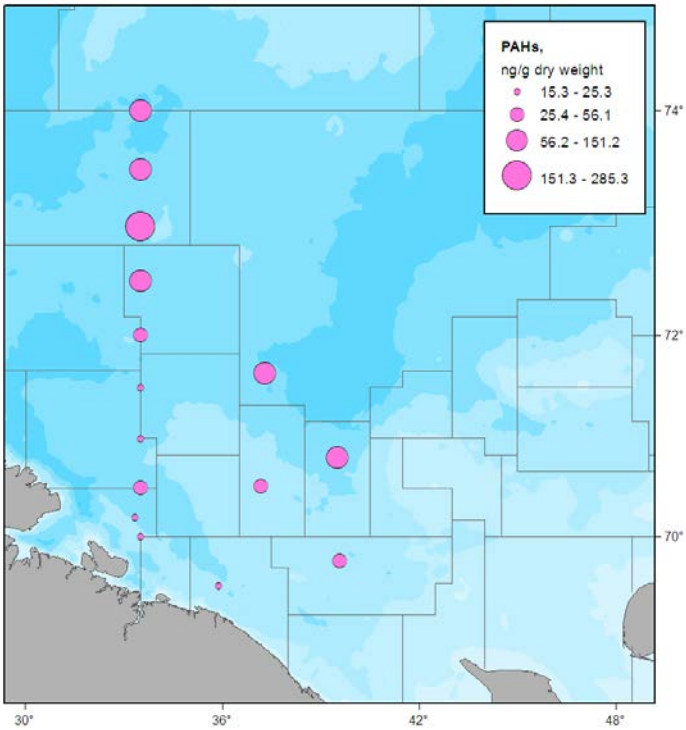


Figure 3.9.6.3b. PAH content in bottom sediments

Total content of α-, β- and γ- hexachlorocyclohexane (HCH) isomers in analysed sediments varied from 0.4 ng/g to 6.0 ng/g with the average concentration of 2.5 ng/g dry weight (Figure 3.9.6.4 a). This level is higher than the level estimated last year (last year the average value amounted to ~1 ng/g dry weight). According to the Norwegian MD classification, concentration of γ-HCH isomer (lindane) in analysed sediments fell into the category "slightly polluted" (<1.1 ng/g dry weight).

Total content of dichlorodiphenyltrichloroethane (DDT) metabolites in investigated sediments of the Barents Sea varied from 0.5 ng/g to 1.7 ng/g with the average concentration of 0.8 ng/g dry weight. (Figure 3.9.6.4b). According to the MD classification, content of ΣDDT at the Station 2 corresponded to the background level (<0.5 ng/g dry weight), the rest stations fell into the category slightly polluted" (0.5–20 ng/g dry weight).

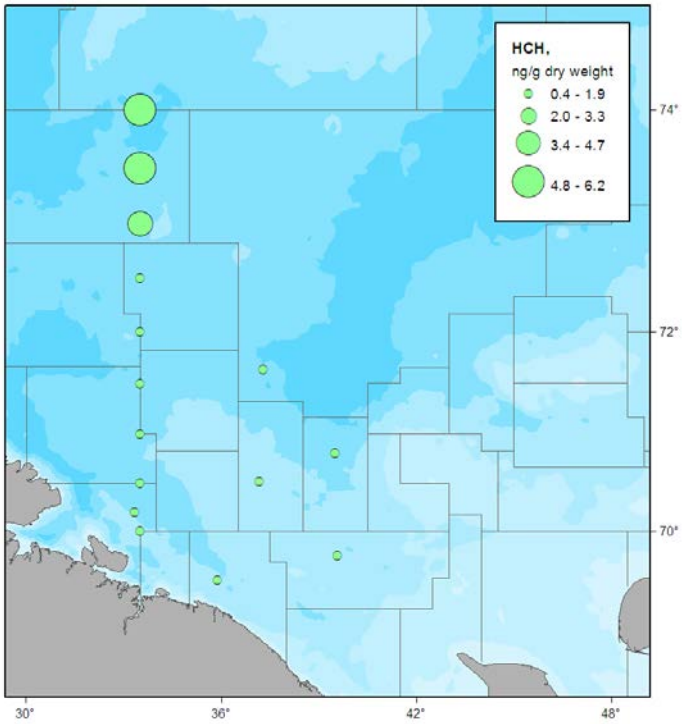


Figure 3.9.6.4a. Hexachlorocyclohexane (HCH) [∑(α-HCH, β-HCH, γ-HCH)] content in bottom sediments.

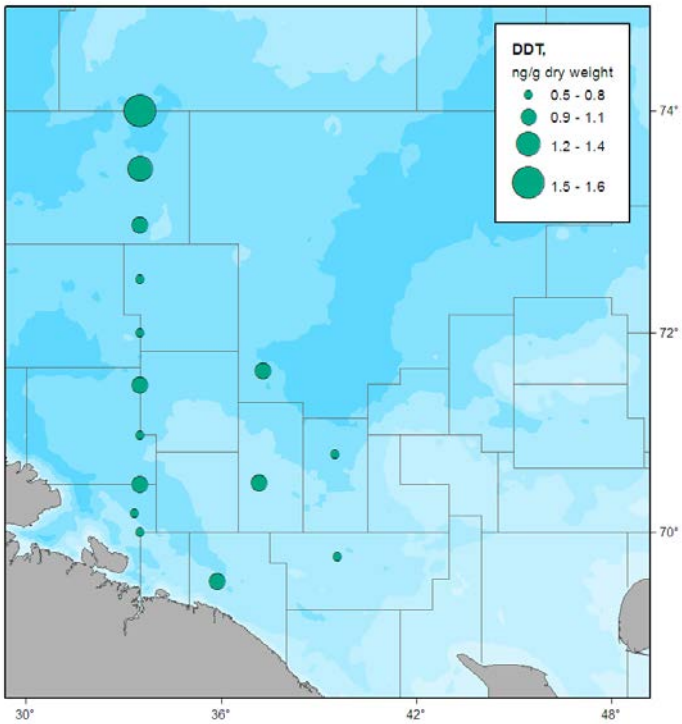


Figure 3.9.6.4b. Dichlorodiphenyltrichloroethane (DDT) [∑(o,p'-DDE, p,p'-DDE, o,p'-DDD, p,p'-DDD, o,p'-DDT, p,p'-DDT)] content in bottom sediments.

The lowest concentrations of copper, zinc, nickel, chromium, manganese, iron, lead, cadmium, arsenic, and mercury were indicated in silty sands at the Stations 29 and 56 (Figures 3.9.6.5 a and b), where sand grading <0.063 mm accounted for about 15% and content of organic carbon was 0.5%. The highest concentrations of mentioned heavy

metals and arsenic were indicated in bottom sediments at the Stations 8–10 in clayed silt, where percentage of fines (0.063 mm) was 60–70% and organic carbon content accounted for 2%. According to the Norwegian MD classification, content of **lead and nickel** in upper sediment layer at the Stations 3, 6–10, 47 fell into the category "slightly polluted" and did not exceed background levels at the rest stations (<30, <30 и <70 μg/g dry weight respectively). Concentrations of nickel and lead are shown in Figure 3.9.6.5 a and b.

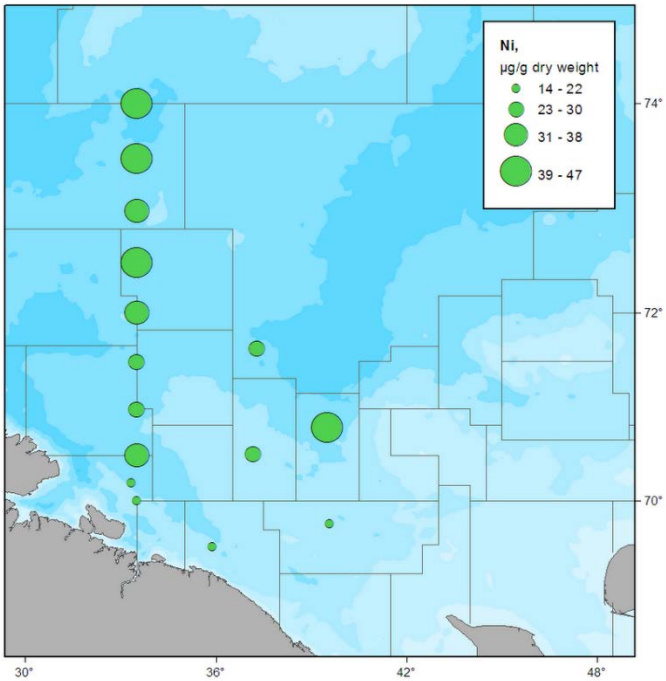


Figure 3.9.6.5a. Nickel content in bottom sediments.

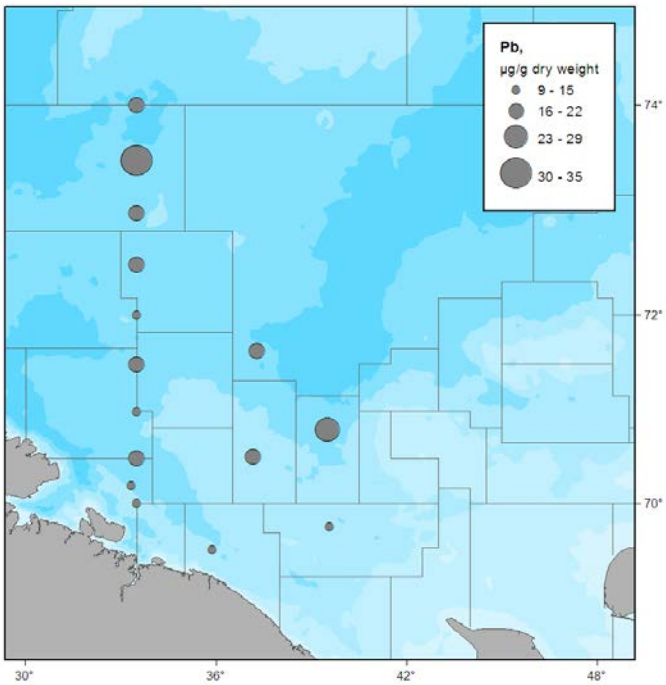


Figure 3.9.6.5b. Lead content in bottom sediments

The highest content of **HCH isomers** was indicated in muscles of Jelly wolfish (4.53 ng/g wet weight) caught at the Station 5 (Figure 3.9.6.6a). Also the highest content of **DDT isomers** was revealed in muscles of Greenland halibut from the same area (9.88 ng/g wet weight, Figure 3.9.6.6b). According to the classification adopted by the Norwegian Environment Agency (MD), mean value of total HCH and DDT isomers concentration corresponded to the category "moderately polluted" (0.5–2.0 ng/g and 1.0–3.0 ng/g wet weight respectively).

High content of **HCH isomers** is indicated **in liver** of American plaice caught at the Station 62 (8.46 ng/g wet weight) and the Station 13 (7.71 ng/g wet weight). According to the Norwegian classification, average concentration of **HCH isomers** in liver of cod corresponded to the category "slightly polluted" (<50 ng/g wet weight).

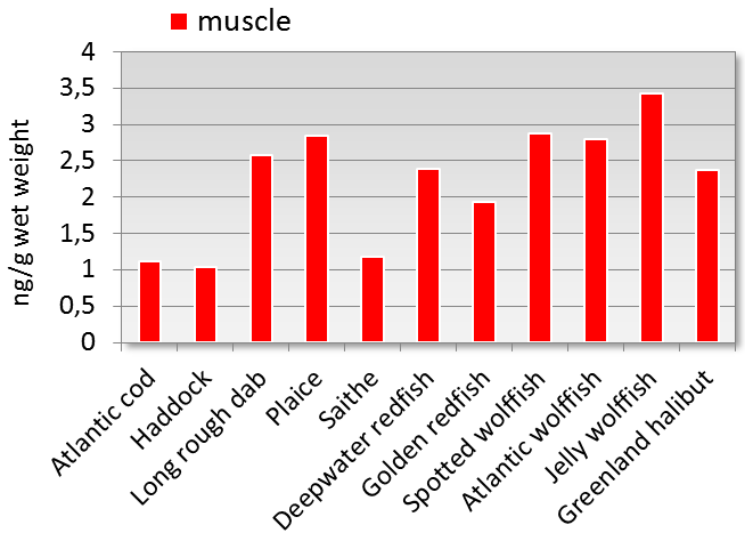


Figure 3.9.6.6a. Average concentrations of hexachlorocyclohexane (HCH) in muscle of fish

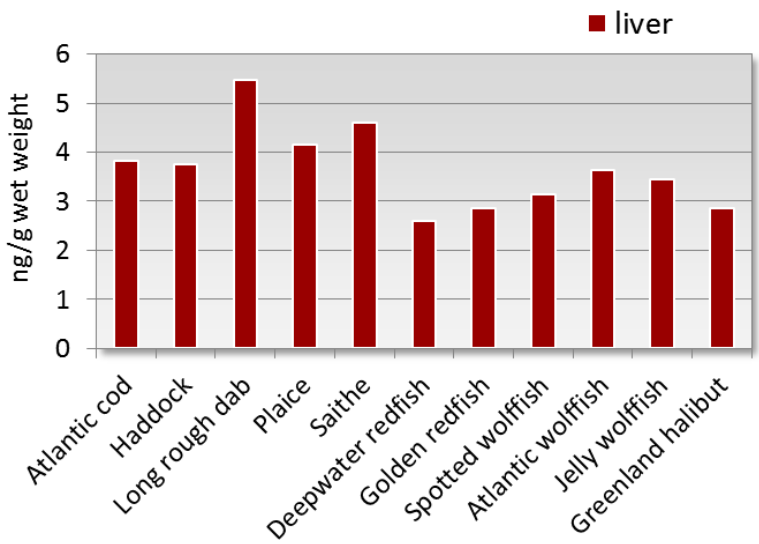


Figure 3.9.6.6b. Average concentrations of hexachlorocyclohexane (HCH) in liver of fish

Total content of polychlorinated biphenyls (PCBs) fluctuated from 1 to 12 ng/g wet weight in muscles of examined fish and from 6 to 470 ng/g wet weight in liver (Figures 3.9.6.7 a and b). The highest concentration of PCB was indicated in liver of cod taken

at the Station 15–474 ng/g wet mass, that fell into the category "slightly polluted" of the Norwegian classification (<500 ng/g wet weight).

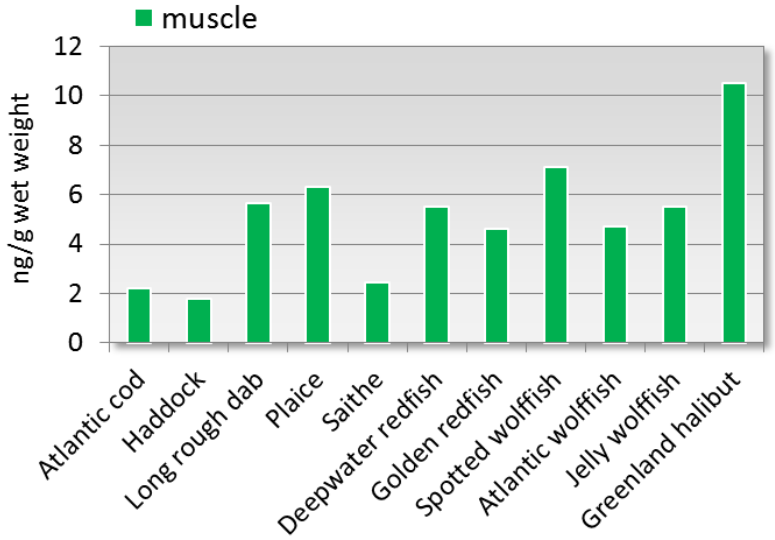


Figure 3.9.6.7a. Average concentration polychlorinated biphenyls (PCBs) in fish muscle

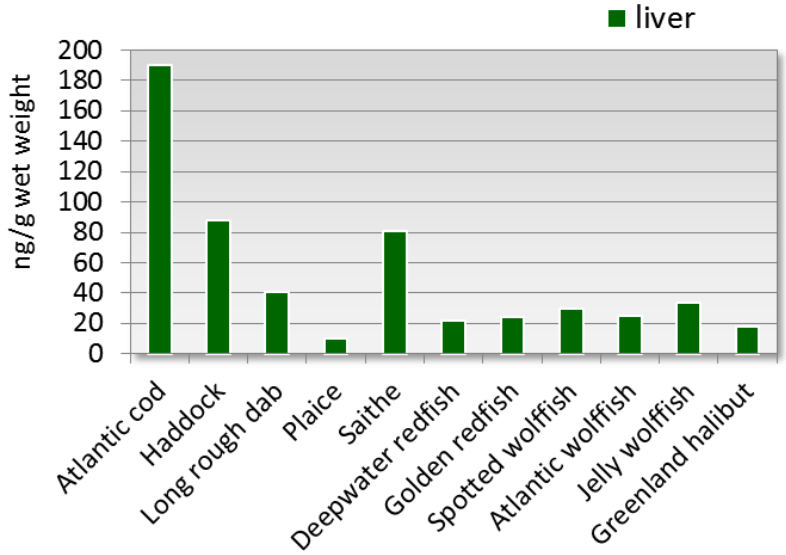


Figure 3.9.6.7b. Average concentration polychlorinated biphenyls (PCBs) in fish liver

Average concentration of arsenic in muscles of haddock, plaice and spotted wolfish exceeded standard of 5 μg/g wet weight. In several samples of cod and American plaice, exceeded levels of arsenic in muscles were also observed (Figures 3.9.6.8a and b). Increase in total arsenic content does not jeopardize human health as it forms stable complexes with low-molecular organic compounds and could be easily removed from the body.

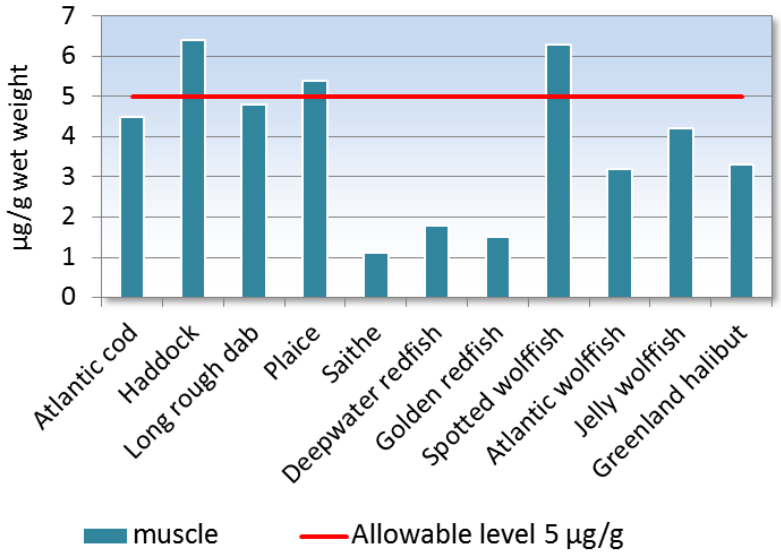


Figure 3.9.6.8a. Average arsenic concentration in fish muscle

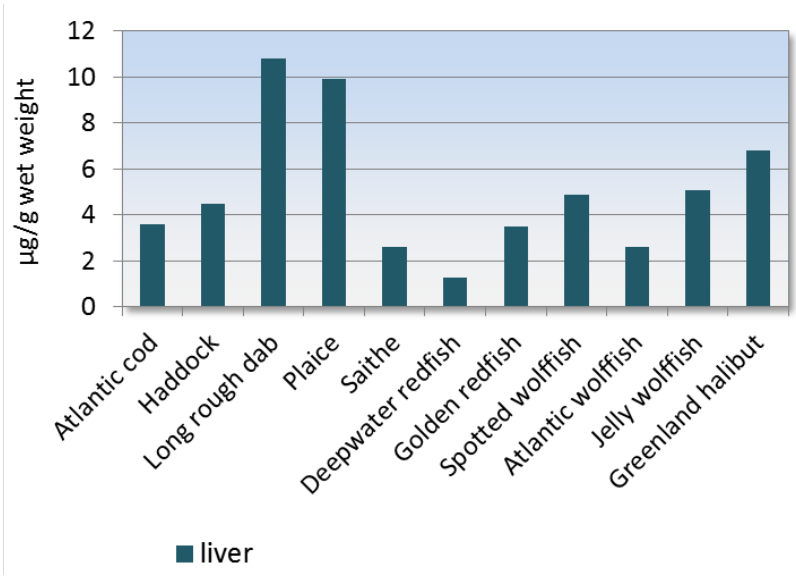


Figure 3.9.6.8b. Average arsenic concentration in fish liver

Surveys over 20 years in the Barents Sea by IMR

Our results from 20 years of environmental surveys vary quite a lot. Levels of some types of contaminants are low or undetectable, whereas others are clearly present. We see, for instance, low levels of brominated flame retardants, while there often are higher levels of PCB and the pesticide DDT than of other substances. The higher we get in the food chain, the greater the concentrations of contaminants. This is as we expected.

Concentrations also increase with age in fish (Boitsov *et al.*, 2016). Although some of the contaminants are present at higher concentrations than others, even the higher levels are usually below the maximum limits for nutritional safety (200 g/kg wet weight for the sum of six PCB congeners in liver).

Several species have been sampled consistently over time, whereas others have been sampled more sporadically. For the species under regular surveillance, we can present

time-series describing changes in the contaminants over time. Levels of some substances have decreased significantly in the past 15–20 years. An example is the pesticide HCH in liver from cod in the Barents Sea (Figure 3.9.6.9). Levels of some other substances seem relatively stable, for instance PCB in liver from the same cod (Figure 3.9.6.9). North East Arctic cod is one of the most valuable commercial species in the Barents Sea and a key component in the ecosystem.

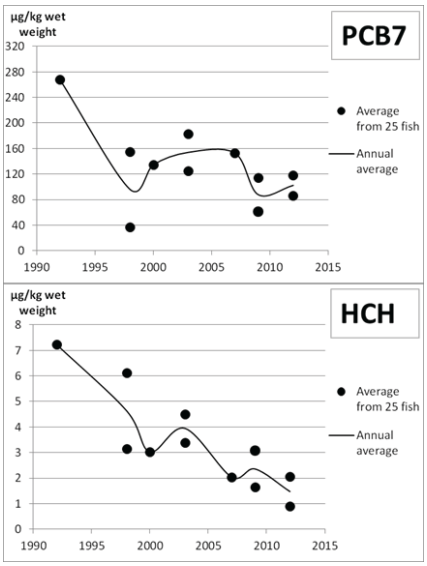
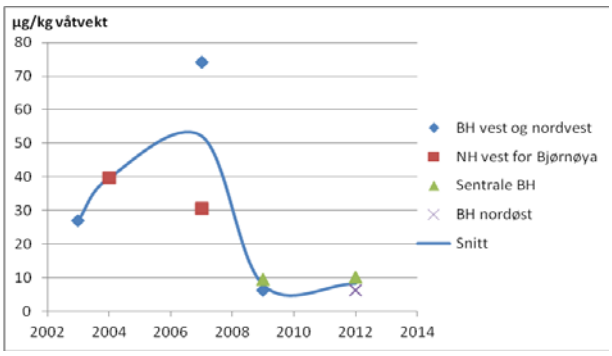
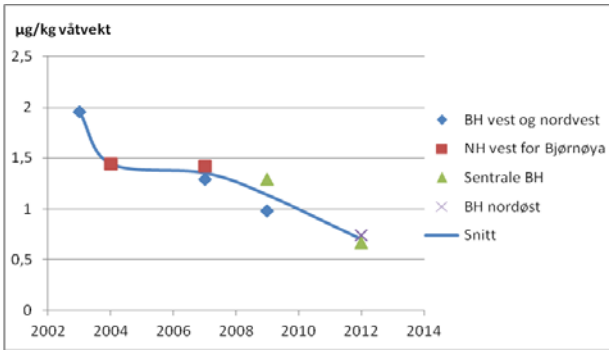


Figure 3.9.6.9. Contaminants in livers from Barents Sea cod. Data for each year represent averages from 25 fish. Levels of PCB7 (upper graph) decreased rapidly, then stabilized from the end of the 1990s, whereas the levels of the pesticide HCH (lower graph) showed relatively steady decrease throughout the study period. A similar development over time has been observed in liver of Greenland halibut (Figure 3.9.6.10).

Levels of environmental contaminants in Greenland halibut has recently received more attention, as high levels of PCBs, dioxins and mercury have been found in muscle, although differences have been observed with areas and size. Highest levels of PCB7 were found in the Norwegian Sea off the coast of Nordland (Northwest of Trænabanken and along the shelf edge), up to 100 micrograms/kg wet weight.



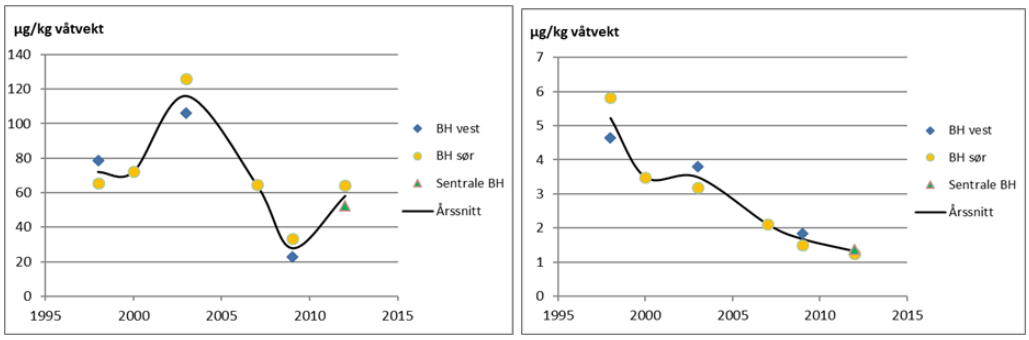
A



B

Figure 3.9.6.10. Average levels of PCB7 (A) and ΣHCH (B) in Greenland halibut liver from the Barents Sea.

Haddock is also a commercial important species in the Barents Sea, and levels in liver shows a similar trend in pollutant over time as observed in Arctic cod and Greenland halibut (Figure 3.9.6.11).



A B

Figure 3.9.6.11. Average levels of PCB7 and ΣHCH in haddock liver from the Barents Sea.

Our surveys show that it is still important to monitor organic contaminants in the marine food chain and in sediment. The contaminants are transported over great distances from their original sources, and background levels are clearly detectable even in the Arctic, where there are few local pollution sources. Despite having been prohibited for several decades in many countries, some of these contaminants persist in the environment.

For some groups of substances, levels in open waters are slowly but surely decreasing, while others are maintaining stable low levels. It is important to document this development, too, and thus continue the time-series established through two decades of surveys.

Radionuclides

The most important sources for radioactive contamination of the Barents Sea are well known and include global fallout from atmospheric nuclear weapons testing during the 1950s and 1960s, river transport by the Ob and Yenisey of radionuclides originating in Russian nuclear enterprises, discharges from European reprocessing plants for spent nuclear fuel (Sellafield and La Hague) and fallout from the Chernobyl accident in 1986. Additionally, liquid and solid radioactive wastes dumped in the Barents and Kara Seas and wrecks of sunken nuclear submarines represent potential sources.

The samples that were collected in the Barents Sea in 2015 was prepared and analysed during 2016. In this report, we present results from analyses of Cs-137 in sediments, seawater and fish. The analyses of Cs-137 in seawater collected in 2015 were performed by the NRPA. Analyses of Sr-90, Pu-238, Pu-239,240 and Am-241 in seawater have also been performed by the NRPA, but will not be presented here.

Activity concentrations of Cs-137 in sediments were found to range from 1.7 to 7.7 Bq/kg (Figure 3.9.6. 12). The highest level was found in the inner Laksefjord in Finnmark, and the lowest level was found in the Central Barents Sea. The levels are low and comparable to previously reported values from the 1990s and 2000s. The contamination sources are a combination of atmospheric nuclear weapons testing, European reprocessing plants and the Chernobyl accident. The highest levels of Cs-137 in sediments in Norwegian Sea areas are found in fjords in mid-Norway. For example, the levels in the inner part of the Vefsnfjord in Nordland have varied between 200 and 350 Bq/kg for the past ten years. The contamination source is the Chernobyl accident.

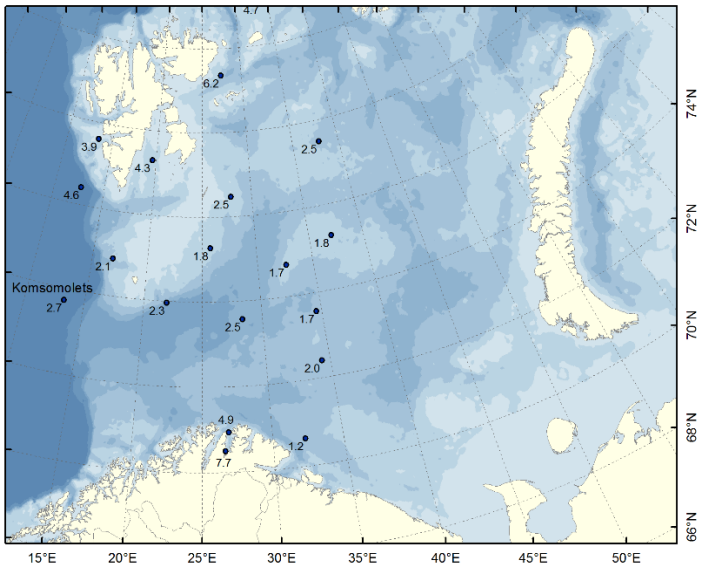


Figure 3.9.6.12. Activity concentrations of Cs-137 in sediments in 2015. The average activity concentration of Cs-137 in four samples collected near "Komsomolets" (2.7 Bq/kg) is also shown.

The activity concentrations of Cs-137 in seawater collected in 2015 at the seven stations shown in Figure 3.9.6.12 range from 1.3 to 1.9 Bq/m3. These levels are low, and the results indicate that Cs-137 is relatively homogenously distributed throughout the Barents Sea. In general, levels of Cs-137 in seawater in the Barents Sea are slightly lower than the levels found in other Norwegian Sea areas. For comparison, the levels of Cs-137 in seawater in seven samples collected in the Skagerrak in 2015 ranged from 4.0 to 5.2 Bq/m3. The higher levels in the Skagerrak are due to the closer proximity to important contamination sources, namely outflowing Baltic water, containing Chernobyl contamination, and the European reprocessing plants for spent nuclear fuel, Sellafield and La Hague.

Activity concentrations of Cs-137 in common species of fish collected in the Barents Sea in 2015 are below 0.2 Bq/kg fresh weigh (Figure 3.9.6.13), and much lower than the intervention level set by the Norwegian Authorities after the Chernobyl accident (600 Bq/kg fw). To place the results into context, time-series of Cs-137 in cod along the coast of Troms and Finnmark, and in the Bear Island area from approximately 1990 until present are shown in Figures 3.9.6.14a and 3.9.6.14b, respectively. It is evident that the levels have decreased during this period, and the levels in cod in the Barents Sea have

been below 0.2 Bq/kg ww (wet weight) for the past ten years. The decrease is due to reduced discharges from Sellafield and La Hague and decay of pollution from nuclear testing during the 1950s and 1960s and the Chernobyl accident 1986. In addition, the pollution is diluted in seawater over time.

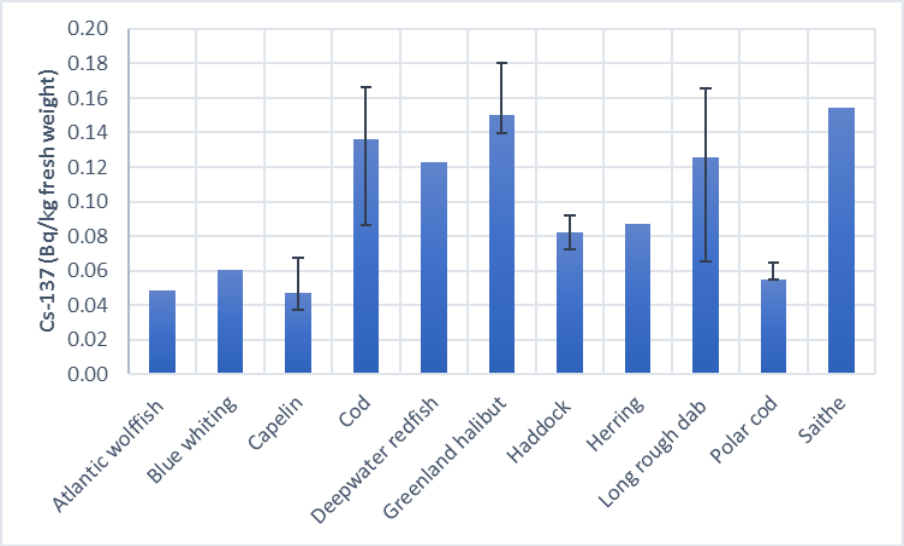


Figure 3.9.6.13. Activity concentrations (Bq/kg fresh weight) of Cs-137 in common species of fish caught in the Barents Sea in 2015. The sampling stations are shown in Figure 2. Between 1 and 5 samples of each species have been analysed. For species where more than one sample has been analysed, the average is shown, and the minimum and maximum activity concentrations are shown with error bars. The uncertainty in single measurements vary between 20 and 50%.

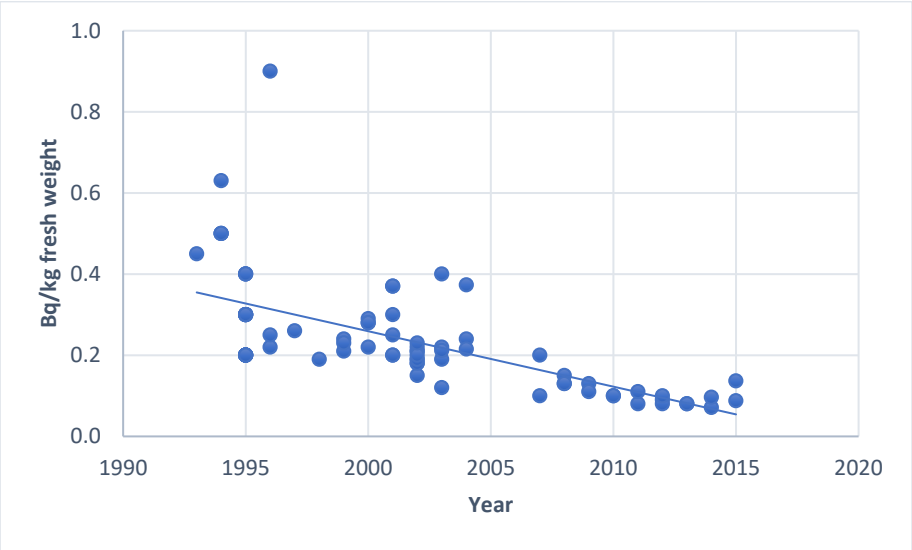


Figure 3.9.6.14a. Activity concentrations of Cs-137 (Bq/kg fresh weight) in cod caught in the Bear Island area in the period 1993 to 2015. Data from NRPA and IMR. Uncertainties in single measurements are generally below 30%.

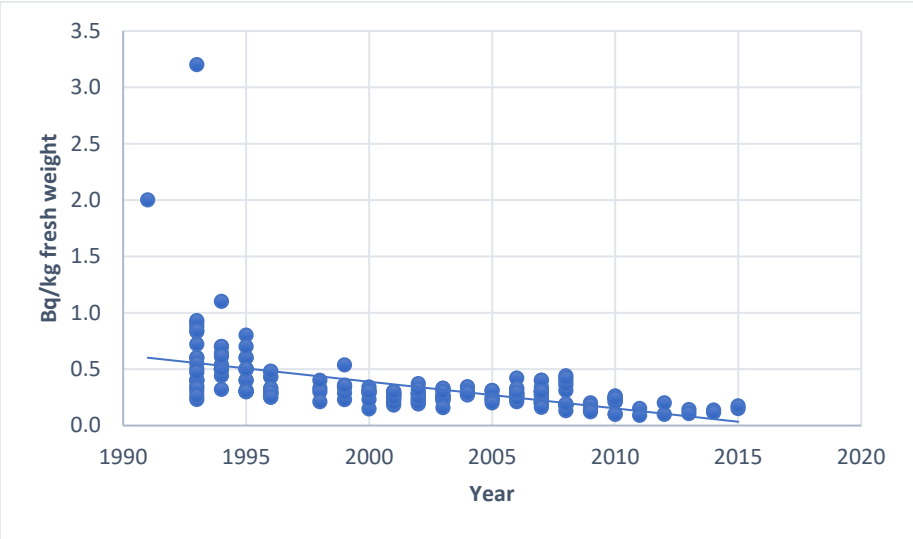


Figure 3.9.6.14b. Activity concentrations of Cs-137 (Bq/kg fresh weight) in cod caught along the coast of Troms and Finnmark in the period 1991 to 2015. Data from NRPA and IMR. Uncertainties in single measurements are generally below 30%.

The Norwegian monitoring of the area adjacent to the sunken nuclear submarine "Komsomolets" do not reveal any significant leakage (Figure 3.9.6.15). Due to the depth at which the submarine lies and effect of subsurface currents, it has, however, not been possible to know how close to the wreck the samples have been collected. In 2013 and 2015, sampling was carried out using an acoustic transponder that allowed samples to be collected at a distance of approximately 20 m from the hull of the submarine. We did not find elevated levels of Cs-137 in these samples.

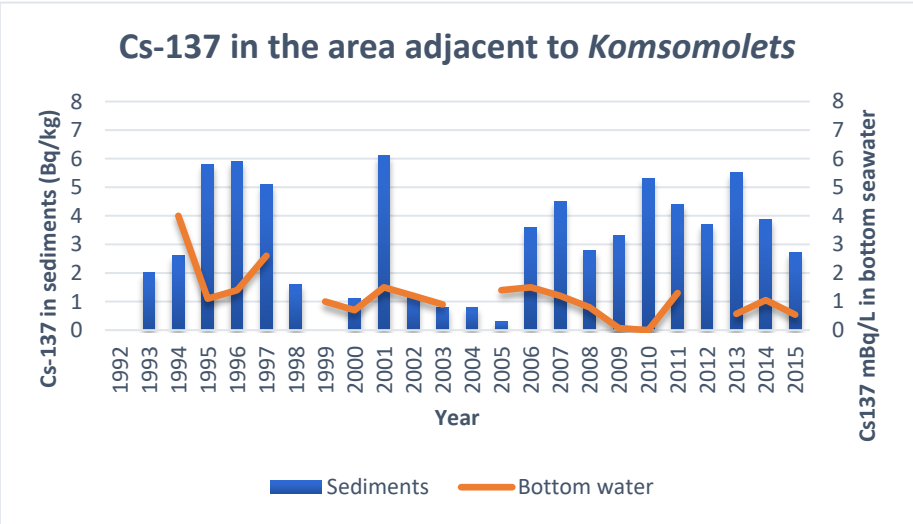


Figure 3.9.6.15. Activity concentrations of Cs-137 in sediments and bottom seawater collected in the area adjacent to the sunken nuclear submarine «Komsomolets» in the period 1993 to 2015.

Summary

Russia and Norway conduct monitoring in the Barents Sea according to national monitoring programs. Russia conduct monitoring every year, and Norway conduct monitoring every third year (last time in 2015).

Concentrations of polycyclic aromatic hydrocarbons (⊚PAH) in water of the investigated Barents Sea areas exceeded global background level of 20 ng/l at several stations.

PAH and benz(a)pyrene content in bottom sediments did not exceed background levels – 300 ng/g and 10 ng/g dry weight respectively. The results show that muscles and liver of commercial fish in the Barents Sea are slightly polluted with carcinogenic PAHs.

Concentrations of organochlorine pesticides (OCP) and polychlorinated biphenyls (PCB) in water did not exceed the Threshold Limit Value (TLV) for fisheries waters that equals to 10 ng/l. Regarding dichlorodiphenyltrichloroethane (DDT) content, bottom sediments fall into the category "moderately polluted". Concentration of PCBs in sediments of the Barents Sea corresponded to technogenic background level of 5 ng/g dry weight. Total concentrations of OCPs and PCBs in muscles and liver of examined fish were much lower than levels set out in sanitary rules and norms for sea fish in Russia.

Concentrations of metals in water were generally lower than the Threshold Limit Value (TLV) for fisheries waters. Concentrations of copper, zinc, lead, cadmium and mercury in bottom sediments of the Barents Sea conformed to background levels. Regarding nickel, chromium and arsenic content, several areas corresponded to the category "moderately polluted". In muscles and liver of examined commercial fish from the Barents Sea, average concentrations of cadmium, lead and mercury did not exceed levels stated in sanitary rules and norms. Mean content of arsenic in muscles of several species (haddock, plaice, spotted wolfish) exceeded the level of 5 μg/g wet weight.

Activity concentrations of Cs-137 in sediments collected in the Barents Sea in 2015 ranged from 1.7 to 7.7 Bq/kg. The highest level was found in the inner Laksefjord in Finnmark, and the lowest level was found in the Central Barents Sea. The levels are low and comparable to previously reported values from the 1990s and 2000s.

Further, the activity concentrations of Cs-137 in seawater range from 1.3 to 1.9 Bq/m3. These levels are low, and the results indicate that Cs-137 is relatively homogenously distributed throughout the Barents Sea. In general, levels of Cs-137 in seawater in the Barents Sea are slightly lower than the levels found in other Norwegian Sea areas. For comparison, the levels of Cs-137 in seawater in seven samples collected in the Skagerrak in 2015 ranged from 4.0 to 5.2 Bq/m3.

Activity concentrations of Cs-137 in common species of fish collected in the Barents Sea in 2015 are below 0.2 Bq/kg fresh weigh (Figure 10), and much lower than the intervention level set by the Norwegian Authorities after the Chernobyl accident (600 Bq/kg fw).

Final Conclusions

The pollution levels have been generally low in the Barents Sea ecosystem for a long time. In the short run, no significant adverse impact of current pollution of organisms or environment would affect stocks of commercial aquatic organisms in investigated areas of the Barents Sea.

Suggestions for future indices

In order to evaluate the dynamics of pollution in the Barents Sea in future, the following indices may prove to be useful:

Bottom sediments: PAH16, Benzo(a)pyren, Cs-137

Cod and Greenland halibut (liver): PCB7 and ΣDDT

Cod and Greenland halibut (muscle): Pb, As, Hg, Cd, Cs-137

Seawater: Cs-137

We have data on all these contaminants for the past 10 years.

4 Interactions, drivers and pressures

4.1 Feeding and growth of capelin and polar cod

Capelin

Ten years (2006-2015) of capelin diet was examined from the Barents Sea where capelin is a key forage species, especially of cod (*Gadus morhua*). The PINRO/IMR mesozooplankton distribution shows low plankton biomass in the central Barents Sea, most likely due to predation pressure from capelin. In the Barents Sea, a pronounced shift in the diet from smaller (<14 cm) to larger capelin (≥14 cm) is observed. Capelin shift their diet from predominantly copepods to euphausiids, (mostly *Thysanoessa inermis* - not shown)), with euphausiids being the largest contributor to the diet weight in most years (Figure 4.1.1). Hyperiid amphipods contributed a small amount to the diet of capelin. The migration of capelin into northerly areas (>80°N) was observed until 2013 due to larger ice free area, which may give capelin more access to the arctic zooplankton. However, since 2014 the northern limit of the capelin distribution is moved southwards, this is probably related to the decrease in the capelin stock.

Figure 4.2.2 shows that the growth of capelin has decreased from 2009 onwards in a similar way as in previous periods of relatively high capelin abundance (1990–1992, 1998–2002). There was a corresponding decrease in stomach fullness of capelin from 2009 onwards. These trends were reversed after the capelin stock started to decrease in 2014, and weight at age and stomach fullness is now both at relatively high levels.

Slow growth is generally associated with slow maturation (since capelin matures according to size rather than age), which is indicated by relatively large proportion of age 3 fish and also some age 4 fish (Figure 3.5.6). The slow growth during the period from 2009–2014 may have been associated also with some individuals maturing at smaller size. During the Norwegian capelin fishery during winter-early spring the proportion of capelin of body length below 14 cm increased from <5% in 2011–2014 to 15 % in 2015.

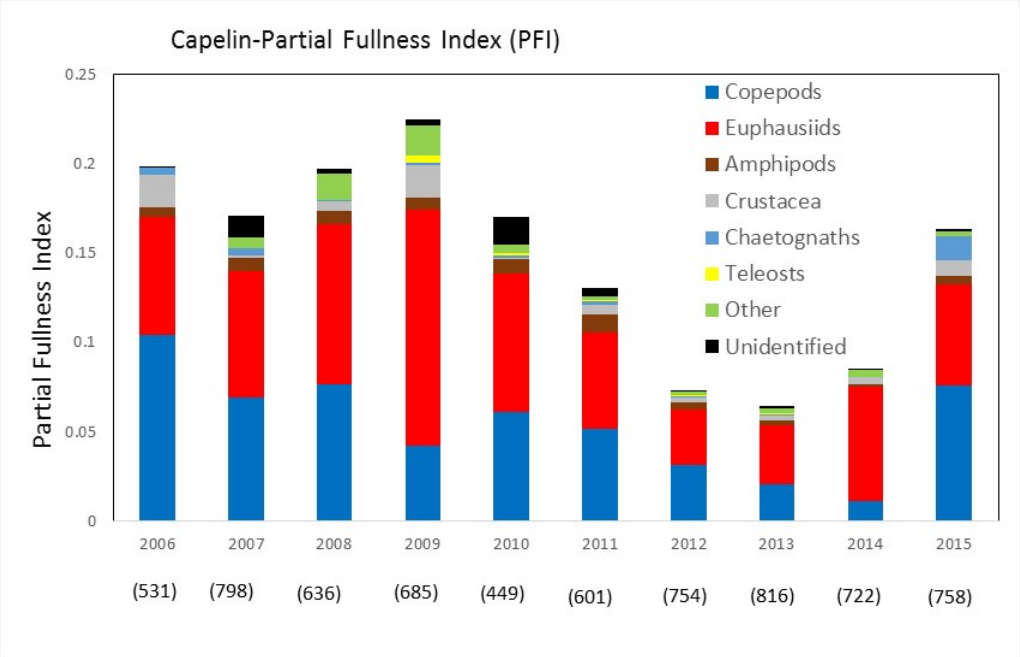


Figure 4.1.1. Stomach fullness of capelin during survey in August-September 2006–2015. Number of fish sampled each year in brackets

The decrease in individual growth rate and condition of capelin observed until 2014 for the large capelin stock in that period may have been caused by reduced food availability due to strong grazing on the largest plankton organisms. This is suggested by reduction of the largest size fraction (>2 mm) in the Norwegian part of the autumn survey (see section 3.3). The plankton species composition in the northeastern area has changed; abundance and biomass of large copepod species (*Calanus finmarchicus*, *C. glacialis*), which are important prey items for capelin, decreased in the last years with increasing abundance of small copepods (*Pseudocalanus minutus*) which are practically not eaten by capelin. The change in the composition of the plankton community is most likely caused by warming in the Barents Sea and high grazing pressure from capelin and other species.

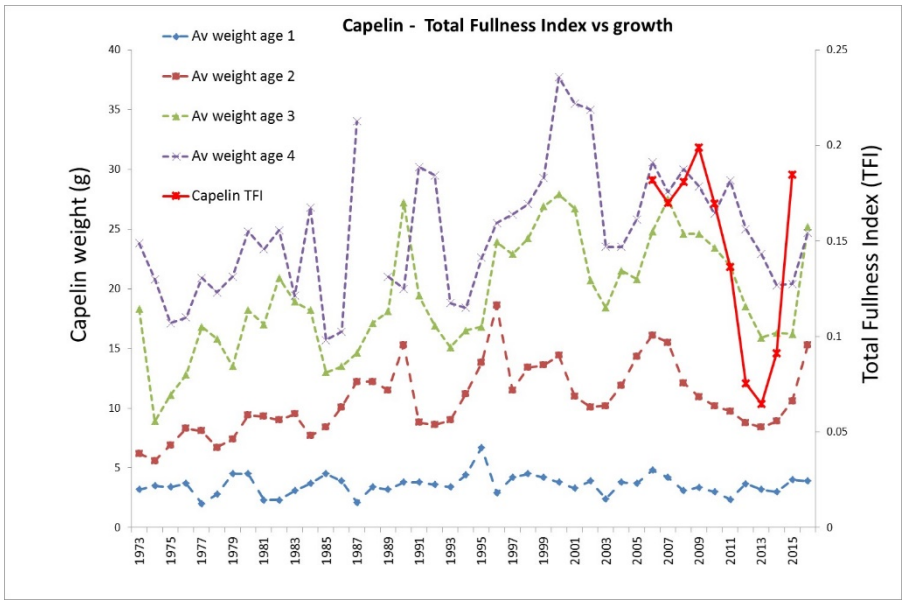


Figure 4.1.2 Growth (weight at age from ecosystem survey) and stomach fullness (TFI) of capelin in 1973–2016

Capelin growth depends on the state of the plankton community (Skjoldal *et al.*, 1992; Dalpadado *et al.*, 2002; Orlova *et al.*, 2010). Capelin is able to produce a strong feedback on zooplankton stock levels through predation (Figure 4.1.3, Dalpadado *et al.*, 2003; Stige *et al.*, 2014), which has been found previously to be particularly pronounced for krill in the central Barents Sea (Dalpadado and Skjoldal, 1996).

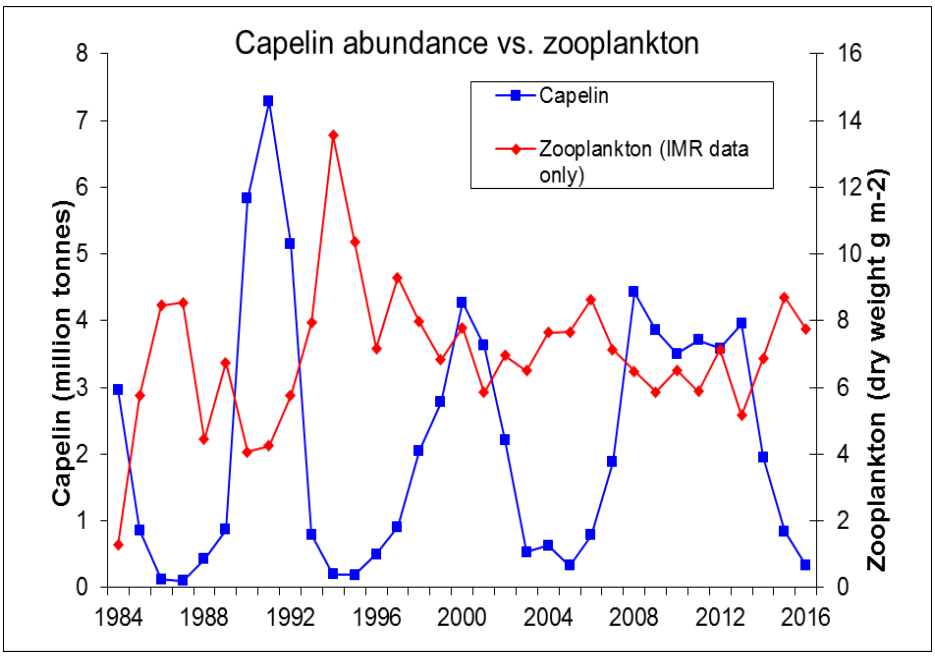


Figure 4.1.3. Fluctuation of capelin stock and zooplankton biomass in the Barents Sea in 1984–2016.

There is some evidence of a density-dependent effect on capelin growth. This is reflected in decreasing individual fish length of 2- and 3-years old capelin with increasing capelin numbers (Figure 4.1.4).

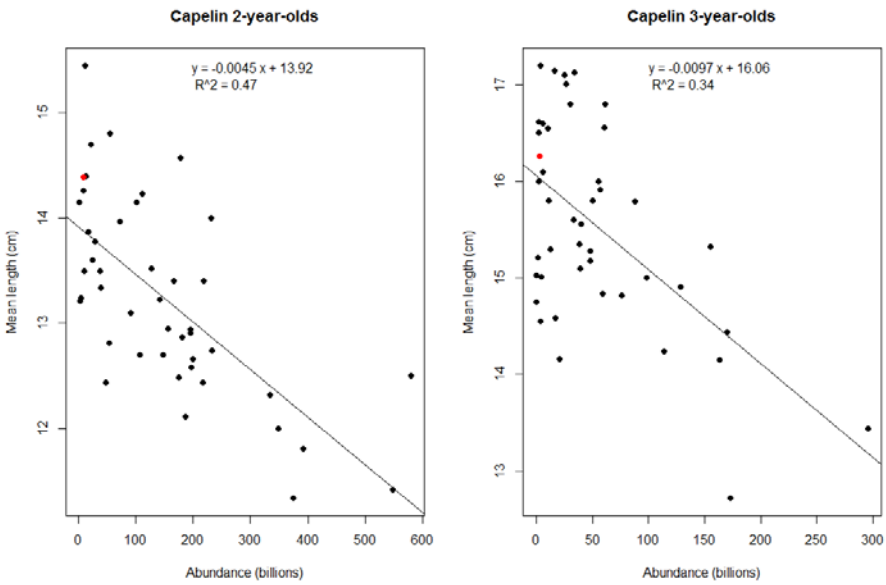


Figure 4.1.4. Average length as function of abundance for capelin at age 2 and 3. The datapoint from 2016 is marked in red.

Capelin length significantly decreases with increasing numbers, which indicates density-dependent growth (Figure 4.1.4). The effect is most pronounced in 2 year old capelin, and not seen in 1-year-olds. Density-dependent growth in capelin has been investigated previously, but should be investigated in more depth in light of more recent data.

Polar cod

The diet data from 2007 to 2015 indicate that polar cod mainly feed on copepods, amphipods (mainly hyperiids *Themisto libellula*, occasionally gammarids) and euphausiids, and to a lesser degree on other invertebrates (Figure 4.1.5). The consumption of amphipods has decreased somewhat since 2010. Large polar cod also prey on fish. The total stomach fullness index decreased after 2011 but now seems to have stabilized at a lower level than in 2007–2011, while growth of polar cod has been relatively stable (Figure 4.1.6).

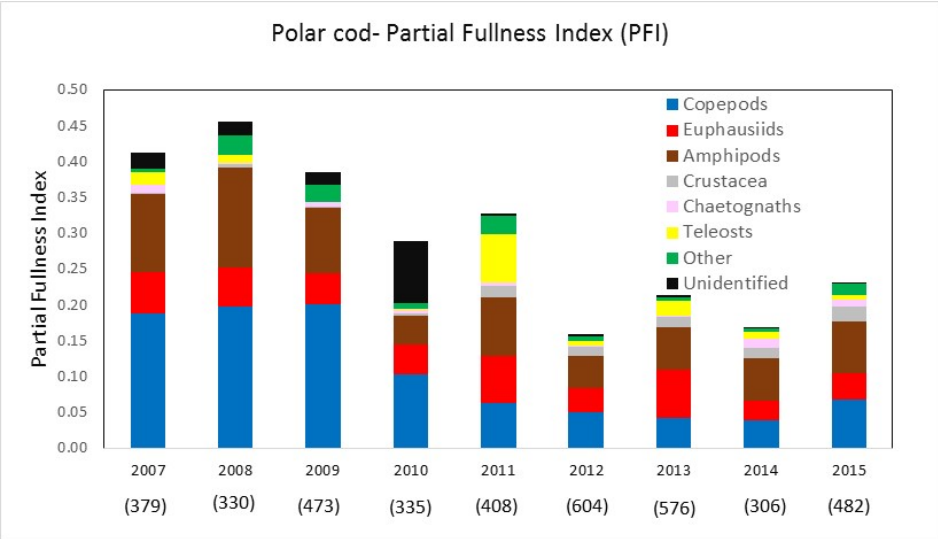


Figure 4.1.5. Stomach fullness of polar cod during survey in August-September 2007–2015. Number of fish sampled each year in brackets.

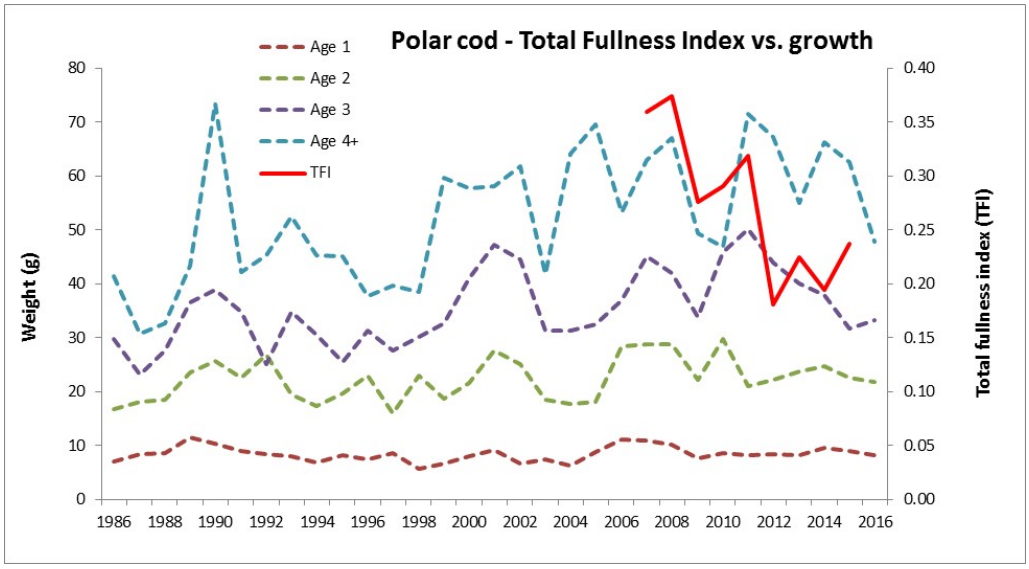


Figure 4.1.6. Growth (weight at age from ecosystem survey) and stomach fullness (TFI) of polar cod in 1986-2016

4.2 Feeding, growth, and maturation of cod

Feeding

Figures 4.2.1 and 4.2.2 shows the consumption and diet composition of cod.

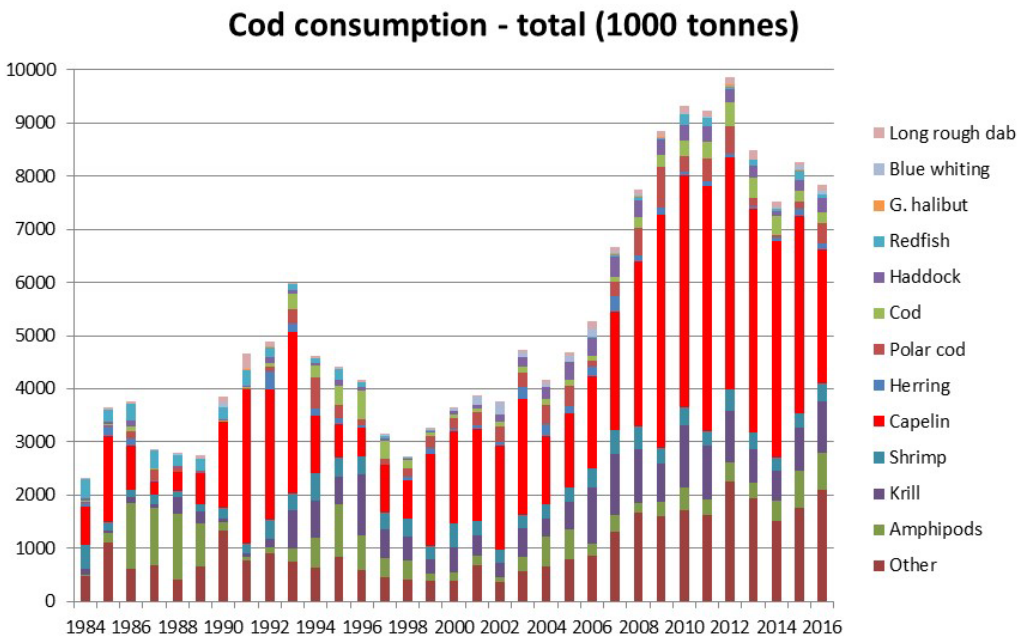


Figure 4.2.1 Cod consumption 1984–2016. Consumption by mature cod outside the Barents Sea (3 months during first half of year) not included. Norwegian calculations, preliminary Figures, final numbers to be found in AFWG 2017.

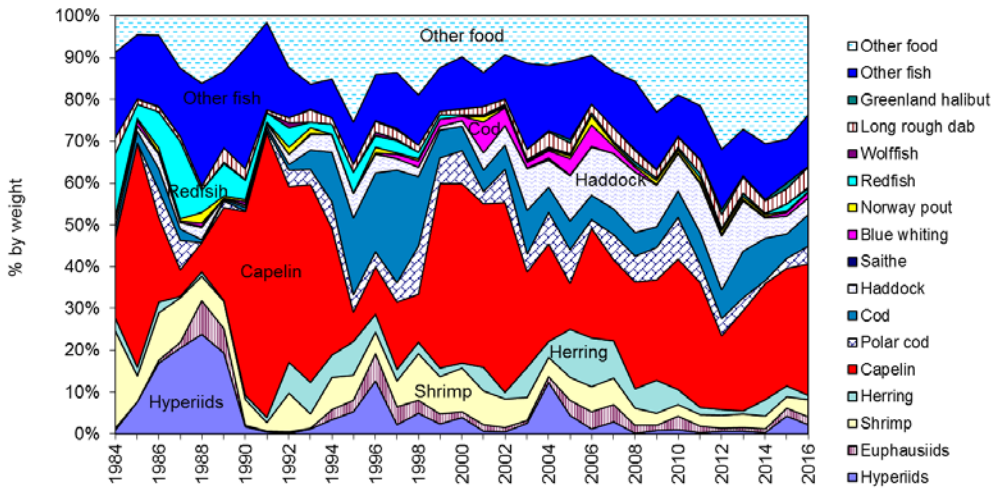


Figure 4.2.2. Cod diet in the Barents Sea in 1984–2016, by weight

Cod is the main predator on capelin, although other fish species as well as seabirds and marine mammals are also important predators. In the last 6-7 years there has been an extremely high cod stock level in the Barents Sea. Estimated biomass of preyed capelin by cod in recent years has been equivalent to the biomass of the entire capelin stock (Figure 4.2.3). Under good conditions the capelin stock tolerated a high grazing pressure; the biomass produced during the year was equivalent to the standing stock biomass measured in autumn. The abundance of predators other than cod is also at high and, to our knowledge, stable levels.

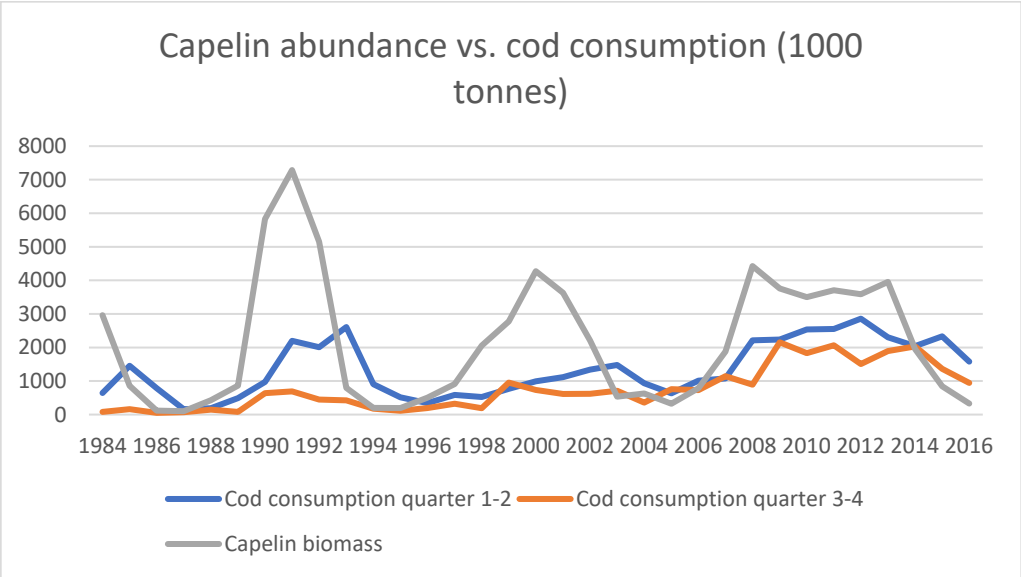


Figure 4.2.3 Size of the capelin stock and estimated consumption of capelin by cod.

The estimated consumption of capelin by cod for the first and second parts of the year has shown different temporal patterns. The consumption during the first and second quarters has been high also in previous capelin periods and includes consumption during the spawning period and also the spring and early summer situation before the seasonal feeding migration of capelin. A major difference, however, is the pronounced increase to a much higher level of consumption in the third and fourth quarters during the last capelin period (Figure 4.2.3). This reflects the northward movement of cod and a larger spatial overlap between cod and capelin under the recent warm conditions compared to the situation earlier, e.g. during the capelin period in the 1990s.

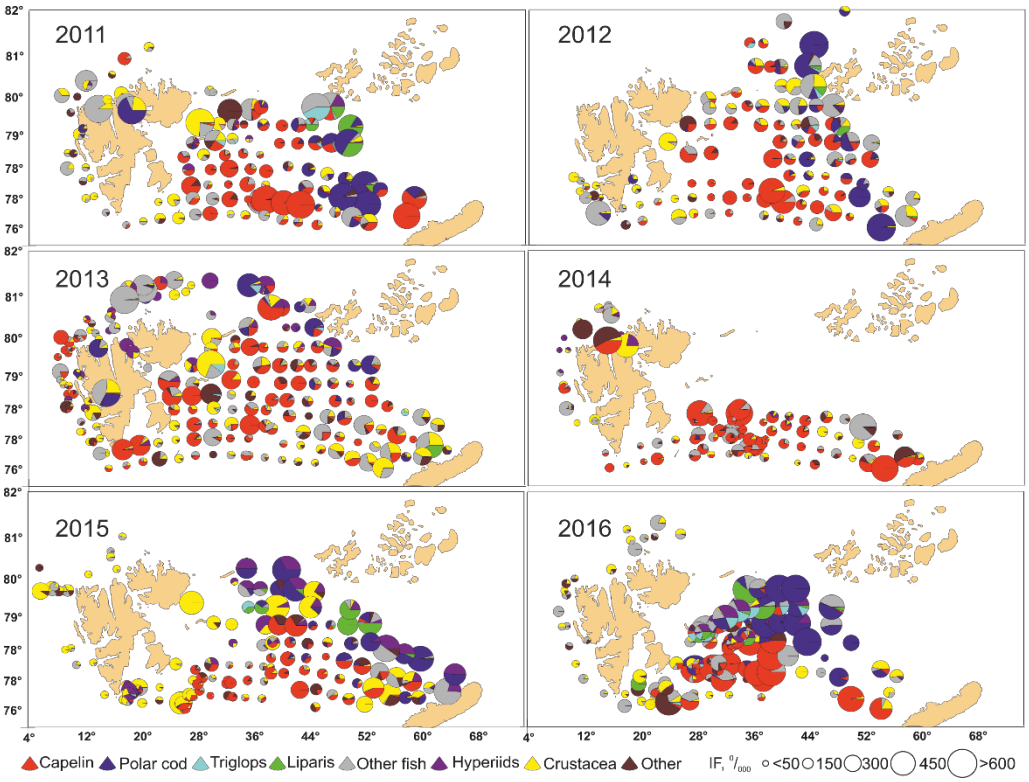


Figure 4.2.4. Cod consumption during the ecosystem survey in August-September 2010–2015. Red dots indicate capelin, and blue dots polar cod.

During the first capelin collapse (1985–1989) the importance of capelin in cod diet decreased from 53% in 1985 down to maximum 20–22 % for the remainder of the collapse period. During that period, an increase of other prey was observed, in particular hyperiids which constituted 7–23% of the diet and redfish with 3–18%.

During the second collapse (1993–1997) weight proportion of capelin in the cod diet was high in the first 2 years (47 and 30%), and then decreased to 6–16%. In this period cannibalism in cod increased sharply from 4–11% to 18–26% of the diet. In addition, more intensive consumption of hyperiids was observed again (1–12%), but the proportion of hyperiids was still much lower than during the first collapse.

During the third collapse period (2003–2006), consumption of capelin by cod was rather high (10–26%). During this collapse, several alternative prey groups for cod were present in the diet in similar quantities: juvenile haddock (6–11%) and cod (5–10%), herring (3–11%), blue whiting (1–5%) as well as hyperiids (1–12%). Consumption of capelin by cod during the most recent years has remained more or less stable (17–31%), but has been much lower compared to earlier periods of high capelin abundance (average 36–51%). In recent years, a relatively diverse diet has been recorded with stable high consumption of juvenile cod and haddock (6–11 and 5–11% respectively) as well as other fish (11–15%) and other food (21–33%) (mainly ctenophores and crabs). It should be noted that there has been an increasing amount of snow crab in cod diet – from 0.1–0.3% in 2009–2010 to 1.2–1.5% in 2011–2012 to 6.1 % in 2014.

Investigations of cod diet in the area northwards 76°N showed that three groups of local areas can be separated (Dolgov and Benzik, 2014). Feeding intensity of cod was low (149–169 ‰) in areas near western and southern Spitsbergen, where cod feed on non-commercial fish. Other group of local areas is characterized by high feeding intensity (MFI 214-251-169 ‰) with dominance of capelin and also non-target fish (snailfish

and sculpins), polar cod and hyperiids. These two groups of areas are more or less traditional for cod distribution in summer period. The third group (Franz Josef Land, northern Novaya Zemlya and adjacent areas) became available for cod only since 2008. Cod extremely actively (MFI 284–340 ‰) feed here on polar cod and capelin. Thus such northward extension of cod and their intrusion in northeastern Barents Sea results to better feeding conditions for cod under their high stock biomass and decreasing of main prey (capelin and polar cod).

In addition, some new prey items appeared in cod diet. Invasive snow crab *Chionoecetes opilio* became a rather important prey items for cod, especially in eastern Barents Sea alongside Novaya Zemlya (Dolgov and Benzik, 2016). Weight percent in cod diet sharply increased from 0.1–0.3%m in 2009–2010 to 5.6–6.1%m in 2014–2015 and start to decrease in 2016 (5.2%m) (Figure 4.2.5). In contrast, two other new crab species has no high importance in cod diet until now, their weight percent did not exceed 1.0%m for red king crab and 0.2%m for *Geryon spp*. probably it related more to overlapping between cod and snow crab and more appropriate body shape and size.

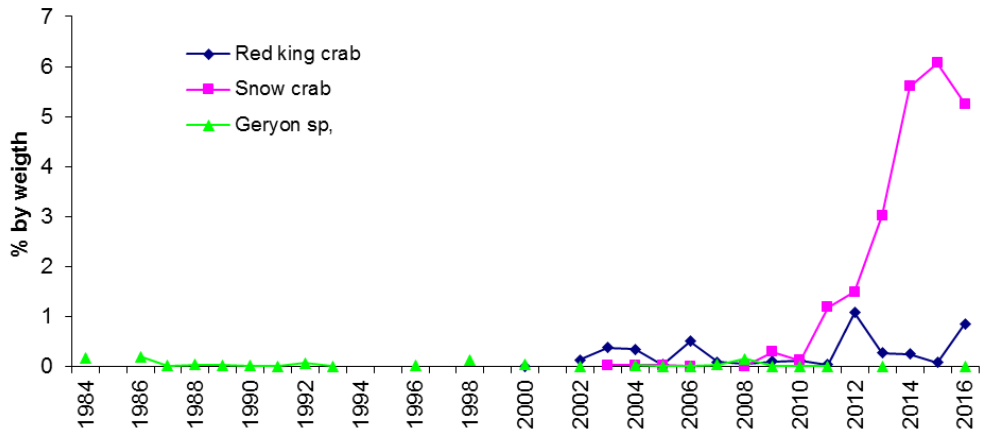


Figure 4.2.5. Importance of three species of invasive crabs in cod diet in 1984–2016

Growth and maturation

Consumption and growth for younger cod has been fairly stable in recent years (Figure 4.2.6), with a slight decrease for older cod (Figure 4.2.7). However, the proportion mature-at-age 6–9 decreased considerably from 2014 to 2016 (Figure 4.2.8), and the decrease in maturation is much stronger than the change in weight at age should indicate (Figure 4.2.9).

The biomass of the main prey species relative to the cod stock size has decreased somewhat in recent years (Figure 4.2.10). However, the consequences of the fourth collapse of capelin stock in the Barents Sea (2015 and onwards) on cod conditions were so far minor compared to previous collapses. It can be related to northward expansion of cod to the northern Barents Sea with available food resources not used by cod earlier.

So, a combination of using new areas in the northern Barents Sea available for cod feeding as well as switch on new prey item allowed to cod compensate for decrease of traditional prey like capelin and polar cod under recent warming period.

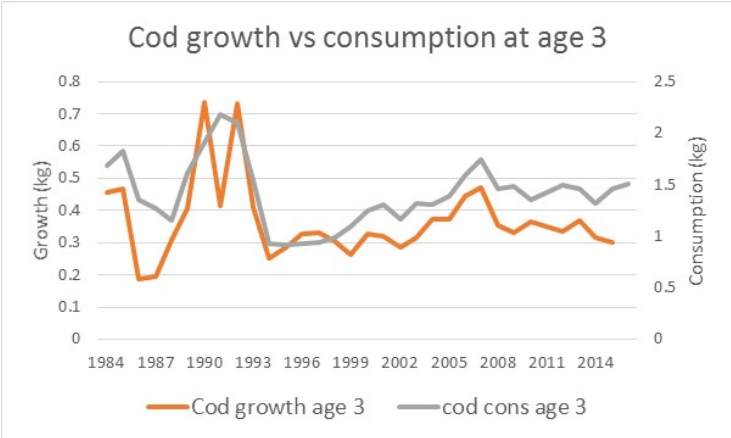


Figure 4.2.6 Cod growth and consumption at age 3 (ICES 2016c)

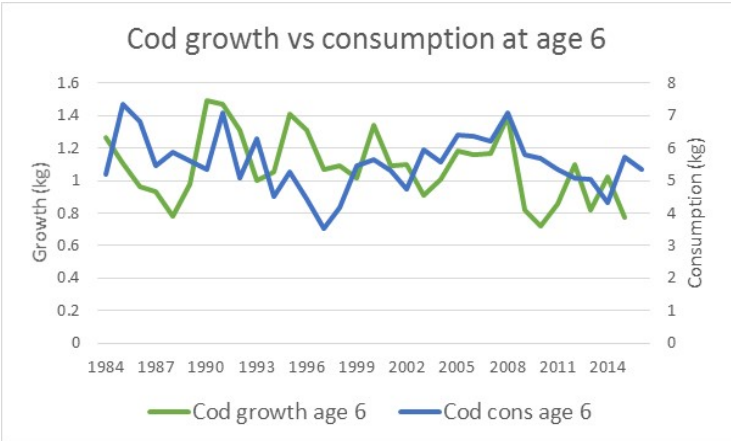


Figure 4.2.7. Cod growth and consumption at age 6 (ICES 2016c)

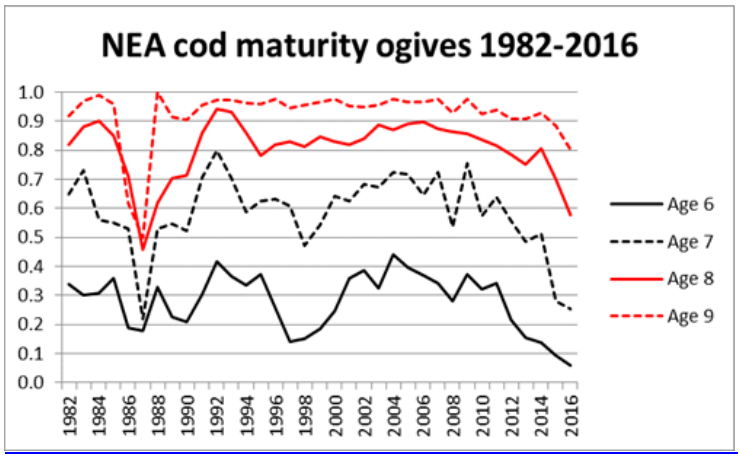


Figure .2.8. Maturity-at-age for cod ages 6-9 (ICES 2016c)

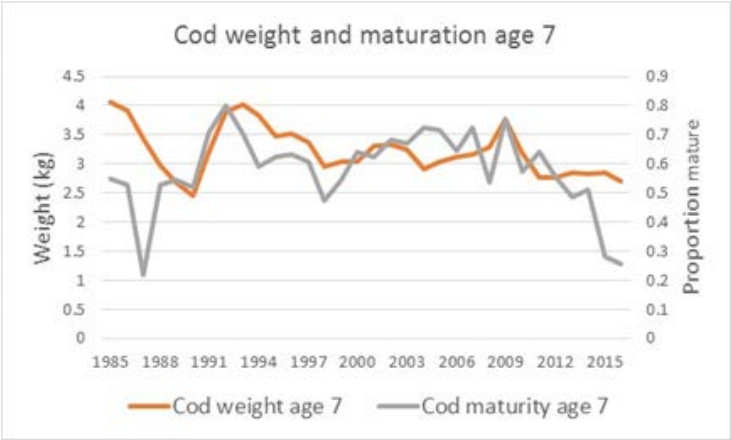


Figure 4.2.9. Cod maturity and weight at age 7 (ICES 2016c)

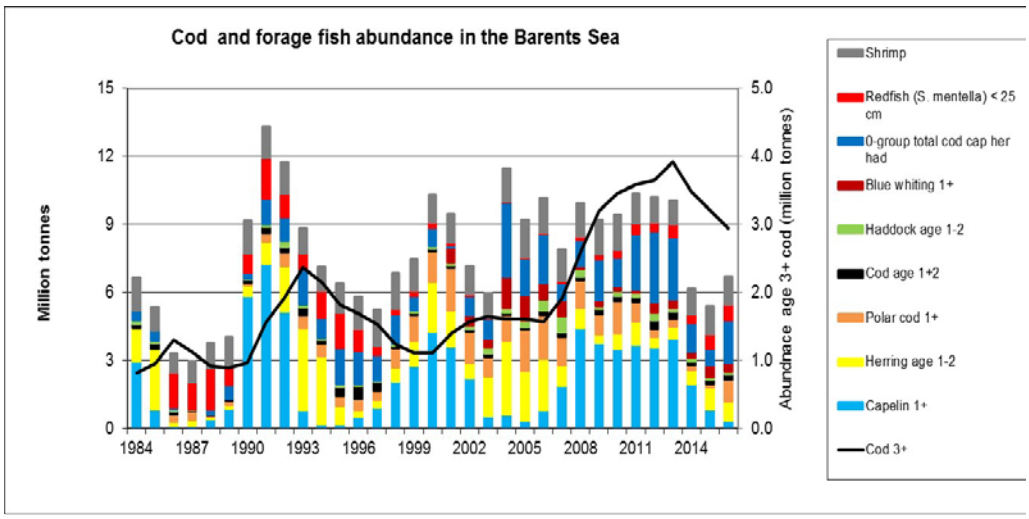


Figure 4.2.10. Abundance of major prey stocks and shrimp compared to cod abundance.

4.3 Causes of capelin decline

Previous stock collapses

The Barents Sea capelin stock has undergone drastic changes in size during the last three decades. Three stock collapses (when the abundance was low and fishing has been stopped) occurred in 1985–1989, 1993–1997, and 2003–2006. A strong reduction in stock size was also observed in 2014-2016, and in 2015 and 2016 the stock biomass has been below 1 million tonnes which earlier has been defined as a threshold for collapse. The previous collapses have caused evident effects both downwards and upwards in the foodweb. The reduced predation pressure from capelin has led to increased amounts of zooplankton during the collapse periods. When capelin biomass was drastically reduced, its predators were affected in various ways. Cannibalism became more frequent in the cod stock and cod growth was reduced and maturation delayed. Seabirds experienced increased rates of mortality and total recruitment failures, and breeding colonies were abandoned for several years. Harp seals experienced food shortage, increased mortality partly because they invaded the coastal areas and were caught in fishing gears, and recruitment failures. The effects were most serious during the 1985–1989 collapse, whereas they could hardly be traced during the third collapse. Gjøsæter *et al*. (2009) concluded that these differences in effect likely resulted from increased availability of alternative food sources during the two last periods of collapse (1990s and 2000s).

The collapses were caused by poor recruitment, most likely in combination with low growth and increased predation pressure. High level of fishing pressure in 1985–1986 also probably amplified and prolonged the first collapse. After each strong stock decline the fishery has been stopped and the stock has recovered in few years due to good recruitment. Predation by young herring has been suggested by several authors to have strong negative influence on capelin recruitment and thus to be a significant factor in capelin collapses (Gjøsæter *et al.*, 2015).

Recruitment

Capelin is a short-lived species and thus the stock size variation is strongly influenced by the annual recruitment variability. This may indicate that the main reason of capelin stock collapses is a poor recruitment (Figure 4.3.1).

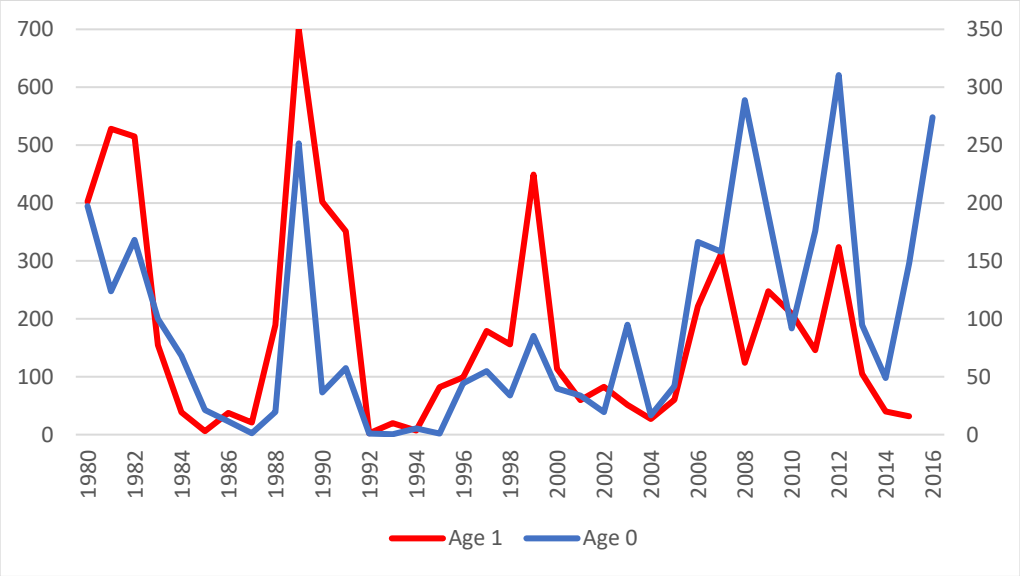


Figure 4.3.1. Fluctuation of capelin at age 0 (blue line) and 1 (red line) for the cohorts 1980–2016.

Recruitment of capelin measured as 0-group during the ecosystem survey has been at an average or high level from 2006 onwards. 0-group abundance gives a first indication of spawning success, while abundance of age 1 indicates recruitment to the adult stock. Recruitment as 1-year olds was also stable and around average for the cohorts 2006–2013, while the 2014 and 2015 cohorts were poor at the 1-group stage. Survival from age 0 to 1 declined considerably during 2014–2016.

Most of the 0-group capelin originates from the spawning in spring. The 0-group from summer spawners is distributed mostly in the southern Barents Sea. Abundance of this portion (3 cm body length or less in August-September) has been relatively low compared with the total abundance of 0-group, and was estimated to make up 15% in 2013, 10% in 2014, 2% in 2015 and 1% in 2016. These small 0-group capelin likely are less able to survive the first overwintering since they have less time to grow during the first-feeding season.

The capelin stock age composition has varied considerably between years but has generally been dominated by age groups 1 and 2 (Figure 3.5.6). The observed increase in older fish (age 3) and relatively high abundance of capelin of age 2 during the period 2008–2013 have contributed in keeping the stock at a relatively high level and provide a good recruitment. A severe decrease in abundance of the age groups 1, 2, and 3 in 2014 and 2015 preceded the present capelin stock collapse.

The mean lengths of 0-group capelin have varied somewhat during the time-series. From biological reasoning, one may hypothesize that the survival rates from age 0 to age 1 might be correlated with the lengths-at-age 0. However, a plot of mean length-at-age 0 and total mortality from age 0 to age 1 reveals no such correlation. From the plot it is evident that 0-group and/or 1-group abundance estimates, and therefore also mortality estimates from age 0 to age 1, are noisy, and this might mask possible relationships that might exist.

Figure 4.3.2 shows stock–recruitment plot from Gjøsæter *et al.* (2015), going back to 1987. This plot shows that 1989 is still the strongest year class at age 1. An estimation of breakpoint from this plot could be attempted. Figure 4.3.3 shows an alternative approach where recruitment-at-age 0 is used and SSB is calculated as mature stock (>14 cm) in autumn (with fishery in take January-March subtracted). These plots are not updated from last year's report.

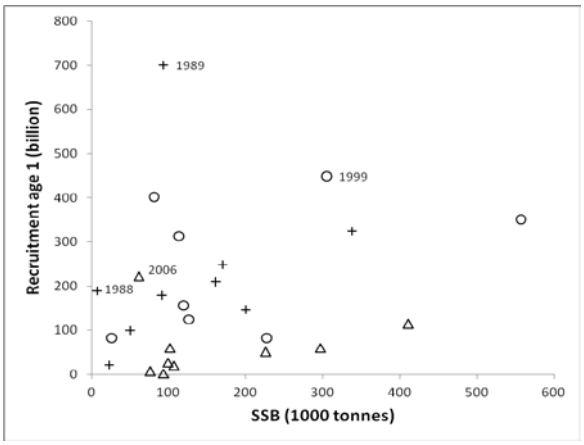


Figure 4.3.2. SSB/R plot for capelin. Cohorts 1987–2012. Points coded according to herring biomass age 1 + 2 in spawning year. Circles—herring biomass <450 000 tonnes, crosses—herring biomass between 450 000 tonnes and 1.3 million tonnes, triangles-herring biomass >1.3 million tonnes. (Figure 7. in Gjøsæter *et al.*, 2015).

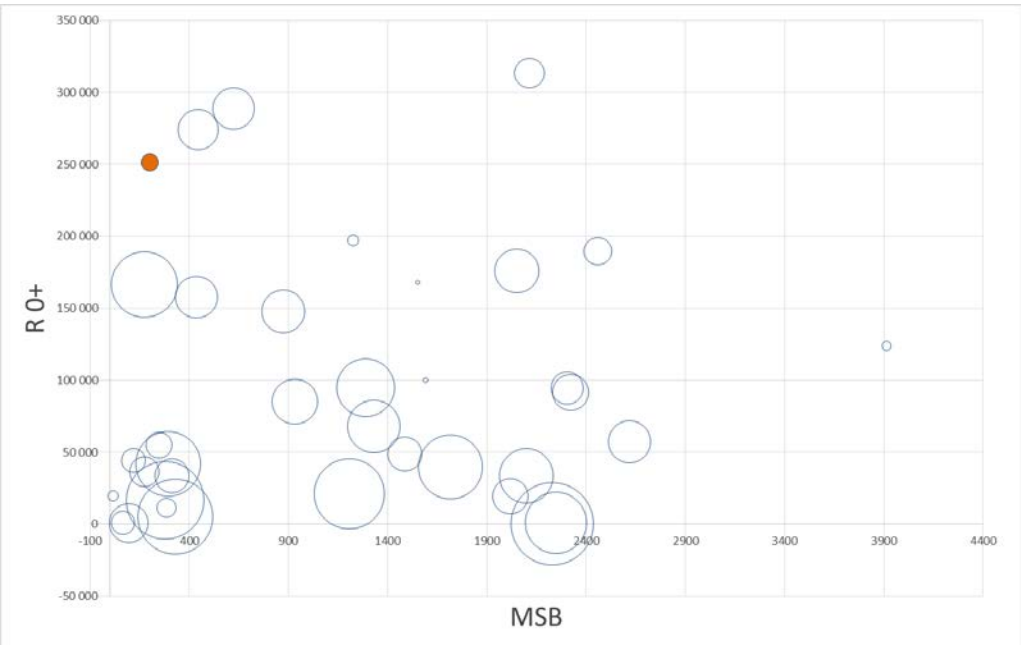


Figure 4.3.3. Relationship between mature stock biomass (>14 cm) take of spring fishery (biomass at 1 Oct. Y, total landings from 1 Jan to 1 Apr.Y+1 are subtracted) and 0-group index (Y+1), covering

the cohorts 1980–2016. The size of bubbles indicates the biomass of herring at age 1 and 2 (ICES WGWIDE data). Minimum diameter of bubble corresponds to 0.01 billion tonnes of herring (1982), the maximum - 3.61 billion tonnes. (1993). The red point is the 1989 cohort which is the basis for the current reference point (B_{lim}).

Natural mortality

The estimated capelin mortality based on the survey results has shown a marked increase in the last years (Figure 4.3.4). This corresponds in time to the strong decline of the capelin stock.

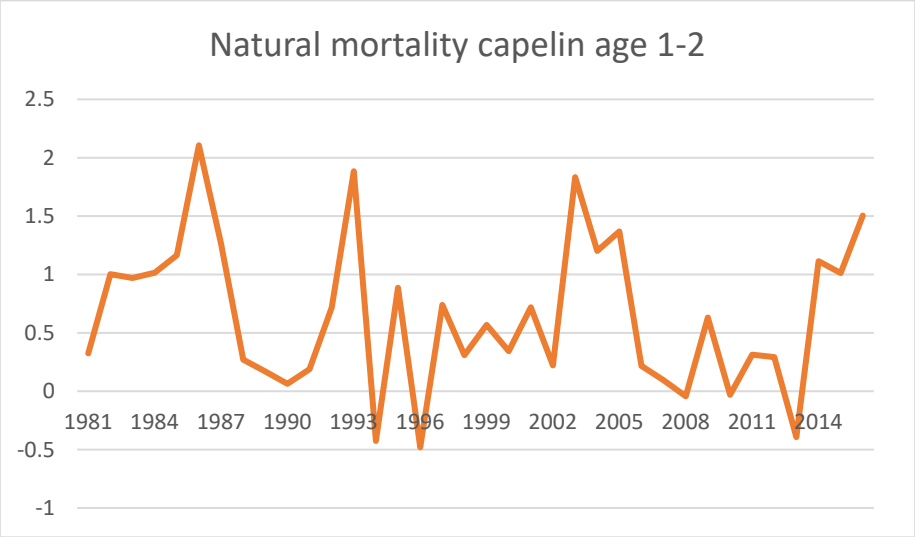


Figure 4.3.4. Natural mortality of age 1-2 capelin.

The stock of polar cod in the Barents Sea also declined until 2015 as described in the next section. The decrease in polar cod abundance during this period may have contributed to increased predation pressure on capelin since polar cod serve as additional prey for cod. The predation pressure from seals and whales may also have changed, but there is little information available regarding this. Assuming that predators such as harp seal and minke whale have a more stable occurrence in the Barents Sea, their food demand by feeding on capelin would come in addition to the heavy predation by cod.

Reasons for the recent collapse

The strong decline in the capelin stock in the last three years appears to be caused by a combination of the same factors as in the previous capelin collapses but with different relative contributions. We have witnessed a good recruitment as 0-group, indicating that predation by herring on 0-group capelin has not reduced the year class considerably, this is also consistent with the low to intermediate herring abundance in the Barents Sea in recent years. However, there has been increased mortality both from age 0-1 and on older capelin. Observations during the Joint winter survey indicate that both the 2015 and 2016 year classes of capelin were observed in large quantities as 1-group during this survey, although no estimates of abundance were made. The 2015 year class seems to have been strongly reduced as 1-group between this survey and the ecosystem survey in autumn. It should be noted that the 2016 year class was even more abundant than the 2015 year class at age 0. This is detailed in the subsections below. Despite the capelin biomass decrease, the weight percent of capelin in cod diet remains practically on the level of previous years with high capelin stock. Similarly, the estimated annual consumption of capelin by cod was around 4 million tonnes from 2009, which

is of the same magnitude as the stock size. A decline in the consumption was observed in the second half of 2015 and in 2016, but the decline is less strong than the decline in the stock estimates.

4.4 Causes of polar cod fluctuations

The Barents Sea polar cod stock is in 2016 at an intermediate level. Norway conducted commercial fisheries for polar cod during the 1970s, and Russia has fished this stock on more-or-less a regular basis since 1970. However, the fishery has for many years been so small that it is believed to have very little impact on stock dynamics. Stock size has been measured acoustically since 1986, and has fluctuated between 0.1–1.9 million tonnes. The stock size declined from 2010 to a very low level in 2015. However, it then increased again to 0.9 million tonnes in 2016 which is around the average level. This increase is due to the strong 2015 year class. The rate of natural mortality for this stock appears to be quite high. This is related to the importance of polar cod as prey for cod and different stocks of seals.

It appears that mortality has increased in recent years. During the recent period with polar cod, when the Barents Sea has been warm, the distribution of sea ice has decreased, and several boreal species have moved northward while the distribution area of Arctic species like polar cod has decreased.

Since the mid-1990s there has been a general rise in both air and water temperature in the Barents Sea (See chapter 3.1). The 2000s have been record warm. The area covered by sea ice has never been so low in the Arctic and the Barents Sea as in 2016. In the Barents Sea the area of Arctic water decreased while a larger part of the sea has been dominated by warmer Atlantic water. These climatic changes may have affected the distribution and abundance of Arctic species like polar cod.

The reduction of sea ice in winter reduces spawning habitat, leading to unfavourable conditions for polar cod spawning (Eriksen *et al.,* 2015c). The eggs have long incubation time and float near the surface where they may be exposed to unstable temperatures and increased water mixing due to lack of ice. Most of the juveniles are found in waters with temperatures below 5°C and reduction of cold water masses in summer and autumn reduces the nursery area for 0-group polar cod. 0-group polar cod prey on small plankton organisms such as copepods and euphausiids, while adults feed mainly on large Arctic plankton organisms such as *Calanus hyperboreus* and *C. glacialis* and hyperiids. The biomass of Arctic forms of zooplankton decreased in recent years and most likely influenced negatively the feeding conditions for 0-group polar cod. However no significant changes in the condition of adults were observed in recent years. This indicates a high degree of adaptability of this species to changes in the environment and enough available food resources.

The current fishing pressure is negligible now compared to the 1970s, when total catches were as high as 350 thousand tonnes. Thus the total mortality is close to the natural mortality. Most likely predation by cod has contributed to the high natural mortality. Cod is a boreal species and associated with the temperate waters. The Barents Sea warming has been beneficial for cod and it has spread further north. In the northern areas cod overlapped with polar cod, and thus predation pressure on polar cod has increased, contributing to the stock decline until 2015. In the overlapping area cod feeds efficiently on polar cod (see chapter 4.2).

4.5 Cod-capelin-polar cod interaction

The interaction cod-capelin-polar cod is one of the key factors regulating the state of these stocks. Cod prey on capelin and polar cod, and the availability of these species for cod varies. In the years when the temperature was close to the long-term mean, the cod overlap with capelin and polar cod was lower than in the recent warm years. Cod typically consume most capelin during the capelin spawning migration in spring (quarters 1+2), but especially in recent years the consumption has been high also in autumn (quarters 3+4) in the northern areas (Figure 4.2.3). A decline in the consumption of capelin by cod was observed in the second half of 2015 and in 2016, but the decline is less strong than indicated by the decline in the stock estimates.

With the recent warming of the Barents Sea, the cod stock increased and became distributed over larger area, overlapping with capelin and especially polar cod to a higher degree than before. Cod can prey intensely on polar cod, especially in mixed (polar cod and capelin) concentrations. The polar cod are most likely more available for cod than the capelin, because they possibly have a lower swimming speed (confirmed by trawl catch analyses) and are distributed closer to the bottom. However, capelin is fatter and energetically more valuable prey item. It should be noted, however, that the length of the period with cod and polar cod overlap is much shorter (September-December) compared to the overlapping time of cod and capelin.

4.6 Snow crab effect on benthos

In most of the measured years, the benthos biomass in the northeast part of the Barents Sea (NE) was above the total Barents Sea mean (Figure 4.6.1). But from 2013 and ongoing, the mean biomass (see also black arrows in Figure 3.4.3 lower panel) was reducing, and was record low (<20 kg/n.ml) in 2016, and below the total Barents Sea mean.

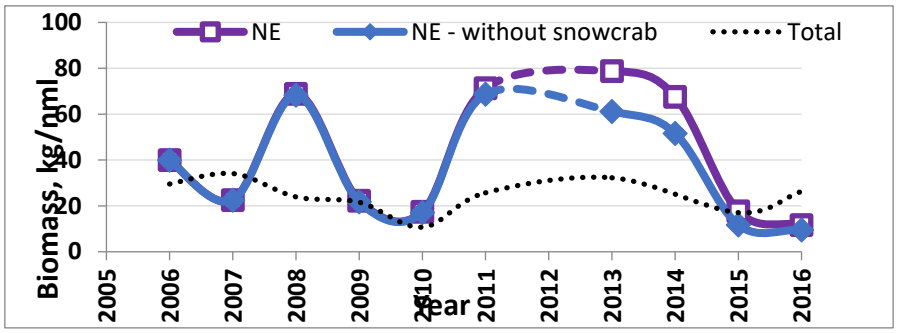


Figure 4.6.1. The interannually mean benthos biomass fluctuation in the NE (blue, box is total mean biomass, diamonds is without the biomass of the snow crab). The dotted line is the total Barents Sea mean biomass.

The area of reduced benthos biomass after 2013 are overlapping with the maximum distribution of the snow crab (Figure 3.4.3.), the period of maximum consumption/killing (Figure 4.6.2).

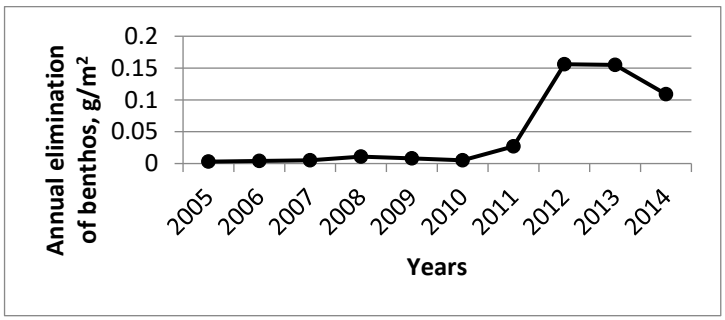


Figure 4.6.2. The mean annual consumption/killing of benthos (g/m²) by the snow crab population. The abundance of the snow crab population was given by the Ecosystem Survey in the Barents Sea (Manushin, 2016).

The spatial impact on benthos biomass done by the snow crab predation (Manushin, 2016) shows that the highest impact is located west of Novaya Zemlya (4.6.3) and in an area dominated by the polychaete *Spiochaetopterus typicus* (deeper areas with adult snow crabs) and the bivalve *Macoma calcarea* (shallower areas with juvenile snow crabs) (Zacharot *et al.*, 2016).

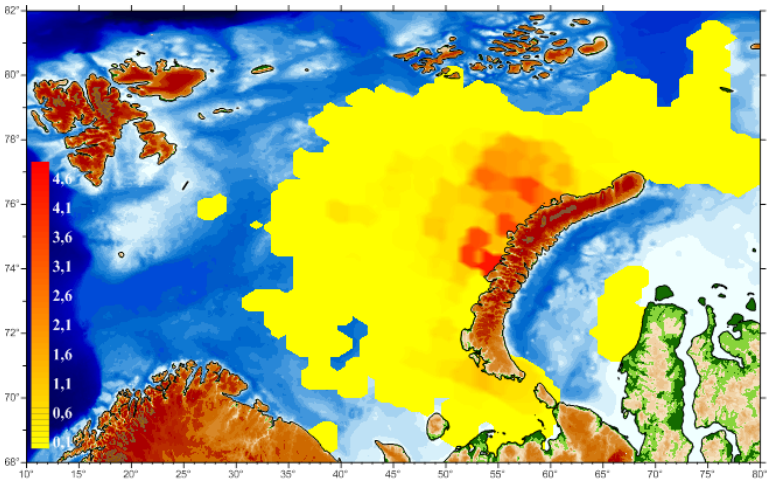


Figure 4.6.3. Total biomass (g/m²) of the benthos consumed/killed by the snow crab population during a nine-year period (2005–2014) (Manushin, 2016).

4.7 Environmental impact of fisheries

The impact of fisheries on the ecosystem is summarized in the chapter on Ecosystem considerations in the AFWG report (ICES 2016c), and some of the points are:

- The demersal fisheries are mixed, and currently have largest effect on coastal cod and *Sebastes norvegicus* (Golden redfish) due to the poor condition of these stocks.
- The most widespread gear is bottom trawl. Trawling has largest effect on hard bottom habitats; whereas the effects on other habitats are not clear and consistent.
- Currently the possibility of using pelagic trawls when targeting demersal fish is explored, to avoid impact on bottom fauna and to reduce the mixture with other species. It will be mandatory to use sorting grids to avoid catches of undersized fish.
- Fishery induced mortality (lost gillnets, contact with active fishing gears, etc.) on fish is a potential problem but not quantified at present.

4.8 Important indirect effects of fisheries on the ecosystem

In order to conclude on the total impact of trawling, an extensive mapping of fishing effort and bottom habitat would be necessary. In general, the response of benthic organisms to disturbance differs with substratum, depth, gear, and type of organism. Seabed characteristics from the Barents Sea are only scarcely known and the lack of high-resolution (◎100 m) maps of benthic habitats and biota is currently the most serious impediment to effective protection of vulnerable habitats from fishing activities. An assessment of fishing intensity on fine spatial scales is critically important in evaluating the overall impact of fishing gear on different habitats and may be achieved, for example, by satellite tracking of fishing vessels. The challenge for management is to determine levels of fishing that are sustainable and not degradable for benthic habitats in the long run.

The qualitative effects of trawling have been studied to some degree. The most serious effects of otter trawling have been demonstrated for hard-bottom habitats dominated by large sessile fauna, where erected organisms such as sponges, anthozoans and corals have been shown to decrease considerably in abundance in the pass of the groundgear. Barents Sea hard bottom substrata, with associated attached large epifauna should therefore be identified.

Effects on soft bottom have been less studied, and consequently there are large uncertainties associated with what any effects of fisheries on these habitats might be. Studies on impacts of shrimp trawling on clay-silt bottoms have not demonstrated clear and consistent effects, but potential changes may be masked by the more pronounced temporal variability of these habitats (Løkkeborg, 2005). The impacts of experimental trawling have been studied on a high seas fishing ground in the Barents Sea Trawling seems to affect the benthic assemblage mainly through resuspension of surface sediment and through relocation of shallow burrowing infaunal species to the surface of the seabed.

During 2009–2011 work between Norway and Russia was conducted to explore the possibility of using pelagic trawls when targeting demersal fish. The purpose with pelagic trawl is to avoid impact on bottom fauna and to reduce the mixture of other species. During the exploratory fishery it was mandatory to use sorting grids and/or a more stable four-panel trawl geometry with square mesh in the top panel of the codend to avoid catches of undersized fish. The efficiency of pelagic trawling was also tested compared with bottom trawling with regards to reduce the oil consumption per kilo of fish caught, i.e. to improve profitability and reduce NOx emissions.

After three years of exploratory fishing with pelagic trawls, pelagic trawling for cod, haddock and other demersal fish are still not allowed, mainly due to on average a smaller size of the fish and too big catches which are difficult to handle. The experiment has, however, led to a further development of the bottom trawls, including bigger trawl openings, better size selection and escapement windows to prevent too big catches.

Lost gears such as gillnets may continue to fish for a long time (ghost fishing). The catch efficiency of lost gillnets has been examined for some species and areas (e.g. Humborstad *et al.*, 2003; Large *et al.*, 2009), but at present no estimate of the total effect is available. Ghost fishing in depths shallower than 200 m is usually not a significant problem because lost, discarded, and abandoned nets have a limited fishing life owing to their high rate of biofouling and, in some areas, their tangling by tidal scouring. Investigations made by the Norwegian Institute of Marine Research of Bergen in 1999 and 2000 showed that the amount of gillnets lost increases with depth and out of all the Norwegian gillnet fisheries, the Greenland halibut fishery is the métier where most

nets are lost. The effect of ghost fishing in deeper water, e.g. for Greenland halibut, may be greater since such nets may continue to "fish" for periods of at least 2–3 years, and perhaps even longer (D. M. Furevik and J. E. Fosseidengen, unpublished data), largely because of lesser rates of biofouling and tidal scouring in deep water. The Norwegian Directorate of Fisheries has organized retrieval surveys annually since 1980. All together 10 784 gillnets of 30 metres standard length (approximately 320 km) have been removed from Norwegian fishing grounds during the period from 1983 to 2003. During the retrieval survey in 2011 the following were retrieved and brought to land: more than 1100 gillnets, 54 red king crab traps, 13 km trawlwire, 12 km of ropes, 40 km longlines, trawl codends, 14 tonnes of fish and about 12000 crabs, mainly red king crab.

Other types of fishery-induced mortality include slipping (pelagic catch is released, but too late to survive), burst net, and mortality caused by contact with active fishing gear, such as escape mortality. Some small-scale effects are demonstrated, but the population effect is not known.

The harbour porpoise (*Phocoena phocoena*) is common in the Barents Sea region south of the polar front and is most abundant in coastal waters. The harbour porpoise is subject to bycatches in gillnet fisheries. Revised estimates of harbour porpoise bycatches in two Norwegian coastal gillnet fisheries suggest an annual bycatch of ~3000 harbour porpoises along the entire Norwegian coast (Bjørge and Moan, 2016).

Fisheries affect seabird populations in two different ways: 1) Directly through bycatch of seabirds in fishing equipment and 2) Indirectly through competition with fisheries for the same food sources.

Documentation of the scale of bycatch of seabirds in the Barents Sea is fragmentary. Special incidents like the bycatch of large numbers of guillemots during spring cod fisheries in Norwegian areas have been documented. Gillnet fishing affects primarily coastal and pelagic diving seabirds, while the surface-feeding species will be most affected by longline fishing. The population impact of direct mortality through bycatch will vary with the time of year, the status of the affected population, and the sex and age structure of the birds killed. Even a numerically low bycatch may be a threat to red-listed species such as Common guillemot, White-billed diver and Steller's eider.

Several bird scaring devices has been tested for long-lining, and a simple one, the bird-scaring line (Løkkeborg, 2003), not only reduces significantly bird bycatch, but also increases fish catch, as bait loss is reduced. This way there is an economic incentive for the fishers to use it, and where bird bycatch is a problem, the bird-scaring line is used without any forced regulation.

In 2009, the Norwegian Institute for Nature Research (NINA) and the Institute of Marine Research (IMR) in Norway started a cooperation to develop methods for estimation of bird bycatch. Data on seabirds taken as bycatch from 2006 to 2009 in the coastal reference fleet programme that is managed by IMR were analysed. These estimates suggest that a total of 4000 to 6000 seabirds are killed by these fisheries. More detailed studies of seabird bycatch in the lumpsucker and Greenland halibut longline fisheries are in progress to provide more accurate data on bycatch and evaluate different measures to mitigate seabird bycatch.

4.9 Benthic habitat integrity and benthos vulnerability

With retreating sea ice, new areas in the northern Barents Sea become available for fisheries, including bottom trawlers. Of special interest to WGIBAR is therefore the vulnerability analysis (Jørgensen *et al.*, 2015). Current knowledge of the response of

benthic communities to the impact of trawling is still rudimentary. The benthos data from the ecosystem survey in 2011 has been used to assess the vulnerability of benthic species to trawling, based on the risk of being caught or damaged by a bottom trawl (WGIBAR report 2016). A clear decline in biomass was noted for all three categories when comparing trawled vs. untrawled areas. This suggests that trawling significantly affects the biomass of all species, but predominantly the "high-risk" taxa. Some Barents Sea regions were particularly susceptible to trawling (WGIBAR report 2016).

5 Expected changes in the coming years

5.1 Sea temperature

Oceanic systems have a "longer memory" than atmospheric systems. Thus, a priori, it seems feasible to predict oceanic temperatures realistically and much further ahead than atmospheric weather predictions. However, the prediction is complicated due to variations being governed by processes originating both externally and locally, which operate at different time-scales. Thus, both slow-moving advective propagation and rapid barotropic responses resulting from large-scale changes in air pressure must be considered.

According to the expert evaluation based on the analysis of the internal structure of the long-term variations in hydrometeorological parameters, over the next two years (2017–2018), the Atlantic water temperature in the Murmansk Current is expected to decline slightly but remain typical of warm and anomalously warm years.

Due to high temperatures and the low sea-ice extent in recent years, ice coverage is expected to remain well below normal.

5.2 Possible development of the stocks

Natural mortality of capelin is currently very high. The main predator for capelin is cod. The size of the cod stock is probably a main factor in the decline in capelin stock size. However, the relationship between changes in stock size of cod and capelin is not very strong. Historical data show that the probability of increase of capelin stock to a high level is low when the cod stock is large (Figure 5.2.1).

The 2016 capelin year class was strong at the 0-group stage and preliminary reports from the 2017 winter survey state that 1-group capelin was abundant and widely distributed. Whether the 2016 year class will be subject to the same high mortality from age 0 to 1 as the 2015 year class is uncertain. However, the low abundance of immature capelin in 2016 indicates that the abundance of mature capelin in 2017 and 2018 will also be low.

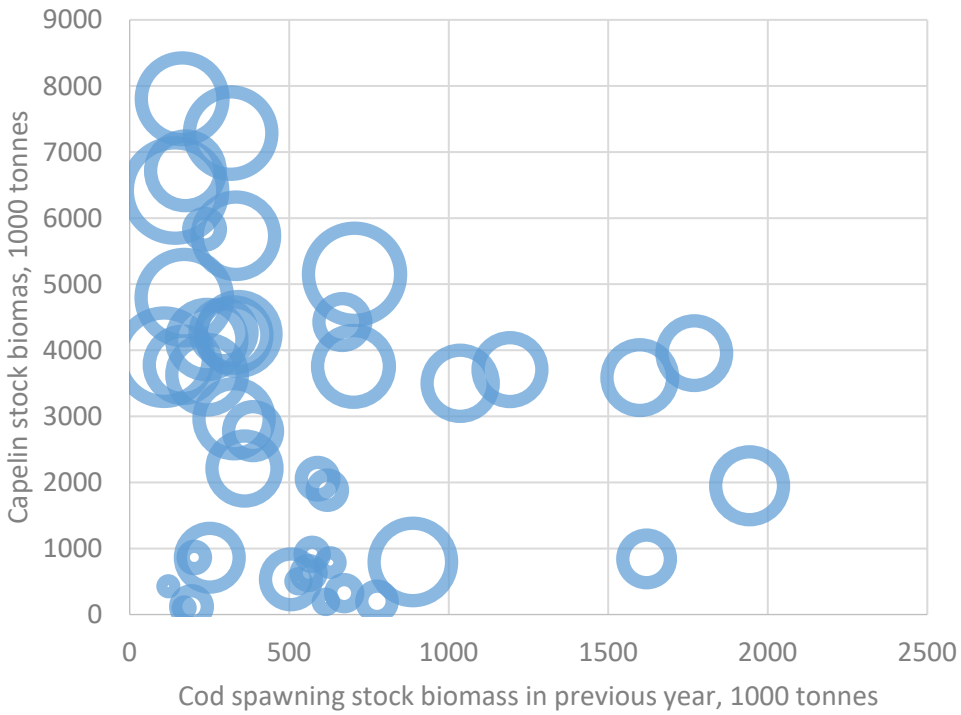


Figure 5.2.1. Capelin total-stock biomass vs. cod spawning-stock biomass in previous year. Circle size is proportional to capelin stock biomass the previous year. Capelin data are from the acoustic survey 1973–2015, cod data are from the report of the AFWG 2015 (ICES 2015c).

Warm conditions are expected in the Barents Sea in the coming years, and with that cod will still have a large area available for feeding. However, given that capelin, as their main prey, is now at a low level and not likely to recover to high levels in 2017 or 2018, cod must compensate by feeding more on alternative prey.

During the first capelin collapse, cod were not fully able to compensate the low amounts of capelin with alternative prey and suffered severe growth decline. During the second collapse, cannibalism was high, whereas during the third collapse no negative impact on cod was detected. However, during the third collapse, the abundance of main fish prey and shrimp (Figure 4.2.10) was higher than it is at present, and the cod abundance was lower.

Other fish and other food including benthos have made up about 40% of the recent diet of cod in the Barents Sea. The abundance and productivity of these food sources is not known and the predation impact by cod is therefore difficult to quantify. Long rough dab, Norway pout and small demersal Arctic fish such as eelpouts, blennies and sculpins are potential prey as are various crabs, shrimps and other benthos. The large cod stock, which will likely continued to feed in the northern Barents Sea, may have a large impact on other parts of the ecosystem. It is desirable to document the feeding and predatory impact of cod on these other prey species in order to distinguish that predatory impact from other direct impact, in particular climate change. This is important also for understanding the effect on the cod stock itself.

Hyperiids and juvenile cod and haddock have been important alternative prey for cod in previous capelin collapses (Figures 4.2.1 and 4.2.2). Currently there is very low amounts of hyperiids in the Barents Sea (see section 3.3). Krill is also an alternative prey for cod, and krill biomass appears to stay high. Snow crab and cod have overlap-

ping distribution on the banks of the Barents Sea, and cod have increased their consumption of snow crab as the latter has become more abundant. The cod could have a top down effect and regulate the snow crab expansion.

There are now more large cod in the stock than previously. Large cod could feed on a wider range of prey and swim faster than small cod so they can exploit a larger area for feeding. This might partly counteract some of the potential negative impact of the capelin decline on cod feeding and growth. Compared to the last capelin collapse, the availability of alternative prey at present appears somewhat lower although accurate quantitative estimates are not available.

If cod switch to feed on a larger proportion of juvenile cod and haddock now when capelin abundance is low, recruitment to the stocks of cod and haddock may suffer. In addition, the cod stock is larger than during the previous collapses, potentially increasing the impact. The likely implication is a moderate decrease in individual cod growth eventually affecting the stock biomass.

Polar cod is a key species in the food chain in the Barents Sea and important prey for cod, Greenland halibut, seals, whales and seabirds. Estimation of harp seal diet shows that harp seals alone can consume up to 100–400 thousand tonnes of polar cod during migration to the whelping area in the White Sea during November -December and up to 350 thousand tonnes during northwards migration in July. The significance of polar cod prey increases in summer when parts of the northern and eastern Barents Sea are free of ice and polar cod becomes available for migratory species. Due to predation pressure from a large cod stock that are distributed to the north in the Barents Sea, and the expected continued warm conditions in the Barents Sea in the coming years, the strong 2015 year class of polar cod may be strongly reduced by predation from cod.

5.3 Temperature effect on benthos biomass (updated in 2016)

The long-term variation of the mean biomass of the NW, SW and the total Barents Sea show strong correlations (Figure 5.3.1). This might indicate that the western Barents Sea are driven by a factor common for the total Barents Sea.

If comparing fluctuations of bottom temperature (Figure 5.3.1) with the benthos biomass (Figure 5.3.2) both shows clear decreasing values during 2007-2010. But previous studies show that benthos has a delay of approximately 3-7 years for macrobenthos to environmental variables (Lyubina *et al.,* 2013; Denisenko, 2013), but with the more long-lived megabenthos, we suggest this delay to no less than 7 years. If we use a maximum delay of 7 years, we see a direct correlation between temperature and benthos biomass.

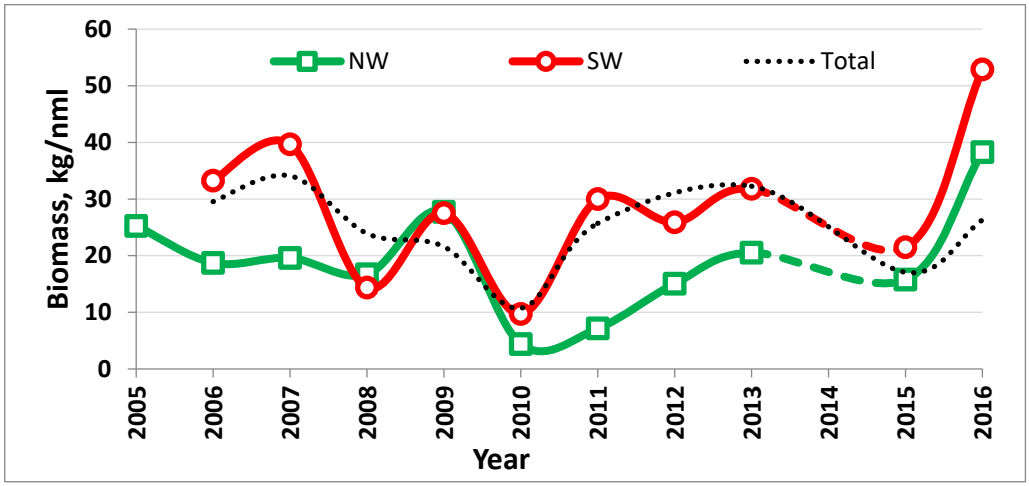


Figure 5.3.1. The interannually mean biomass fluctuation of the SW (red, all <1T catches of sponges excluded) and NW (green) from 2005–2016. The dotted line is the Barents Sea mean biomass (see also Figure y3). NW = 74–80°N and 15-40°E but excluding all stations W and N of Svalbard, SW = 65–74°N and 10–40°E. All stations west and north of Svalbard and all sponge catch >1T excluded.

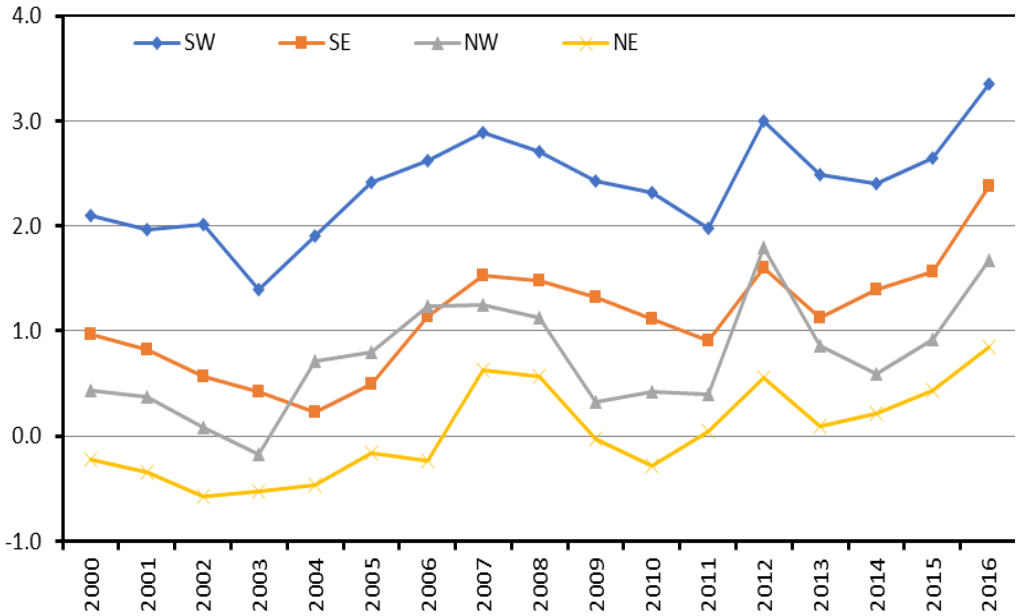


Figure 5.3.2. Bottom temperature fluctuations of the SW, NW, SE, and NE Barents Sea from 2000 to 2016. NW = 74–80°N and 15–40°E but excluding all stations W and N of Svalbard. NE = 74–80°N and 40–62°E, SW = 65–74°N and 10–40°E, SE = 65–74°N and 40–62°E.

The SE are experiencing high level of commercial trawling which might, together with possible effect from temperature, be part of the explanation to the low benthos-biomass in this area. This become more evident when the SE is compared to the high biomass of benthos in the NE which have no trawling activity (Ljubin *et al.*, 2011).

The highest biomass (sponge catch >1T excluded) in the Barents Sea was recorded in the NE (>60 kg/n.ml). The area of reduced benthos biomass after 2013 (black arrows in Figure 3.4.3 for 2013–2016) are overlapping with the maximum distribution of the snow crab (Figure 3.4.8), the period of maximum consumption/killing (Figure 4.2.5), but also with an increasing bottom temperature from 2007 (Figure 3.1.9b). We therefore suggest the strong decrease in benthos biomass to be an effect multiple impact factors.

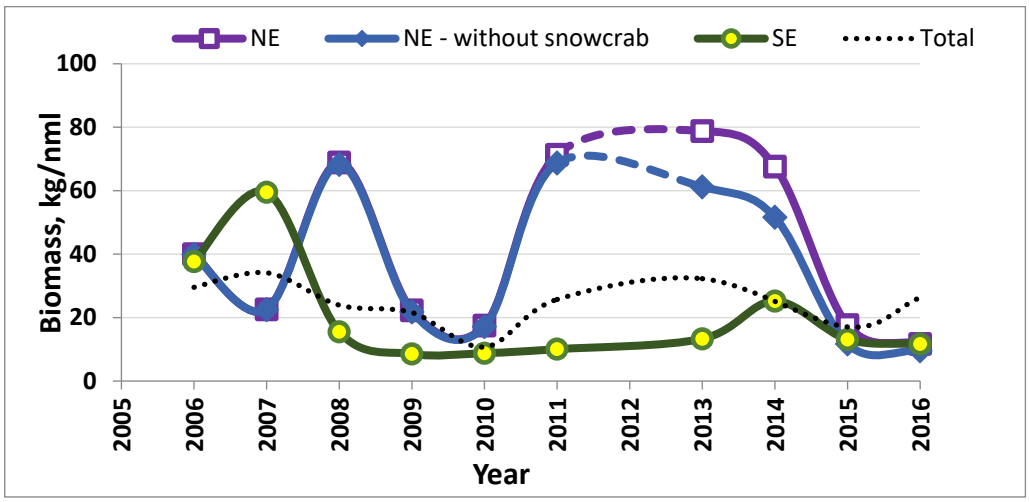


Figure 5.3.3. The interannually mean biomass fluctuation of the SE (red line with yellow circles) and NE (blue, box is total mean biomass, diamonds is without the biomass of the snow crab). The dotted line is the Barents Sea mean biomass (see also Figure y3). NE = 74–80°N and 40–62°E, SE = 65–74°N and 40–62°E.

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Annex 6: Time-series used in Integrated Trend Analysis

Description of the time-series used in the Integrated multivariate analysis, grouped into abiotic, biotic and pressures (see below and Table 1).

A PCA analysis was run with 13 abiotic variables reflecting oceanographic conditions.

A PCA analysis was done on a set of variables including zooplankton biomass in three size fractions and sum total for the Barents Sea (Figure 2.2.3), 3 time-series of krill, and abundance of 0-group fish of 8 species (capelin, cod, haddock, herring, polar cod, Greenland halibut, long-rough dab, redfish, and saithe).

A PCA analysis was run with 23 variables reflecting stock size, growth and maturation of cod (7 variables), haddock (6 variables), capelin (5 variables), polar cod (2 variables), and herring, long-rough dab and shrimp (1 variable each).

a. Abiotic

Atmosphere and Air:

Winter North Atlantic Oscillation (NAO) index (PC-based) from December January February March. TaAnom_East and TaAnom_West - Air temperature anomalies in the eastern (69–77°N, 35–55°E) and western (70–76°N, 15–35°E) Barents Sea based on monthly data from the ERA Interim (ECMWF).

Ice:

IceareamaxApril and IceareaminSept - Ice area in the Barents Sea (10–60°E, 72-82°N) at maximum (April) and minimum (September) ice coverage. Sea ice concentration was obtained from the National Snow and Ice Data Center (NSIDC)

Fluxes:

The Barents Sea is a through-flow system with Atlantic water entering from the Norwegian Sea in southwest and leaving modified between Novaya Zemlya and Franz Josef Land in northeast. Here, we use modelled volume transports from a 4 km resolution model hindcast for the Barents Sea. BSO is the modelled net eastward volume transport between Norway and Bear Island (positive into the Barents Sea). BSX is the modelled net eastward volume transport between Franz Josefs land and Novaya Zemlya (positive out of the Barents Sea). NBSO is the modelled net southward volume transport between Svalbard and Franz Josef Land (positive into the Barents Sea). SBSO is the modelled net eastward volume transport between Kola and Novaya Zemlya (positive out of the Barents Sea).

Water masses:

Areas of Arctic Water (Area_ArW, T<0°C), Atlantic Water (Area_AW, T>3°C) and Mixed water (Area_MW 0°C<T<3°C) were calculated based on the mean 50-200 temperature fields from temperature measurements taken during the annual scientific surveys in the third quarter. To ensure complete data coverage each year, the area calculations were restricted to the area 72–80°N, 20–50°E.

Ocean temperatures:

TempNE and TempNW - Average temperature in two boxes representing the northern and northeastern Barents Sea based on data from the annual scientific surveys in the third quarter. FB-aug - The temperature averaged over the 50–200 meter depth range

between 71.5°N and 73.5°N in the Barents Sea Opening in August. Kola_Temperature - The temperature averaged over the 50–200 meter depth range between 70.5°N and 72.5°N in the Kola Section.

Salinity:

Kola_Salinity- The salinity averaged over the 0–200 meter depth range between 70.5°N and 72.5°N in the Kola Section

b. Biotic

Plankton

Meso-zooplankton – Biomass estimate (interpolated from catches by WP2 plankton nests) from survey in August-September, total and by three size fractions (Zoopl_Total, Zoopl180, Zoopl1000, Zoopl2000). The mesozooplankton biomass data consist mainly of copepods.

Krill- There are four species of krill in the BS, our data are not separated by species We include two krill biomass index series Krill_S is from the Russian winter survey (October-December), sampled with a plankton net attached to the demersal trawl, this survey covers mostly the ice free BS. The dataseries is the longest time-series of zooplankton in the Barents Sea, going back to the 1950s. The series was discontinued in 2016. The second series is from 0-group survey (now the ecosystem survey) covering most of the BS shelf in August-September (Krill). A pelagic trawl is used, and only larger (>15 mm) specimens are retained in the trawls.

Jellyfish - This is a biomass index based on data from 0-group survey (now the ecosystem survey) covering most of the BS shelf in August-September (Jelly).

Benthic invertebrates - *Pandalus borealis* index (Shrimp) from stock assessment.

Pelagic fish

Mallotus villosus- Capelin is a key species in the BS, capelin total-stock biomass (age 1+) acoustic estimate from survey in August-September (Capelin_TSB), length growth from age 1 to 2 (Capelin_gr12), condition at age 2 (Capelin_cond), % mature age 2 (Capelin_Mat2). 0-group abundance is from the ecosystem survey/0-group survey, pelagic trawl (Capelin_0).

Boreogadus saida – Polar cod is a true arctic species. Polarcod_biom is acoustic estimate of biomass from the acoustic survey in August-September. The acoustic survey was originally targeted towards capelin, and the polar cod distribution area extends northeast outside the survey area, so the estimate of the polar cod is uncertain, especially before 2004. 0-group abundance is from the ecosystem survey/0-group survey, pelagic trawl (Polarcod_0).

Juvenile *Clupea harengus*. Juvenile herring is a key species in the Bs, and strong year classes of herring are often associated with recruitment failure of capelin: VPA data age 1 and 2 on herring multiplied with individual weight by age (Herring1-2_biom). 0-group abundance is from the ecosystem survey/0-group survey, pelagic trawl (Herring_0).

Demersal fish

Gadus morhua – Cod is the most important piscovore in the BS and a very important commercial species. Cod total-stock biomass (Cod3+_biom), recruitment-at-age 3 (Cod

_Rec3), weigth at age (Cod_w3y, Cod_w5y, Cod_w8y), weight at age 3, proportion mature at age 7 (Cod _mat7), all these series are obtained from assessment. 0-group abundance is from the 0-group survey, pelagic trawl (Cod_0).

Melanogrammus aeglefinus – Haddock is an important commercial species, and is more benthivor than cod. Haddock total-stock biomass (Haddock3+_biom), spawning-stock biomass ages 6-8 (Haddock_SSB68), recruitment-at-age 3 (Haddcok_R3), and predation mortality age 3 from cod (Haddock_M_age3). Data from assessments (ICES 2016c) 0-group abundance is from the ecosystem 0-group survey, pelagic trawl (Haddock_0).

Hippoglossoides platessoides – long rough dab is of limited commercial importance but one of the most abundant and widespread fish in the BS. We used a cpue index from the Russain demersal survey in Nov-Dec (LRD) 0-group abundance is from the ecosystem survey/0-group survey, pelagic trawl (LRD_0).

c. Pressures

Fishing mortality of shrimp (Relative_F_Shrimp) is from the last shrimp assessment (ICES 2016a)

Fishing mortality and haddock (Cod_F510 and Haddock_F47) are from the last stock assessments (ICES 2016c)

Fishing Mortality of Capelin (Relative_F_Capelin) in year y was calculated as the sum of catches in autumn year y-1 and the next spring (year y) divided by biomass in autumn year y-1. This was shifted one year compared to the analyses done last year, to reflect that most of the catches are taken in spring.

Table 1. The time-series used in the integrated multivariate analysis, grouped into abiotic, biotic and pressures

Variables	PCA abiotic (Figure 2.2.1 and 2.2,2)	PCA drifted organisms (Figure 2.2.3) and abiotic (2.2.4)	PCA Biotic (2.2.6) and abiotic (2.2.7)
NOA	X	X	X
SBS	X	X	X
SBSO	X	X	X
IceMin	X	X	X
IceMax	X	X	X
Kola_Temp	X	X	X
Kola_Salinity	X	X	X
FB.aug	X	X	X
Plank_S		X	
Plank_M		X	
Plank_L		X	
Plank_T		X	
Krill_T		X	
Krill-NW		X	
Krill_SB		X	
Cap_0N		X	
Cod_0N		X	
Her_0N		X	
Had_0N		X	
Saithe_0N		X	
Polar_0N		X	
LRD_0N		X	
GH_0N		X	
Sebas_0N		X	
Cod_3W, _5W, _8W, _mat7, _Rec, _3_plus, _TSB			X
Cap_Cond, -mat2, _gr12, _TSB, _F			X
Had_5W, _R3, 3plus, _SSB6, _M_ag, _F47			X
Her1_2B			X
Polar N, _2W			X
Shrimp_F			X