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Integrated Arctic Observation System

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Deliverable 6.13

Extension of ecosystem management:

Final results

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EXECUTIVE SUMMARY

The main aim of this deliverable, 6.13, is to offer advice on how the practice of applying existing observational data, ecosystem models, and indicators may be expanded from the Barents Sea and Disko Bay, West-Greenland to a wider range of Arctic sea regions and ecosystems. Further, we build advice and recommendations upon the established Norwegian Barents Sea ecosystem management plan, the more local management system for Disko Bay and focused individual and group interaction with **a wide range of stakeholders** in both areas. The **expected impact** is to provide advice on the most relevant and useful scientific basis for better-informed decisions and better-documented processes for managers and policymakers on local, regional and pan-Arctic scales.

We conclude that **both observational data and models are needed** to get a holistic overview of the ecosystem status and to make reliable projections. The ecosystem models applied have different structural complexity and spatial resolutions making them suited for different roles in supporting the existing and future integrated Arctic Observation System (iAOS). The NoBa Atlantis model, applied to the Barents Sea, is the most complex model including many trophic levels and a range of anthropogenic pressures. It is highly suitable to make management scenarios and indices of higher trophic levels but is more coarsely resolved in time and space than the other two models we use. NORWECOM.E2E is a well-established model system with high temporal-spatial resolution for the Barents Sea. It has the carbon cycle and key fish species included. NORWECOM.E2E is well suited for making Observing System Simulation Experiments. FlexSem-ERGOM is a relatively new model for lower tropic levels with the highest spatial resolution among the three models, but with focus on smaller coastal systems and environmental changes. In INTAROS it has been set up for the Disko Bay. It has the advantage of being very flexible and can easily be adapted to a wide range of local ecosystems in the Arctic.

Interaction with stakeholders from fisheries, maritime, and petroleum management and industry, and especially environmental management, has been a central part of our work. How the different stakeholders want to be informed, and what kind of information they seek, is presented, showing that managers are not negative to inclusion of well tested models in future ecosystem state and trend reports. Stakeholders generally found that models are useful, but that model uncertainty should be clearly communicated. Hence, there is a basis for future application of models for advice to especially environmental management.

The interaction between scientists and a wide range of managers and industry representatives established in INTAROS and other ongoing projects will be continued despite no established dedicated long-term funding.

The current report is based on the work carried out in INTAROS Task 6.2 "Improved ecosystem understanding and management" and Task 6.8 "Demonstrations for fisheries and environmental management agencies".

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1. Introduction

1.1 Background and aim

This report presents INTAROS' deliverable D6.13, *Extension of ecosystem management: final results*. The aim is to *use the existing environmental and fisheries reporting and management systems of the Barents Sea and off Greenland to demonstrate how data from an integrated Arctic Observation System (iAOS) may allow for implementing similar procedures in other parts of the Arctic*. This contributes to the INTAROS WP6 objective to *demonstrate significance of enhanced integration of data from Arctic observing systems covering a range of remote sensing and in-situ platforms in geographically different locations.* Towards these goals we use a range of state-of-the-art ecosystem models. Further, to ensure that our approach and results are relevant to our end users we have had extensive interaction with stakeholders, both through larger group meetings and face-to-face discussions. The work is carried out within the two INTAROS tasks 6.2 and 6.8. Task 6.2 uses selected cases to analyze how data from observations and models, including those available through the INTAROS data catalogue (https://catalog-intaros.nersc.no/), may contribute to advances in ecological and environmental understanding and allow for expanding existing environmental and fisheries reporting and management systems into new geographic areas. This task is tightly linked with Task 6.8, which through direct interaction demonstrates the use of INTAROS based products for stakeholders from management and industry, especially those involved in management of the environment and living marine resources. The expected impact is to provide enhanced scientific basis for better-informed decisions and better-documented processes for managers and policy makers on local, regional and pan-arctic scales. This deliverable builds upon the work documented in D6.3 *Extension of ecosystem management: first results*, and D6.10 *Report on ecosystem management for managers*.

The Barents Sea, north of Norway and northwest Russia, and Disko Bay, western Greenland are chosen as our study areas (Figure 1). As the two areas are physically and ecologically different, and the observations, models applied and management differ, they are in the first part of the report presented separately.

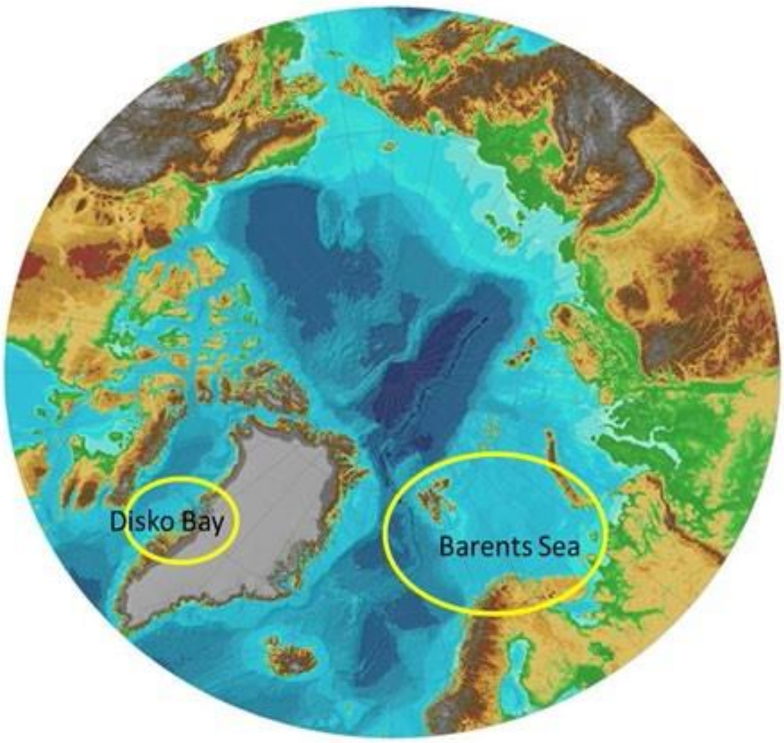


Figure 1. Location of the two study areas, Disko Bay and the Barents Sea.

A focus of the Barents Sea case was to evaluate the appropriateness and significance of the indicators in the Norwegian Barents Sea ecosystem management plan (BSMP; Anon., 2015). Two different end-to-end ecosystem models, NORWECOM.E2E and NoBa Atlantis (explained later in the report) has been used. Time series of a set of the proposed indicators have been estimated using the suggested methodology in BSMP under a future climate projection. Through an Observing System Simulation Experiment (OSSE) the effect of sampling scheme has been investigated, and the design of a minimum cost monitoring program has been suggested. The BSMP suggest 70 different indicators, with different degree of covariance. To reduce the number of indicators, the models have also been used to search for an optimal indicator subset, and finally the present use of reference points has been discussed among scientists and with stakeholders. While the concrete outcome is specific for the Barents Sea, the approach and methods developed may be adjusted to be applicable to other regions. By building on models in addition to observations, the approach may also be applicable to data poor regions.

An important aim for the off-Greenland task was to demonstrate downscaling from large-scale regional models to fine-scale local models of Arctic coastal waters, demonstrated for the Disko Bay. An ecosystem model based upon the FlexSem model system and the biogeochemical model ERGOM (explained later in the report) is used to evaluate external impacts of climate and environmental change on local marine resources to support management decisions and stakeholder involvement. The downscaling approach provides intelligent extrapolation of ocean parameters to under or un-sampled areas, as well as a platform to conduct OSSE studies to optimize future observational design, including selection of mooring deployment sites and cruise survey stations.

Both the Barents Sea and Disko Bay studies contribute to advances in ecological modelling and understanding of Arctic ecosystems more generally and suggests approaches for expanding management practices into new geographic areas, e.g., other coastal areas of Greenland or northwards from the Barents Sea into the Arctic Ocean.

This document is structured as follows:

- Background and aim, including brief introduction to the two tasks where the work has been carried out.
- Description of the two case studies and study areas, The Barents Sea and Disko Bay, west Greenland.
- Results from interaction with stakeholders from management and industry
- Requirements and suggestions for extension of management systems to other parts of the Arctic

2. Case Barents Sea

2.1 Description of the case study area

Physical factors that make arctic marine ecosystems unique are a high proportion of shallow continental shelves, strong seasonality, low temperature, extensive permanent and seasonal ice-cover, and a large supply of freshwater from rivers and melting ice. Because of these conditions, many of which are challenging for marine biota, arctic marine ecosystems include many specialists, many of which are not found elsewhere. These organisms have, through time, been able to adapt to the environment, but they are still challenged by extreme inter-annual variations. The Barents Sea is one of the shallow shelf seas that collectively form the Arctic continental shelf. Its western boundary is defined by the shelf break towards the Norwegian Sea, the eastern boundary by Novaya Zemlya, the southern boundary by Norway and Russia, and the northern boundary by the continental shelf break towards the deep Arctic Ocean. Stretching from 70N to over 80N, it is subject to large seasonal variations in light levels, experiencing 24 hours of darkness in winter and of sunlight in summer.

The most thorough relatively recent descriptions of the Barents Sea ecosystem are given in the books by Sakshaug et al. (2009) and Jakobsen and Ozhigin (2011). There is ample evidence of the effects of climate variability on the marine ecosystems, e.g. the response of the abundance and distribution of fish species associated with short- and long-term temperature changes. Much of the CTD data collected by IMR's research vessels (e.g., along the Fugløya-Bear Island transect, Figure 2) has been made openly available in NetCDF format by the Norwegian Marine Data Center on the INTAROS data catalogue https://catalog-intaros.nersc.no/organization/institute-of-marine-research-imr

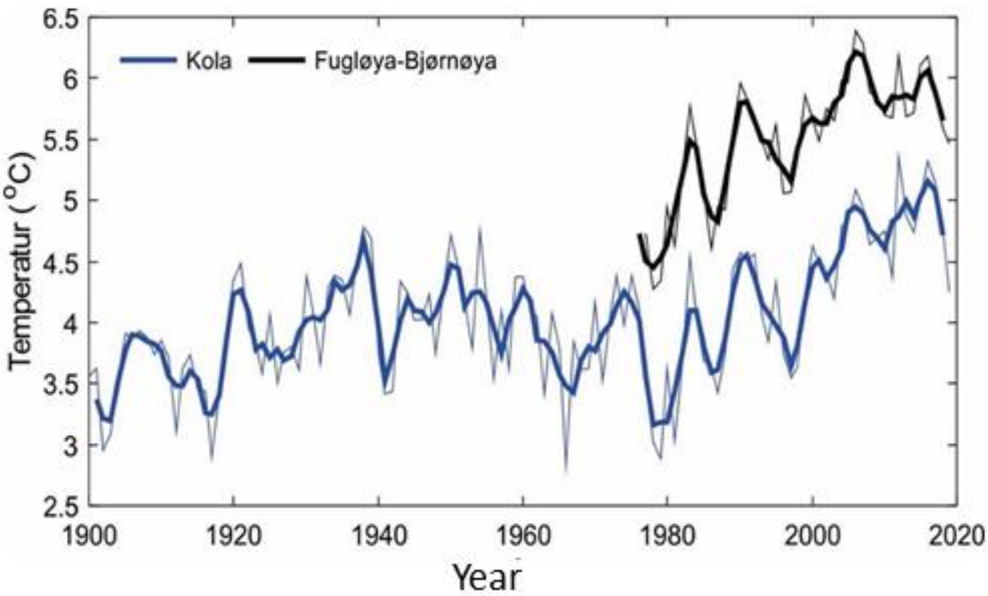


Figure 2. Kola and Fugløya-Bjørnøya transects in respectively the south-central and southwest part of the Barents Sea.

However, many aspects of the interaction between the atmosphere and the ocean, and between climate and the marine ecosystem require a better understanding before the high levels of uncertainty associated with present predicted responses to climate change can be significantly reduced (Hollowed and Sundby, 2014; Meredith et al. 2019). This understanding can only be achieved through monitoring and research. The latter should include comparisons between and among other subarctic and arctic regions. Predicting the responses of the ecosystem to future climate change in the Arctic is of great interest to scientists, governments and fishing communities.

2.2 The Norwegian Barents Sea ecosystem management plan (BSMP)

Ecosystem management plans are developed to consider, evaluate, and ideally control the multiple anthropogenic pressures that affect marine ecosystems (Frank et al., 2005; Butchart et al., 2010). To assess the status of marine ecosystems worldwide, a range of indicators have been suggested, defined, calculated and evaluated, to track ecosystem status and inform managements (Shin and Shannon, 2009; Coll et al., 2016). The indicators for BSMP were selected through scientific workshops assessing the quality of data for each suggested indicator, the length of time series, and the access to systematic updates. These indicators should show the development of the entire ecosystem, including physical and chemical oceanography, phytoplankton and zooplankton, benthic, fish, sea birds and sea mammal populations and communities. The same process was later done in a joint Russian-Norwegian report (McBride et al., 2016). In 2006, an integrated management plan for the Barents Sea-Lofoten area was endorsed by the Norwegian Parliament (Anon. 2006). BSMP has been updated since and now includes a large selection of indicators, a majority being simple ecosystem indicators describing temperature, primary production, biomass and distributions of a selection of species (Olsen et al., 2011; Anon. 2015). The expression “indicator” is not well defined in the BSMP. In this report an indicator is: a quantity based on calculating trends and changes in ecological key species or processes by a selection of one or more single parameters with known or perceived relationship, where a parameter is an observation or model value of a particular physical or biological component.

2.3 Modelling of the Barents Sea

2.3.1 Data and subareas applied in BSMP

The data sets used for indicators in the existing management plans consists mainly of a simple time series (Arneberg et al., 2020). However, to develop indicators to measure changes that is expected to be sensitive to human impact and climate change and variation, more complex time series are being developed (Jepsen et al., 2019; Siwertson and Arneberg, 2019). These time series cover a large part of the ecosystem from ocean physics to fish and marine mammals. Some of the suggested indicators are spatial, with a focus on ecosystem-type.

The Barents Sea was divided into four different domains based on ecosystem-type: Arctic shelf, Arctic shelf edge, Atlantic shelf, and Atlantic shelf edge. Further, as these areas are large, the NoBa Atlantis polygons (Figure 3; described in 2.4.4) are suggested for sub-areas in BSMP.

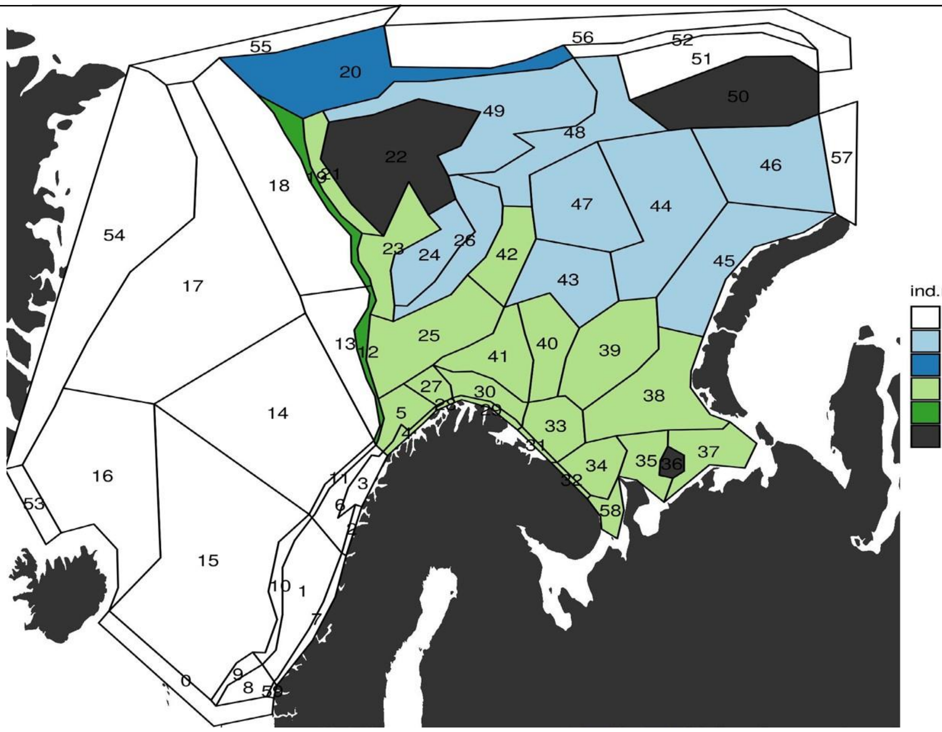


Figure 3. Colors indicate the polygons used in NoBa Atlantis and Barents Sea indicators. The six different categories are outside of Barents Sea (white), land (black), and the four domains Arctic shelf (light blue), Arctic shelf edge (darker blue), Atlantic shelf (light green) and Atlantic shelf edge (darker green). Numbers designate the individual polygon numbers.

2.3.2 Physical forcing and set-up

Physical forcing is taken from a downscaling of the Norwegian Earth System Model (NorESM1-ME, Tjiputra et al., 2013) using the Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams 2005) under the RCP4.5 emission scenario. NorESM1-ME is a fully coupled climate carbon cycle model developed in Norway in collaboration with researchers from the USA National Center for Atmospheric Research (NCAR). The ROMS model set-up is initialized from the NorESM1-ME model, and outputs from NorESM1-ME are also used at the open boundaries and as atmospheric forcing. The model domain for the ROMS downscaling covers the North Atlantic, the Nordic and Barents Seas, and the Arctic Ocean from 30°N to the Bering Strait, with a horizontal model resolution of approximately 10 x 10 km.

2.3.3 NORWECOM.E2E

The NORWegian ECOlogical Model system End-To-End (NORWECOM.E2E; Figure 4), a coupled physical, chemical, biological NPZD model system (Skogen et al., 1995; Skogen and Søiland, 1998), was originally developed to study primary production, nutrient budgets and dispersion of particles such as fish larvae and pollution. The model has been validated by comparison with field data in the Nordic and Barents seas (Hjøllo et al., 2012; Skaret et al., 2014). The model is further extended with a module to project ocean acidification (Skogen et al., 2014), and has several modules Individual Based Models (IBMs) for key species in the Nordic and Barents seas such as *Calanus finmarchicus* (Hjøllo et al., 2012) and pelagic fish (Utne et al., 2012). In the present study the model is run in offline mode using the NPZD and ocean acidification modules (Figure 4).

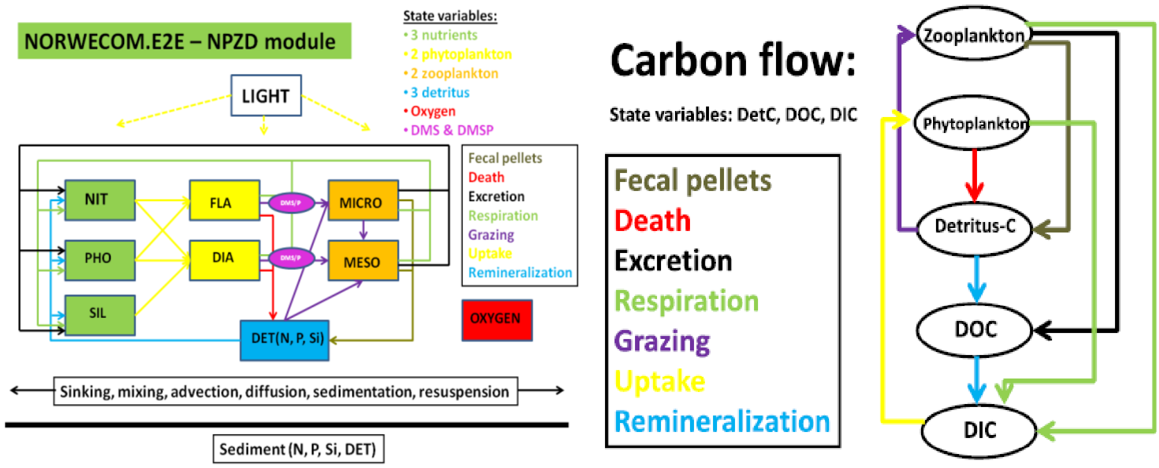


Figure 4. Schematics of the NORWECOM.E2E NPZD module (left) and the carbon flow (right)

Physical ocean fields (velocities, salinity, temperature, water level and sea ice) from the ROMS downscaling (Section 2.4.2) has been interpolated from 5-daily means and used as physical forcing together with daily atmospheric (wind and short-wave radiation) fields from the NorESM1-ME simulation. The horizontal grid used is identical to a subdomain of the original ROMS grid.

Our simulation started on January 1, 2006. After a 12year spin-up (running the first year 12 times) the full model period (2006-2070) was run sequentially. The time step used was 3600 seconds. The biochemical model is coupled to the physical model through the light, the hydrography, and the horizontal and vertical movements of the water masses. For more details, see description in Skogen et al. (2014, 2018).

2.3.4 The Nordic and Barents seas NoBa Atlantis model

The Nordic and Barents Seas Atlantis model is an application of the Atlantis framework (e.g. Fulton et al., 2011, Weijerman et al., 2016, Audzijonyte et al., 2017), implemented for the Nordic and Barents seas Hansen et al. (2019a, b). Atlantis is an end-to-end model, including multiple modules depending on the complexity of the model (Figure 5).

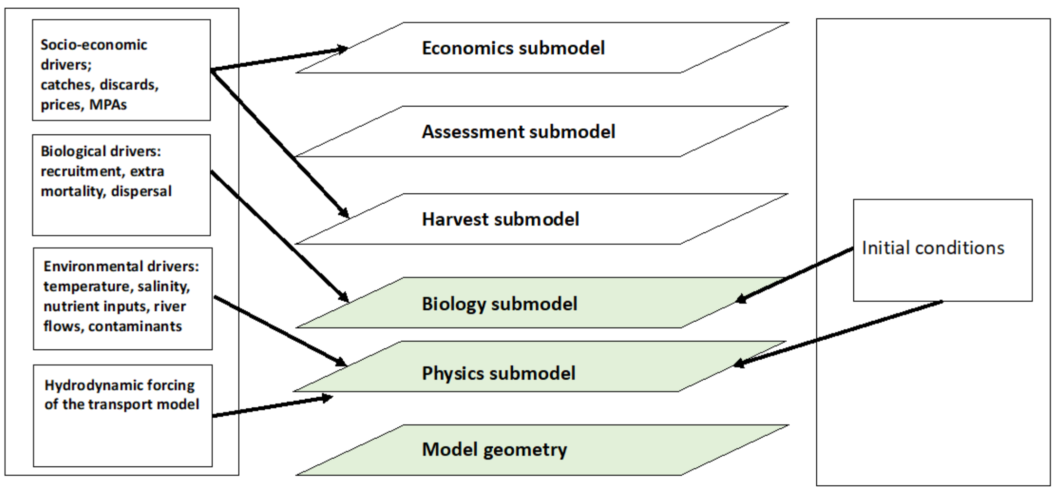


Figure 5. Modules in Atlantis. Light green is always turned on (for functionality), whereas those in white can be turned off/on after needs. NoBa has been run with the three green modules, in addition to the harvest sub-model. Box to the right shows where initial conditions are needed, drivers to the left.

In this study, the harvest module was included in addition to physics and biology. Atlantis includes the same bottom-up physical forcing as Norwecom.E2E for the period from 2006-2068. However, the model started with spin-up in 1981 (looping 1981 24 times), using two other applications of the ROMS model to cover the period until 2006 Hansen et al. (2019b). The model grid covers 4 million km2 by 60 polygons (Figure 3), which each have up to 7 vertical layers depending on the mean depth of the polygon. The version applied here included 53 functional groups and species, representing key components of the ecosystems in the Nordic and Barents Seas. These represented 'everything' from phytoplankton, bacteria, zooplankton to fish, seabirds and marine mammals (Figure 6).

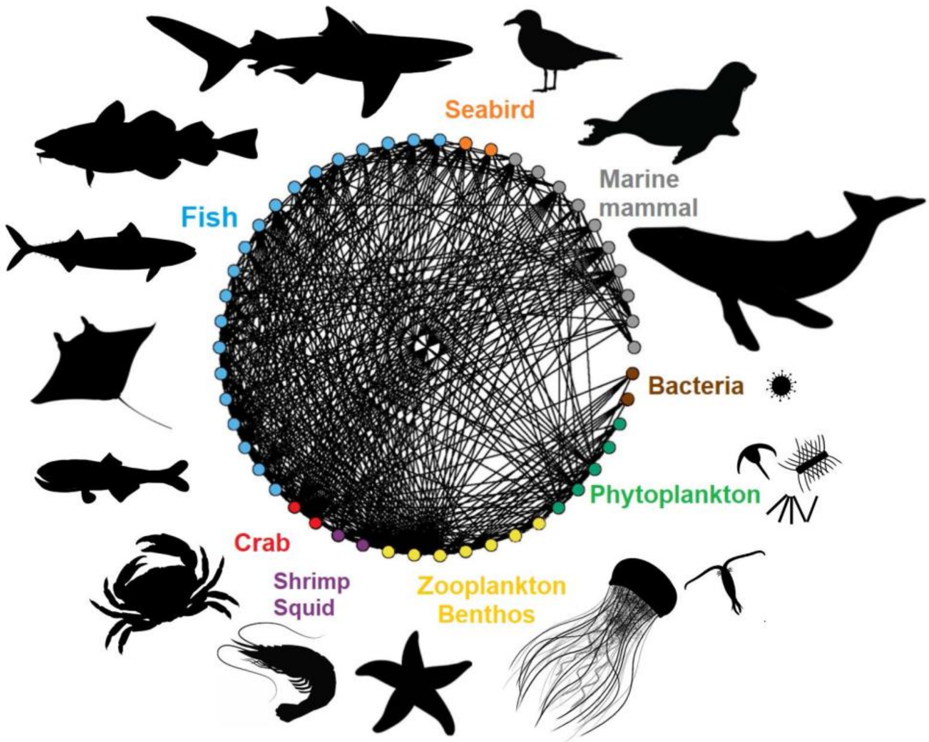


Figure 6. Diet matrix from NoBa Atlantis, displaying the complexity of the food web. Illustration by Ina Nilsen, IMR.

The components are coupled through a somewhat flexible diet matrix, where the prey availability for the predator is defined (Audzijonyte et al., 2017). Fisheries for the 12 components in the model that are harvested, were implemented as time series of fisheries mortality for the period from 1981-2017. From 2017 and onward, the fisheries followed a flat maximum sustainable yield (MSY) fishery, Fmsy, for a majority of the commercially important species, prawns, capelin and snow crabs being the only ones excluded from this strategy. In this study, 112 simulations were run (Hansen et al. 2019b). These were divided into eight different scenarios, defined by four different fractions of Fmsy (Fmsy x 0.6, 0.8, 1.0 and 1.1) and for each of these the number of components harvested were either a) currently harvested only ('comm only') or b) currently harvested + additional species ('all in'). Within each scenario there were 14 different simulations, each somewhat changing the mesozooplankton (perturbing growth rate of mesozooplankton according to the observed time series of mesozooplankton biomass in the Norwegian sea).

Among the additional five species were mesozooplankton and meso-pelagic fish, relevant to include because of a recent increased interest in harvest of these components. The additionally harvested components were fished at Fmsy calculated within NoBa from 2017 and onward, to avoid making changes in the historical period from 1981-2017. The changes in fisheries between the simulations provide us the opportunity to evaluate how the indicators were able to pick up differences in the harvest level or in the number of components that are being harvested.

2.4 Model results and evaluation

2.4.1 Long term trends of simple indicators

Some of the indices in the list proposed within the BSMP list can be directly estimated from the models. However, as the models differ in both state variables and processes, the available modelled indices will differ between them, therefore only some examples of modelled indices from each model are given below. In Figure 7 time series from the NORWECOM.E2E model are shown for the four Barents Sea domains.

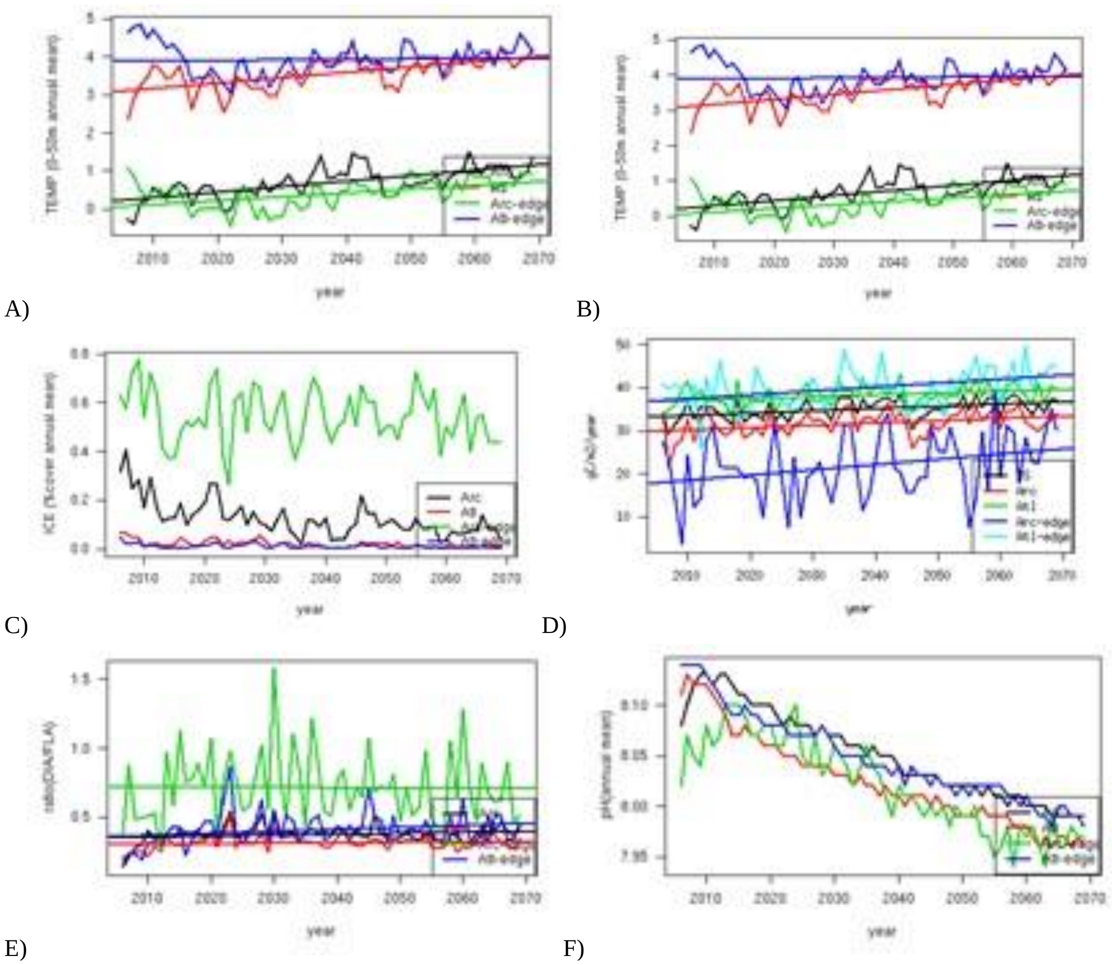


Figure 7. Time series for A) temperature (50-200 meters), B) freshwater height, C) ice cover, D) net primary production, E) ratio diatoms:flagellates and F) pH for the Arctic shelf, Arctic shelf edge, Atlantic shelf, and Atlantic shelf edge parts of the Barents Sea, from the NORWECOM.E2E model. All values are annual means, except net primary production, which is the annual depth integrated value. Figure from Hansen et al., 2021.

Abundance of juvenile herring and Greenland halibut and biomass of NEA cod were among the simple indicators defined by BSMP for higher trophic levels. The modelled projections of these three can be seen in Figure 8. Results from other model simulations by NORWECOM.E2E, on future distribution of commercially important fish species, can be found in the INTAROS data catalogue: https://catalog-intaros.nersc.no/organization/institute-of-marine-research-imr

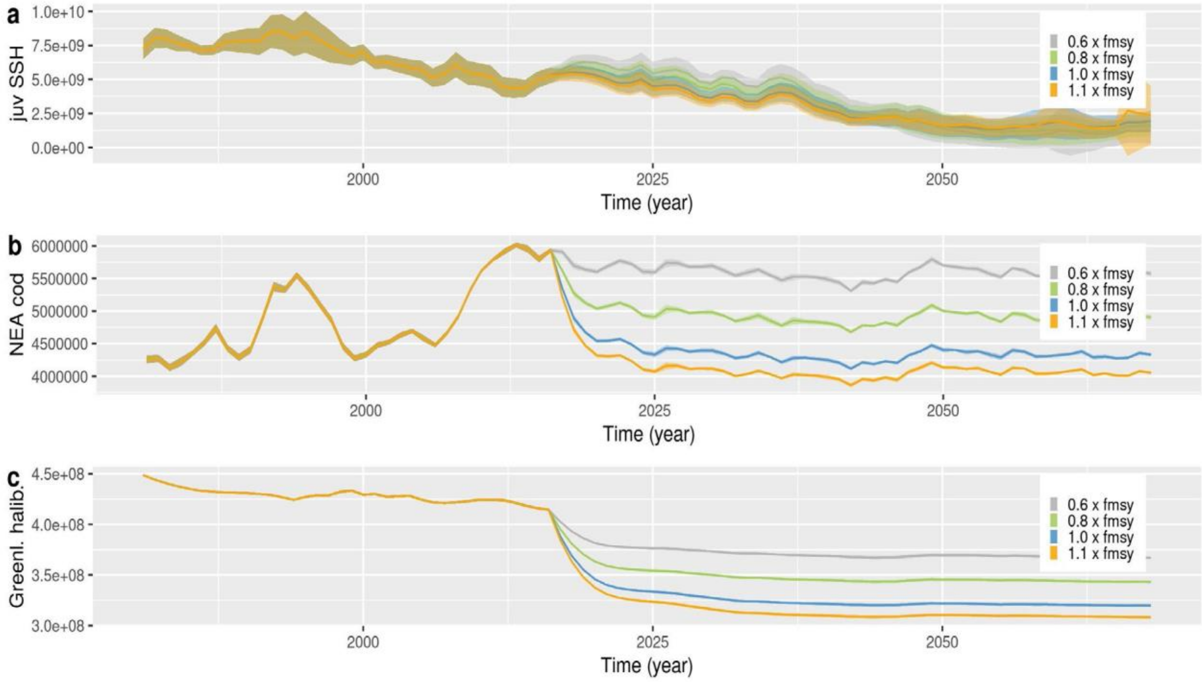
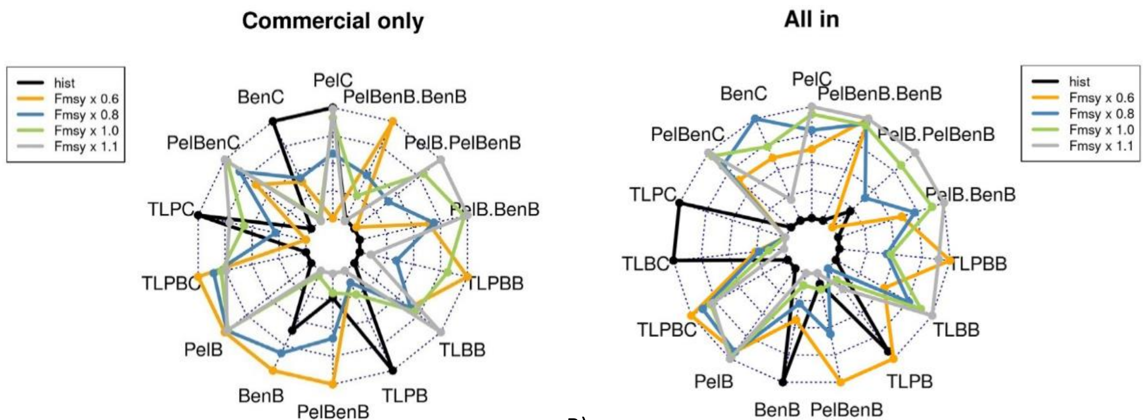


Figure 8. Simple indices for juvenile herring (a), northeast Atlantic cod (b) and Greenland halibut (c) for the period from 1981-2068. Shades represents one standard deviation across the 14 replicates of each scenario, whereas the solid line is the average across the simulations. Figure from Hansen et al., 2021.

2.4.2 Complex indicators

2.5.2.1 Biomass at different trophic levels

Using NoBa Atlantis, fluctuations in biomass between different trophic levels in the four different scenarios were studied. For the whole Barents Sea, there were little to no changes in the pelagic and benthic groups. However, due to the enormous zooplankton biomass in the pelagic group, the other two groups (benthic and benthic-pelagic) made up only a very small part of the total biomass (less than 5%). The bentho-pelagic group experienced a large increase toward the end of the simulation, for all scenarios. This was a result of the deep-water shrimps (prawn) and saithe biomass, potentially caused by a combination of climate (slight warming) and management settings. Figure 9 shows examples of indicator development for four scenarios.



A) B)

Figure 9. Indicators calculated for the historical time slice (2005-2015, in black), and for the future time slice (2055-2065) for the four scenarios. In A) the results from the scenarios only including the currently harvested species are displayed, while B) a show the scenarios including harvest on e.g., meso-zooplankton and meso-pelagic fish. The historical time slice is equal across all simulations. Indicators are all shown with maximum (best) value at the outer edge of the spider plot. The indicators shown include catches (C) and biomass (B) for the functional groups (Pel - pelagic, Ben - Benthic and PelBen - bentho-pelagic) and for the trophic levels (TL).

The low response to different harvest strategies found in these complex biomass-dependent indicators shows the importance of a *suite* of indicators, as suggested in the management plans. The commercial species are represented by abundance or biomass indexes, which easily pick up the differences in the harvest levels. However, any increased ecosystem vulnerability (Hansen et al., 2019b) is not evident from the suggested indicators, and it should be further discussed how this can be made clearer.

2.4.3 Optimal sampling strategy

When estimating the value of an index, one is often limited to available observations from existing monitoring programs. Regarding the validity of an index this is not necessarily the best approach, as one also should ask how many observations is needed to achieve an acceptable precision. The quality of observations is largely affected by the sampling scheme. Numerical models can contribute to the efficient design and optimization of observing systems for science and operational uses (e.g., Arnold and Dey, 1986). OSSE has been used to optimize monitoring programs and design observational networks in both coastal (Mey-Fremaux et al., 2019) and open oceans (Fu et al., 2011; Garcıa et al., 2019).
OSSE has successfully been conducted for the Barents Sea monitoring program. A similar OSSE for the Disko Bay as support to the newly established monitoring program GEM is planned and the approach can be applied to all areas with existing or planned sampling programs.

Using monthly mean outputs from the NORWECOM.E2E model the following question has been asked: *which polygon in which month is the best one to approximate the inter-annual variability in the full regional indices*. The answer to this question was approximated by comparing detrended annual time series to similar time series from each polygon and each month within a region.

2.4.4 Model evaluation of Barents Sea case

Using a future climate projection in the Barents Sea case, several indicator time series have been computed by two ecosystem models, NORWECOM.E2E and NoBa Atlantis, based on indicators suggested in the BSMP for the period 2000-2070. The present-day situation is in good agreement with published levels (Hansen et al. 2021).

Evaluating sampling strategies by means of an OSSE using the ecosystem models showed that it is possible to get a high degree of covariance between local monthly values to regional annual means with only a small observational effort. It also proved that there are many pitfalls from using arbitrary observations to approximate the same without any further analysis. For instance, we show that using temperatures from August in polygon 33 (which includes the Kola section; see Figure 3), gives a very good representation of the Atlantic part, better than the full year means of e.g., nearby polygons 30 and 41 (Figure 3). Temporally, this overlaps with the Barents Sea Ecosystem Survey, suggesting that these temperatures can be applied in the indicators, although for the Arctic area, the optimal timing for such a survey would be May/June.

A number of harvest strategies were applied in the NoBa Atlantis model analysis, increasing the fishing pressure from 0.6 to 1.1 relative to the maximum sustainable yield for a selection of species, both commercial and non-commercial (including mesopelagic fish and meso-zooplankton). We found only a low response to these harvest strategies in the complex biomass-dependent indicators. The simple abundance or biomass indexes easily picked up on these, showing the importance of a combination of complex and simple indicators.

3. Case off-Greenland

3.1 Description of case study area

About 60,000 people live in Greenland and most of them along the West coast. They are traditionally highly dependent on the marine ecosystem and Greenland's economy is presently strongly related to the productivity of the marine waters. With a changing climate regime, i.e. reduction in ice thickness, an increase in commercial fisheries is likely, but also offshore resource extraction. Increased shipping activities are also to be expected due to anticipated greater use of the Northwest Passage for shipping between the Atlantic and the Pacific (Christensen et al. 2012).

Disko Bay is located at the west coast of Greenland at the southern border of the Arctic sea-ice and is influenced by both sub-Arctic waters from southwestern Greenland and Arctic waters from Baffin Bay (Figure 10; Gladish et al. 2015). The large glacier Jakobshavn isbræ is found in the bottom of the bay.

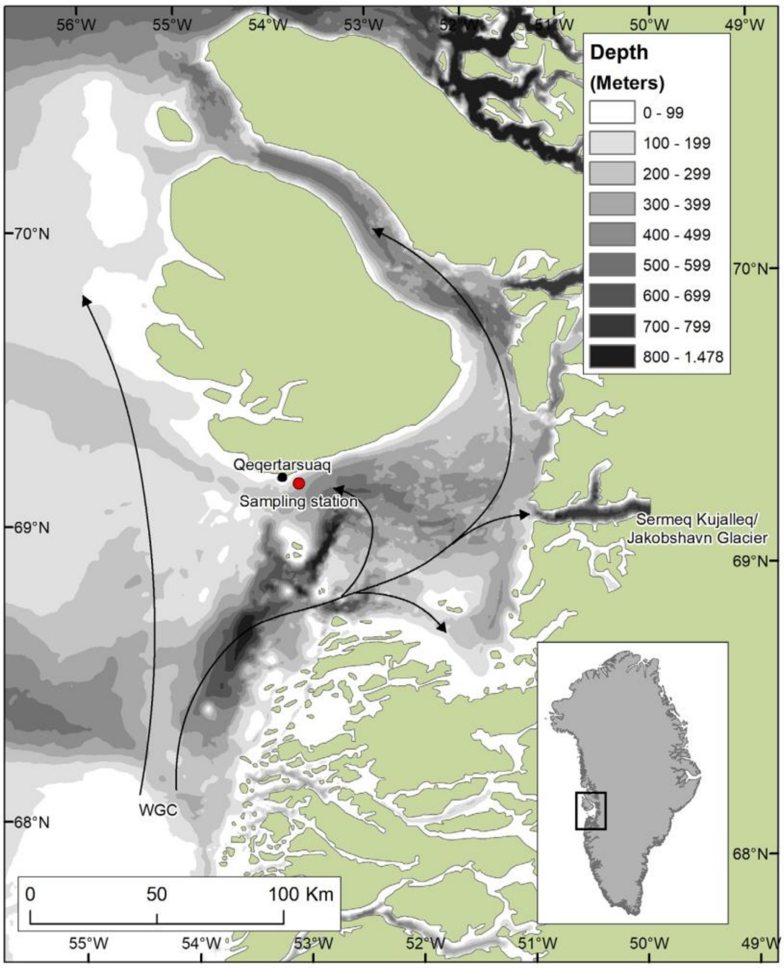


Figure 10. Map of the Disko Bay, the major pathways of the West Greenland Current (WGC), the position of the station of Qeqertarsuaq where most in situ data are available, and the bathymetry of the bay.

It has been estimated that about 10% of the total Greenland ice sheet (GIS) solid ice discharge occurs from this glacier (Mankoff et al. 2019), and that it drains about 5% of the GIS. Over the last three decades, Disko Bay has experienced a large decrease in sea ice cover; in addition, year-to-year variations have increased in the last decade (Hansen et al. 2006). This and other relevant data are available through the Greenland Ecosystem monitoring program at http://data.g-e-m.dk, and documented in the INTAROS data catalogue https://catalog-intaros.nersc.no/dataset/greenland-ecosystem-monitoring-programme . The change in sea ice conditions has been accompanied by a shift in the zooplankton community from Arctic to Atlantic species (Møller and Nielsen 2019). Disko Bay is an important "hot spot" for biodiversity and fisheries (Christensen et al. 2012), and one of the best studied areas in Greenland. Still, integration of physical measurements of oceanography, GIS discharge and the impact on the marine ecosystems has been limited.

There are no ecological models for Greenland coastal waters in place, whereas there are some global or Atlantic Ocean models with coarser horizontal resolution applied to open waters provided by the Copernicus Marine Ecosystem Monitoring Service (CMEMS).

3.2 Modelling of the Disko Bay

3.2.1 Hydrodynamic model

A coupled hydrodynamic and biogeochemical model for the Disko Bay area, West Greenland, was set up using the FlexSem model system (Larsen et al. 2020). FlexSem is a modular framework for 3D unstructured marine modelling. The system contains modules for hydrostatic and non-hydrostatic hydrodynamics, 3D pelagic and 3D benthic models, sediment transport and agent based models (https://marweb.bios.au.dk/flexsem).

The 96300 km^2 large computational mesh for the Disko Bay area was constructed using the mesh generator Jigsaw (https://sites.google.com/site/dengwirda/jigsaw) (Figure 11). It consists of 6349 elements and 25 z-layers with a total of 76464 computational cells. The horizontal resolution varies from 1.8 km in the Disko Bay proper, 4.7 km in Strait of Vaigat and 16 km towards the semi-circular Baffin Bay open boundary. In the deepest layers, the vertical resolution is 50 m, decreasing towards the surface, where the top 5 layers are 10 meters thick. The model has been run in yearly setup for the period from 2004 to 2018.

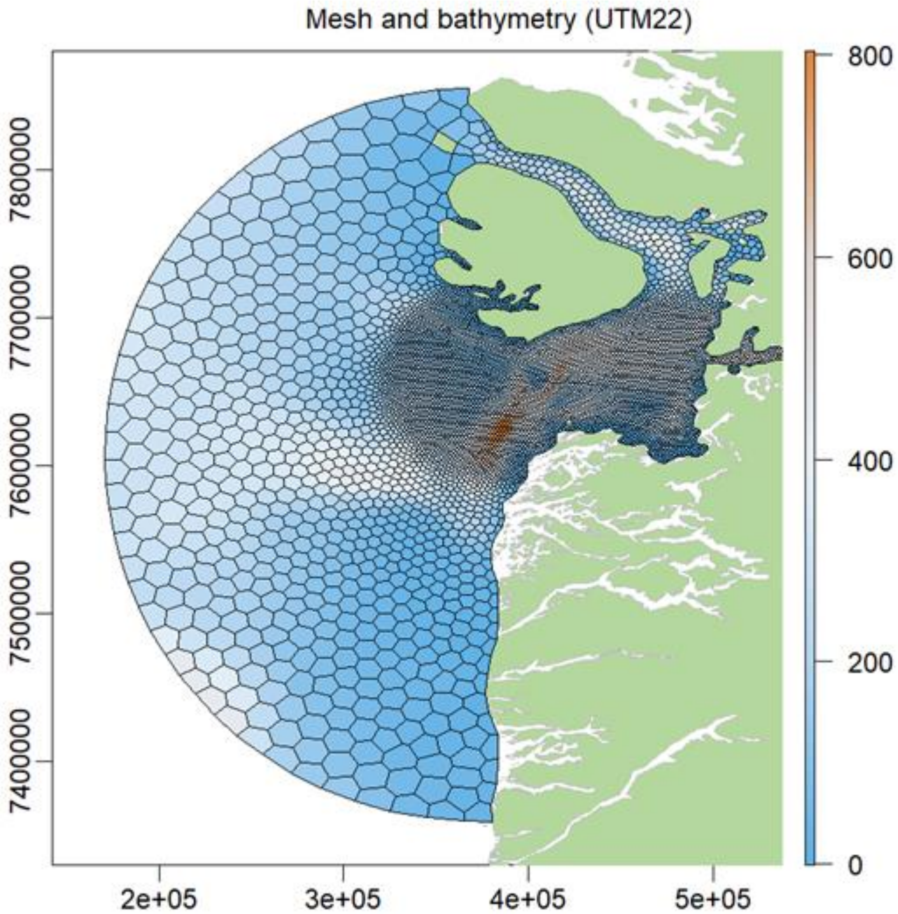


Figure 11. Computational mesh (polygons) and bathymetry for the Disko Bay area. Bathymetry is interpolated from the IceBridge BedMachine Greenland (Version 3) bathymetry and shown in colors.

3.2.2 Biogeochemical model

The biogeochemical model ERGOM was coupled to a 3D hydrodynamic module in the FlexSem framework. ERGOM simulates the cycling of nitrogen (N), phosphorous (P) and silicon (Si) and was originally applied to the Baltic Sea and the North Sea (Neumann 2000, Maar et al. 2011, Maar et al. 2016). The 11 state variables describe concentrations of four dissolved nutrients (NO_3, NH_4, PO_4, SiO_2), three functional groups of phytoplankton (diatoms, flagellates, picoalgae), micro- and mesozooplankton, detritus and oxygen (Figure 12). The model considers the processes of nutrient uptake, growth, grazing, egestion, respiration, recycling, mortality, particle sinking and seasonal mesozooplankton migration in the water column and overwintering in bottom waters.

The pelagic ERGOM model is two-way coupled to a sediment biogeochemical model through sedimentation and resuspension of organic matter and diffusive fluxes of nutrients and oxygen (Petersen et al. 2017). Pelagic detritus and diatoms sediment into an organic detritus pool and a dead diatom pool, respectively, in the unconsolidated top layer of the sediment (Figure 12). Organic matter in the unconsolidated sediment can be resuspended, respired or gradually transferred to the consolidated sediment layer.

Recycled nutrients (NH_4, PO_4 and SiO_2) in the sediment porewater are exchanged with the bottom water through diffusion and a fraction of the recycled NH_4 is lost in a coupled nitrification-denitrification process. Under oxidized conditions, PO_4 and SiO_2 are retained in the sediment by adsorption to metals and released, when the sediment becomes reduced. Benthic suspension feeders ingest phytoplankton and detritus in the bottom water, whereas deposit feeders ingest freshly deposited diatoms and detritus in the sediment. The pelagic- and benthic model parts were previously validated for the Baltic Sea - North Sea area (Maar et al. 2011, Maar et al. 2016, Petersen et al. 2017, Maar et al. 2018).

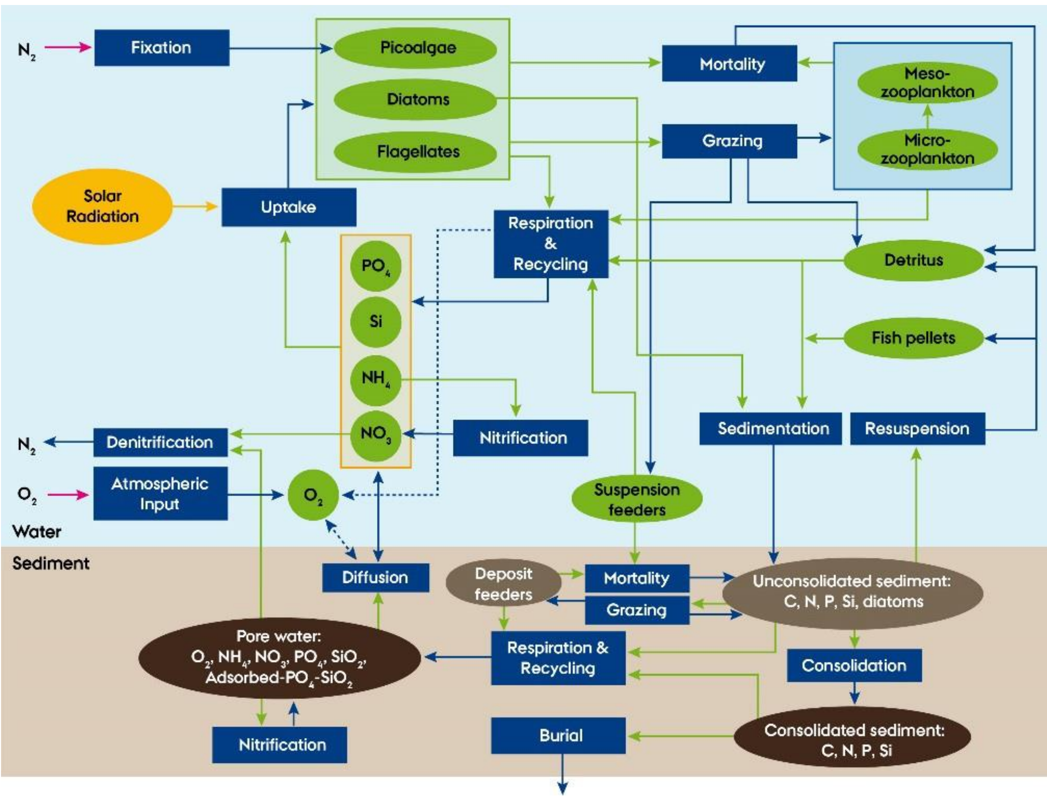


Figure 12. Model diagram showing the pelagic (green circles) and benthic (brown circles) state variables and associated fluxes (blue boxes) in the ERGOM model. The model diagram was modified from Maar et al. (2018) by exchanging cyanobacteria with picoalgae.

3.3 Use of the INTAROS iAOS data catalogue and other data to support model development

3.3.1 Hydrodynamic model forcing data

The150x150 m resolved *IceBridge BedMachine Greenland*, Version 3 bathymetry was downloaded from the website https://nsidc.org/data/IDBMG4 and interpolated to the FlexSem computational mesh using a distance-squared approach. The obtained bathymetry is shown in Figure 11. Meltwater run-off from the Programme for Monitoring the Greenland Ice Sheet (PROMICE) was provided by the Geological Survey of Denmark and Greenland (GEUS) and used for freshwater input (Mankoff et al. 2020). The freshwater input is estimated as 'ice runoff = melt + condensation - evaporation + liquid precipitation – refreezing', whereas precipitation, land runoff and solid ice (ice bergs) are not considered. The data set was cropped to the Disko Bay area, where 235 point-sources were located. The 30 largest of these sources provide 95.7% of the total freshwater input and they were aggregated into point sources at 14 locations, distributed throughout the model domain.

At the semi-circular open boundary towards the Baffin Bay, the model was forced with velocities, water level, salinity and temperature obtained from the HYCOM-CICE model provided by the Danish Meteorological Institute (DMI) (). The DMI HYCOM-CICE set-up covers the Atlantic, north of about 20°S and the Arctic Ocean, with a horizontal resolution of about 10 km. The model uses data assimilation in the surface for temperature from daily remote sensing data. Model results from the HYCOM-CICE model are also available through the Copernicus MEMS data portal on a 12.5x12.5 km grid.

However, here data is only available as daily means in the period 1991 to 2018 and as hourly instantaneous from 2016 to present. Daily means are not suitable as open boundary forcing and from 2016 and onwards, the vertical resolution is coarser in the CMEMS product that in the original HYCOM-CICE output that was provided by DMI. The 2D (water level) and 3D parameters were interpolated to match the open boundary in the FlexSem Model setup using a distance square interpolation. Correspondingly, initial fields of temperature, salinity and water level were interpolated from the HYCOM-CICE model output. At the surface, the model is forced by wind drag and the surface radiance model by 2 m atmospheric temperature, cloud cover, specific humidity and ice cover. The atmospheric forcing was also provided by DMI from the HIRLAM and HARMONIE meteorological models. Ice cover was obtained from the HYCOM-CICE model output.
The ice cover percentage modifies the wind drag, heat balance and light penetration in the model.

3.3.2 Biogeochemical model forcing data

Initial data and open boundary conditions for ecological variables were obtained from the HYCOM-ERSEM model at NIVA Norway. The ERSEM model provided nutrients (ammonium, nitrate, phosphate, silicate), oxygen, detritus (small, medium and large fractions), 6 groups of phytoplankton and 3 zooplankton groups. The picophytoplankton and synechoccous functional groups from ERSEM were added to the picophytoplankton group in ERGOM, the nano-, micro-phytoplankton and prymnesiophytes were added to the autotrophic flagellates in ERGOM and diatoms were the same in both models. The detritus in ERGOM was the sum of the three detritus size fractions in ERSEM. The ERSEM data was provided as weekly means on a 1°grid (112 km lon and 40 km lat) and linearly interpolated to the FlexSem grid.

Nutrient inputs from land/ice were obtained from literature values. For model validation, it is possible to use data from the Greenland Ecological Monitoring (GEM) program, which was established in Disko Bay in 2016. The GEM database currently contains publicly available data from only 2018, however, data from 2016 and onwards are expected to be available in the near future. The ICES database has reported data from sporadic monitoring cruises in the area, but there has been no consistent monitoring before 2016. Research data has been collected during short-term field campaigns at the Disko Bay station 69° 14’ N, 53° 23’ W from 1992 to 2012 (Møller and Nielsen 2019). A monthly climatology was calculated based on these research data and the GEM data from 1992 to 2012 and used to verify the model results for periods with few or no observations.

3.4 Model results and evaluation

The Disko Bay FlexSem-ERGOM model was specifically developed in the project as a starting point for Greenland coastal modelling and the first model validation results are shown for some selected dates and variables. CTD profiles of temperature and salinity from the area were downloaded from the ICES oceanographic database. The hydrodynamic model was validated against a monthly climatology for the station near Qeqertarsuaq south of Disko Island for the years 1992-2012. Surface temperature and salinity showed good agreement with the seasonal development according to the climatology (Figure 13). Further, the model was compared with selected vertical profiles of temperature and salinity. Initially, the model was run with a simple Fick’s law heat exchange at the surface, but as this proved unable to reproduce the vertical temperature profile, a full surface radiation model forced with wind speed, cloud cover, specific humidity and ice cover was added to the setup. The vertical temperature profiles were improved considerably in comparison to CTD data, when including this surface radiation model with the extra forcing. However, there is still some underestimation of bottom temperature and salinity probably due to the bias in the open boundary data from HYCOM-CICE.

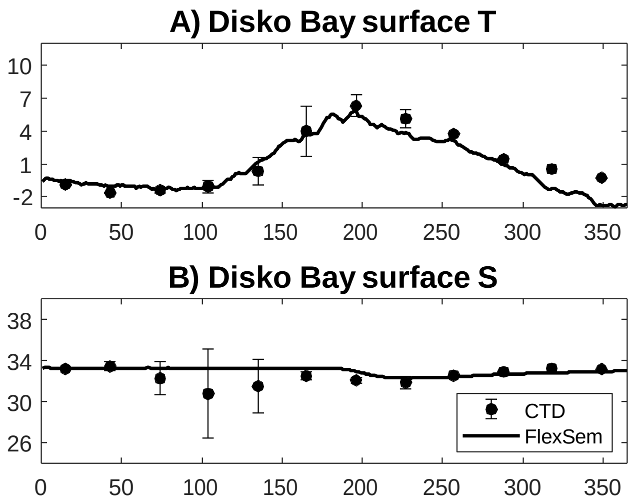


Figure 13. Time-series of A) surface temperature and B) salinity during from CTD data (means±SD: 1992-2012) and FlexSem (2004) from a station near Qeqertarsuaq south of Disko Island.

The ecological model was validated for available data on surface nitrate, phosphate, silicate, Chl *a* and meso-zooplankton biomass from the Disko Bay station year 2004 using monthly climatology data from 1992 to 2018. There was a good agreement for seasonal surface nutrient- and Chl a concentration (Figure 14). The spring bloom was initiated in April followed by nitrate depletion. Ammonium, phosphate and silicate showed less depletion than for nitrate and silicate was overestimated by the model during summer. Meso-zooplankton appeared in surface waters from April and peaked between May and June in agreement with observations (Figure 14).

ERGOM was applied to the Disko Bay set-up with a few changes (picoalgae, Calanus copepods, background light attenuation) applicable to Arctic waters. The first results showed overall good agreement with climatology data for the period from 2004 to 2018.

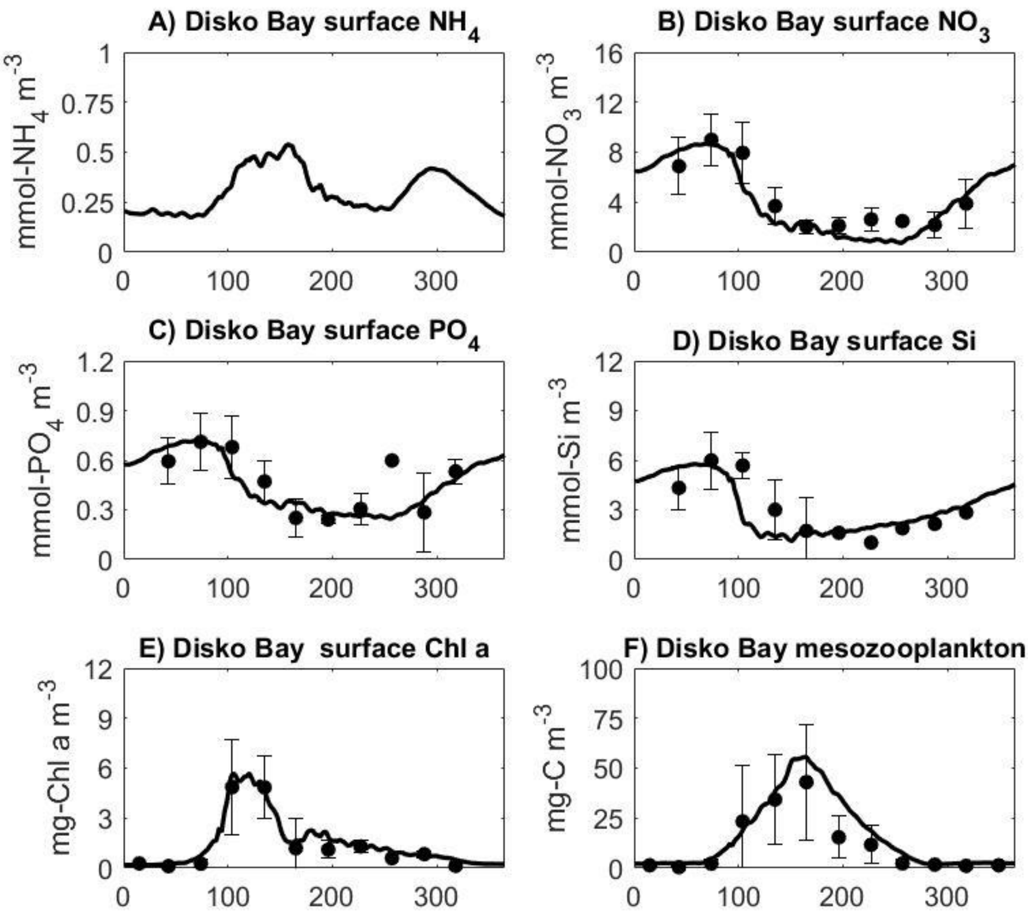


Figure 14. First results from ERGOM 2004 showing the seasonal development (days on x-axis) of A-D) nutrients, E) Chl a and F) microzooplankton and mesozooplankton south of Disko Island plotted against monthly climatology data from 1992-2018 (means ±SD).

3.5 Conclusions for off-Greenland case

The model applied for the Greenland case, Disko Bay, is the first local-scale, ecological model for Greenland marine coastal waters using available forcing data. The model resolved the Disko Bay with a high horizontal resolution (down to 1.8 km) in comparison to the regional models providing the open boundary data, which had a resolution of 10 km for physics and 40 km for ecology. The sea surface temperatures were improved in FlexSem by implementing a full surface radiation model forced with model data of wind speed, cloud cover, specific humidity, and ice cover. Freshwater inputs were improved by including state-of-the-art data of meltwater run-off from PROMICE. The model showed in general good agreement with vertical profiles of temperatures and salinity, except for the bottom values, which generally were underestimated for both HYCOM-CICE and FlexSem in comparison to CTD data.

The biogeochemical model ERGOM was applied to the Disko Bay set-up with a few changes (picoalgae, Calanus copepods, background light attenuation) applicable to Arctic waters. The first results showed overall good agreement with climatology data for the period from 2004 to 2018. The model was used to evaluate the impact of sea ice and freshwater discharge from the Greenland ice sheet on the primary productivity. It showed that under the current climate, glacier runoff has a strong local effect but for primary productivity at bay scale, sea ice cover is most important. The experience from the Disko Bay study will help to expand ecological modelling into new areas along the Greenland coastline as support for management and research.

4. Results from stakeholder interaction

4.1. Stakeholder requests and requirements

We here summarize information arising from interaction with participants in the two stakeholder workshops, for respectively the Barents Sea and coastal Greenland (Maar et al. 2021). Table 1 presents the requests from stakeholders to science, grouped into six main categories.

Table 1 Requests from stakeholder participants at INTAROS' workshops relating to data and model output. The requests are grouped into four main categories and colour-coded accordingly: Data quality, Data accessibility, Data relevance, Sharing of data and knowledge, Combining observational and model data, and Other types of data.

Request	Stakeholder	Category
Ensure the data sources are the best available	Norwegian Environment Agency (NEA)	Data quality
Monitoring the simple indicators that are actually used	NEA	
To continue the long-term data series and include more variables to inform management and research activities	Norwegian Directorate of Fisheries (DoF)	
Recommend that all observational data sets, model results and products coming from INTAROS work and analysis and relating to Norwegian Economic Exclusive Zone, are registered at the Norwegian Marine Data Centre (NMDC) and/or Geonorge for easy access.	Norwegian Mapping Authority (NMA)	Data accessibility Data accessibility
Seek to find ways to build on the INTAROS deliverables and outcome, also after the termination of the projects. Find ways to get the results from INTAROS included in the future merging of established, planned and developing indicators	NEA	
It is important to keep a critical view on the model results and to explain model uncertainties to stakeholders	Greenland Institute for Natural Resources (GINR)	
Suggests that observational data, model output and other products of the INTAROS tasks are made available and kept according to the FAIR principles.	NMA	
Make sure that you get a starting point that people can understand. E.g., pull out some concrete examples.	Sustainable Fisheries, Denmark (SF)	Observations/ model output relevance
If no objectives or the like have been set, it is difficult to use the model's options. If it is not concrete, it can easily be marked by knowledge for the sake of knowledge. Ensure sufficient input from the political / manager side.	SF	
The models and conclusions are focused on climate and fisheries impact. Could further model analyses include indicators that may be guidelines also other human impacts? Is it possible to look at the common impacts of more than one activity at a time?	NEA	
Ensure good interaction between stakeholders (in my case the fishing industry) and researchers. This can, for instance, be through PhD studies linked to industry/management	SF	
How to connect these fisheries-based analyses to other human activities? It is and will be a growing conflict of area use conflicts between sectors, also including shipping.	Norwegian Coastal Administration (NCA)	

Request	Stakeholder	Category
In general, models could provide more knowledge and more knowledge should reduce the risk of cross-sectorial conflicts and unresolved questions.	NCA	
More insights into collaboration between sectors would be useful	DoF	Sharing of data and knowledge
The Arctic Council has for years worked in this field of issues, as in CAFF (Conservation of Arctic Flora and Fauna). A comparison of this work to the sections integrated in INTAROS would be useful to look for synergy and shared information.	NEA	
Comparisons on OSPAR and same-topic Norwegian indicators, could be made.	DoF	
Important to work towards aggregated indicator analysis, like in the Baltic Sea, OSPAR and other international activities	NMA	
INTAROS should look not only at national management tools, but also include international indicators, used by international organization like OSPAR. Can OSPAR indicators be analysed in models and compared to the established Norwegian indicators? When changes are suggested to move from the national indicators to international indicator sets like EFMD and OPSAR, will such changes be beneficial or not? How is the scientific monitoring and management set up to meet such changes? It would be inefficient and costly if Norway should report by two sets of ecosystem indicators, with overlapping intensions.	NMA	
The National Surveillance Group, reporting on the state of Norwegian open seas, are to be informed about the OSPAR indicators and the coming Quality State Report 2023.	NMA	
INTAROS and other projects are encouraged to either participate or ensure that their results flow to relevant ICES Integrated Ecosystem Assessment Working Groups since the ICES condensation of information for an ecoregion is a well-established and routinely advice flow to stakeholders (and the scientific community).	Technical University of Denmark	
More work by modelers to show usefulness for manager would be welcome.	DoF	Combining observational data and model output
More effort and focus on combined data. It was pointed at that the present status reports on the ocean ecosystem mainly are based on single data series, stocks, pollution s, etc.	NEA	
NEA and others have requested ecosystem modelling for a long time.	NEA	
The use of models may find some indicators being less valuable than others, may turn about to be very valuable later on if the ecosystem or climate changes are getting severe.	NEA	
With increased shipping, it will be an increase in pollution risks and actual pollution. Pollution issues should be considered for future model analyses	NCA	Other types of data
There are 40 different components listed as pollution indicators in the Norwegian marine management plan, incl. BSMP; that can be included	Norwegian Maritime Authority	

4.1.1 Further specific ideas from stakeholders

Monitoring:

- To continue the long-term data series and include more variables to support and help improve on management measures and research activities

Research and ecosystem modelling:

- To continue research on processes and improve understanding of food web interactions
- To continue developing more complex models in the same way as for the Barents Sea to inform managers on food web interactions and potential future changes in stocks, productivity, etc.
- To better integrate monitoring programmes and modelling
- To run comparative tests, by analysing among others, Joint Norwegian/Russian Environmental Commission, OSPAR, Arctic Council indicators alongside with Norwegian-developed indicators.
- To develop and run model scenarios to study climate effects
- To consider including more human impacts and societal indicators in the models.

Collaboration and sharing of information

- To have a special session at the Greenland Science week
- To arrange or join smaller stakeholder meetings with a more targeted focus or question, e.g., on a particular species, impacts of climate change, model uncertainty, etc.
- To collaborate more with existing working groups (ICES, CAFF) and, concretely, establish new NAFO (North Atlantic Fisheries Organisation)/ICES working group on the west Greenland-Canadian system.

5. Extension of ecosystem management systems to other parts of the Arctic

5.1 *Data requirements (minimum)*

The Greenland case was chosen to test how a data-poor region still may benefit from ecosystem modelling if a minimum of data requirements is met. For the extension of the coastal Greenland modelling to new areas, the main identified obstacle is to get good forcing data, especially for the ecology. The Copernicus MEMS products have horizontal resolution of 12 km for physics but could only provide daily means (and not instantaneous values) from 1992 to 2016. For ecology, the CMEMS model product could provide data on a 25 km grid, but for few simulated years (2007-2010) and few variables (Chl-a, nitrate and phosphate). In the Disko Bay set-up, it was possible to obtain open boundary data with higher temporal and spatial resolution for physics, more ecological variables and more years through personal contacts within the INTAROS project, but those data are not yet open access. Further, there are few spatio-temporal observations of ecological variables, and the available data was compiled into a monthly climatology for model validation. The newly established GEM program in Disko Bay will probably help to resolve this problem and it is expected that there will be a good synergy between the developed ecosystem model FlexSem-ERGOM and the GEM in closing existing data gaps. The Greenland meltwater run-off from PROMICE data was used to provide freshwater input to the marine model and was provided by GEUS. It is expected that the developed Disko Bay ecological model can be transferred to other Greenlandic fiord and coastal systems, e.g., the Young Sound system included in the GEM program.

5.2 Expanding to include model output

Observation-based marine ecosystem data are often scarcely resolved and may not cover the whole seasonal cycle, year-to-year variability or the whole 3D spatial domain. This is because they often are based on few data points or transects from monitoring cruises conducted during a limited period. Continues sampling devices can provide data with high temporal resolution, but not spatially, and have problems during periods with ice cover. Models can on the other hand provide cheap and intelligent interpolation between monitoring data and extrapolation to larger areas and periods (Skogen et al. 2021), as well as spatially explicit forecasts at different time scales (daily to decadal).

Models can further quantify biogeochemical processes that are difficult to measure. Monitoring programs are often focused on measuring concentrations (e.g., nutrient concentrations, plankton biomass, fish stocks) rather than food web fluxes. The only rate that is routinely measured in some areas is primary production, whereas research cruises also provide sporadic data on e.g., copepod egg production, grazing rates, growth rates and sedimentation rates. However, it is not possible to measure all fluxes in a food web and to resolve the emergence of trophic responses fully and more realistically in the plankton community. Therefore, coupled hydrodynamic-biogeochemical models are required (Maar et al. 2018). The models can e.g., be used to evaluate feeding strategies (e.g., prey selection and food quality) and how this affects nutrient cycles, to estimate the fate (respiration or burial) of carbon sequestration in the food web, to estimate the controlling factors for productivity and to estimate cascading effects in the food web due to changes in mortality of higher trophic levels. Therefore, models and observations should be used closer together to generate synergies, and to allow a better support for science and management (Skogen et al. 2021).

5.3 Application within INTAROS of models to ecosystem-based management

Modelling products are more and more being generated and made available for free download, for example through the Copernicus Marine Environment Monitoring Service (CMEMS) home page. However, undigested modelling products are often gridded big data sets of several terabytes and not directly useable for stakeholders. Thus, it is mainly the scientific community that uses the data. An important part of the modelling work is to translate model results into useful tools for stakeholders, create digested products like ocean state reports and to communicate strengths, weaknesses and opportunities of models and observations. Model components can be used to evaluate the status of the ecosystem and detect/predict changes in ecosystem components, which is useful for ecosystem-based management of marine areas. Models can also be used to design and evaluate observational campaigns and monitoring systems and used to identify ecological key areas.

Models can perform scenarios of environmental and climate changes in order to predict the future conditions of the marine ecosystem processes (e.g., productivity) and key components (e.g., fish species). If the model results are aggregated into maps, time-series or other easily understandable products or services, they can be used to interact with stakeholders and local populations to increase awareness and support management decisions. For example, the FlexSem-ERGOM model is the first biogeochemical model for Greenlandic coastal waters and since these ecosystems to a large extent are unexplored, the modelling can give insight into the functioning and potential future changes of the different types of ecosystems with respect to e.g., productivity, zooplankton migration, carbon removal, pollution and biodiversity. The NORWECOM.E2E model combines the physics and lower trophic with detailed models of key species, and can be used to e.g., quantify food web fluxes and processes that are hard or impossible to measure, and through a module for fishing, to investigate ecosystem effects of, e.g., a zooplankton fishery. NoBa Atlantis takes it one step up, including the links between the physics and all the way to the higher trophic levels. It provides the opportunities to explore the cumulative effects of climate and fisheries, and to evaluate processes that are difficult to assess, such as indirect predator-prey relationships.

6. Concluding Remarks

So far, to our knowledge, no ecosystem models have been incorporated in assessments for use in ecosystem management systems for any Arctic region. The main **exploitative value** of our work is that we show concretely that this would be a useful addition to the extensive use of observational data and indicators in the Norwegian Barents Sea environmental management system, and more locally for Disko Bay in Greenland. Further, we provide a foundation for how this observation and model practice may be **exploited** by expansion into other parts of the Arctic.

The scientific modelling work gains from interaction with stakeholders from management, industry and policy. However, models also need observational data for forcing, calibration and validation, and depend upon continuation of existing time-series and monitoring programs. Both models and observations are needed to get a holistic overview of the ecosystem status and to make reliable model projections. As the models get more advanced, complex food web interactions can be resolved and multi-pressure scenarios can be conducted.

Some **recommendations** for designing a system of indicators based upon our findings: Simple copying the same indicators from one region to another may miss out key information on ecosystem components in the “new” region. In the worst case, it may give faulty signals of the ecosystem state (Coll et al.2016). Very often some monitoring programs already exist in an area, and to be able to continue these operational time series, a convenient solution is therefore to just establish the new indicators based on these. Even if this seems cost-effective, old monitoring systems are not necessarily designed to meet the purpose of the new indicator time series, and the representation error of a monitoring program is usually unknown. Therefore, before an observational system is decided on, a model based Observing System Simulation Experiment should be performed based on the purpose to be met by the indicators. Only after such an exercise, a well-designed and cost-effective observational system can be established. A system of indicators should consider all available data sources, including in situ and remote sensing observations, and model results.

Our stakeholders generally found that model results are useful, but that model uncertainty should be clearly communicated. We provide new information on how stakeholders want to be informed, and what kind of information they seek. We can conclude that the stakeholders we have interacted with are not negative to inclusion of well tested models in future ecosystem state and trend reports. Hence, there is a basis for in the future to apply models in the preparation of advice for ecosystem management. However, some **recommendation** through cautionary advice is also deduced:

- Beside biological and physical parameters, data on the most important anthropogenic pressures should be monitored, to provide long times series with sufficient spatial resolution. The requirement of observation data continuity necessitates long term funding, political commitment and prioritization.
- The models should be based on input data with known uncertainty, tested and validated as sufficiently reliable. Modelling premises, like technical descriptions and validation results should be readily available and fully transparent.
- Models, like observation-based data, must be found relevant for, and appropriate to inform managers and other users on ecosystem drivers and interactions.
- The communication between modelers and managers established during the project period should be continued to improve model products and the confidence in model results. The interaction should be

consolidated with a regular cycle where user needs are turned into research funding opportunities.

Acknowledgements

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