Final Report for Project **1108**
Project title: **MiMeMo**
Principal investigator: **Ute Daewel**
Report period: **July 1, 2019 - June 30, 2022**

Summary

The Arctic is one of the regions most affected by climate change. Rapid warming and sea ice retreat affect not only marine mammals but the entire ecosystem and may lead to a restructuring of the Arctic food web. Mathematical models offer a way to estimate possible climate-related changes in the marine ecosystem and to identify management options in advance. The aim of the MiMeMo project was to quantify changes in spatial and seasonal patterns of biomass, production and fishery yield under climatically changing conditions using two differently structured mathematical models of the Arctic food web. This was done by using the models to test the hypothesis that environmental changes associated with climate warming lead to a bottom-up determined trophic cascade from a) increasing primary production, to b) increasing zooplankton production, to c) increasing fish and benthic production and, associated with this, increasing fisheries potential, to d) an increase in marine mammal population. Furthermore, the project investigated when and where in the future, under warmer, ice-free environmental conditions, maximum concentrations of algae, zooplankton, and fish are likely to be expected as feeding hotspots for higher trophic levels.

A series of simulations were performed with the developed model systems to address the two key questions associated with the above hypotheses.
i. How do the spatial and temporal patterns in the region's primary production change? To this end, SCHISM-ECOSMO-Polar hindcast simulations for the period 1991-1999 and sensitivity experiments on the role of sea ice biogeochemistry were performed using the model systems developed in the project.
ii. What changes in the marine food web can be expected under future climate conditions? For this purpose, both models were configured to represent the Barents Sea ecosystem for a past (2011-2019) and a future time period (2040-2049), with the necessary boundary data coming from the global biogeochemical model NEMO-MEDUSA. For the future simulation, the rather extreme IPCC emissions scenario RCP8.5 was used, for which the global model predicts that the nearshore waters of the Barents Sea will be 2°C warmer and nearly ice-free year-round by the late 2040s. The two models are consistent with historical observational data and provide consistent predictions of how the lower trophic levels of the food web will be affected by the changes.

The following key results emerge from the simulations:

Regarding question i)
- From simulations with high spatial resolution model system SCHISM-ECOSMO-Polar, it appears that the progressing "Atlantification" of the Barents Sea leads to a redistribution of production patterns, with increasing production in the southern Barents Sea.
- The decrease in sea ice cover generally leads to an increase in production in the region due to the improved light conditions. However, the simulation results also indicate that the highest primary production occurs in years with thin ice cover and early onset of ice melt, while being lower again under ice-free conditions.
- Consideration of sea ice biogeochemistry is leads to a change in production distribution along the ice edge in the simulation and should not be neglected in ecosystem simulations of the Arctic.

Regarding question (ii).
- Both models predict that the combined effects of the expected physical, oceanographic, and biogeochemical changes will result in an increase in annual net primary production of about 5%.
- The StrathE2E model predicts an increase of more than 50% in the average annual biomasses of planktivorous and demersal fish, seabirds, and cetaceans. However, declines are predicted for finfish and especially marine mammals (polar bears) that depend on sea ice habitats.
- Maximum sustainable yield (MSY) and corresponding fishing mortality reference points (FMSY) are projected to increase by a factor of about 2.1 for groundfish and 1.5 for planktivorous fish in the 2040 scenario compared to 2010.
- Both models show that expectations of future ecosystem and fishery health in the Barents Sea are more complex than we might expect based on simple extrapolations of historical time series. The expected changes in ice extent have profound implications for those groups that are highly dependent on the ice, and there are cascading consequences for other groups.
- In principle, the originally formulated hypothesis of a 'bottom-up' determined trophic cascade under changing climate conditions in the Barents Sea could be confirmed.

1 Model Development and validation

Hereon's focus was on the development and application of SCHISM-ECOSMO-Polar (Fig. 1). Overall, model development was carried out in WP 2-3, hindcast simulations and sensitivity experiments on specific influences on ecosystem production in the region were carried out in WP 4, and finally comparative future scenarios were carried out in WP 5. The project was carried out in a bi-lateral collaboration with Strathclyde University (SU) and the University of St. Andrews (UStA) under the Changing Arctic Ocean (CAO) program.

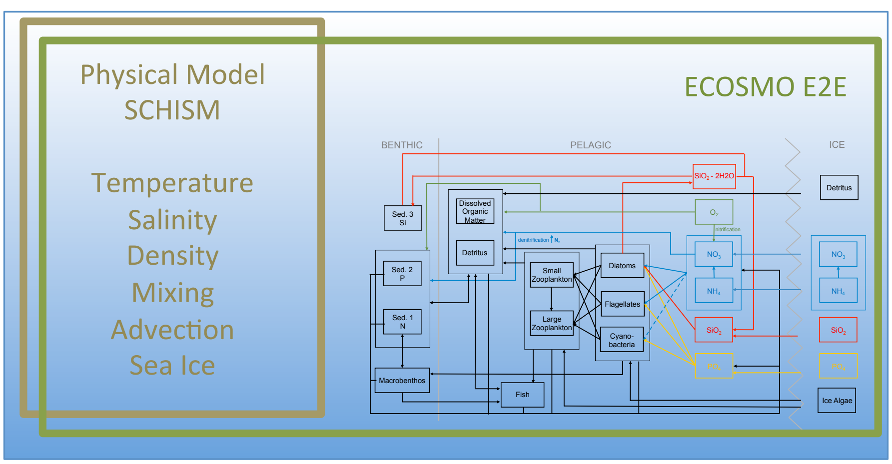


Abbildung 1: Modelstruktur des Geplanten SCHISM-ECOSMO-E2E Modelsystems.

2 Implementation of the physical model SCHISM

For the planned model simulations, the circulation model SCHISM [1] was first implemented in the Barents Sea/Fram Strait region (Fig. 2.1). SCHISM is a three-dimensional, baroclinic physical model based on unstructured grids that has been tested and validated in a number of applications. The unstructured model grid allows optimal resolution of the study area, which is independent of grid convergence in spherical coordinate grids or refinements in curvilinear grids. For vertical resolution, a hybrid coordinate system was developed in SCHISM (LSC[2]; [1]), ranging from sigma coordinates in flat areas to geopotential

coordinates. SCHISM is coupled to ECOSMO [2] via the FABM framework [3], which allows flexible extension of the ecosystem model component to meet the needs of this project.
The model uses an unstructured model grid based on finite volumes with a resolution of about 5km - 50km. The advantage of this model structure is that it allows for higher resolution in shallower, coastal regions without increasing the number of grid points and thus computational time in the overall region (Fig. 2.1). The model computes currents, density, tides (coupling to the GOTM turbulence model), ice cover (coupling to the FESIM [4] sea ice model), and the light climate needed for the ecosystem model. For an initial simulation, boundary conditions from MERRA2[5] (athmosphere), HAMTIDE[6] (tides), and WOA2013[7] (baroclinic boundary conditions) were used. For the further hindcast simulations, the boundary conditions at the open boundaries were provided by simulation results from the NEMO-MEDUSA[8] simulations, a global model that was used within the CAO program.

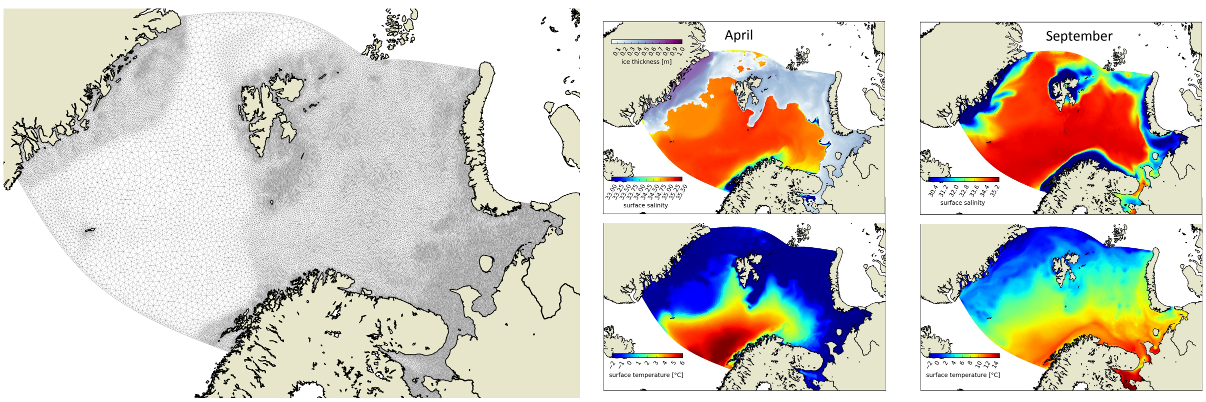


Figure 2.1: left: Model region with representation of the model grid. Right: simulated ice cover, surface temperature and surface salinity in April and September of the simulated year.

The model was initially simulated for one year only and the distributions of temperature, salinity, water level changes due to tides and ice cover were compared with observations.
To validate the tides in the model, water level changes at four different stations in the region were compared with corresponding measurements, showing that the simulated tidal phase agrees very well with the observed one, but the amplitude is generally somewhat underestimated by the model.

Simulated sea surface temperature and salinity were also compared with observations (available from the International Council for the Exploration of the Sea database www.ices.dk) (Fig. 2.2) and generally show good agreement in the central Barents Sea. Uncertainties in the comparison were found primarily at the entrance to the Barents Sea and in the very coastal areas heavily influenced by fresh water, and likely stem from the boundary conditions for temperature and salinity chosen here. Since these are from a climatology of the World Ocean Atlas, they cannot accurately reflect interannual variability.

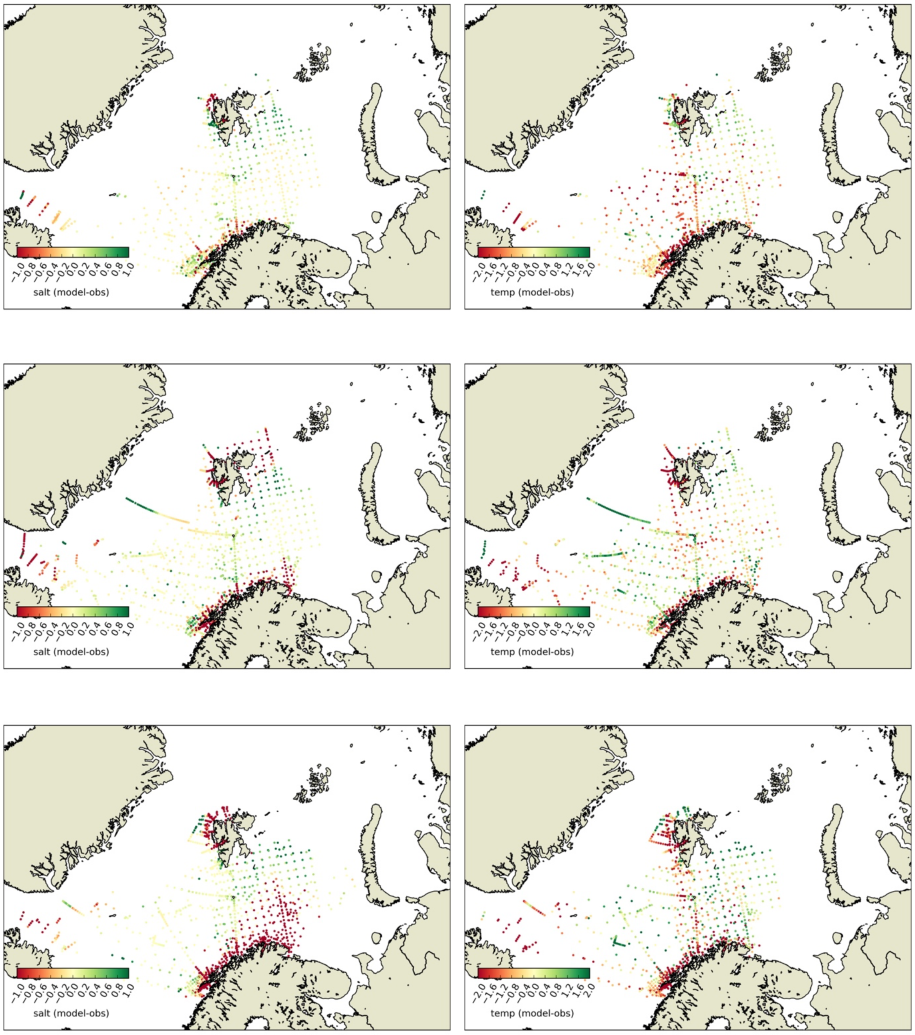


Figure 2.2 Difference plots comparing model results with surface observations from the ICES database for salinity (left) and temperature (right), for three different years (2012 - top to 2014 bottom). The model is forced with boundary data from the World Ocean Atlas and runs with the ice model.

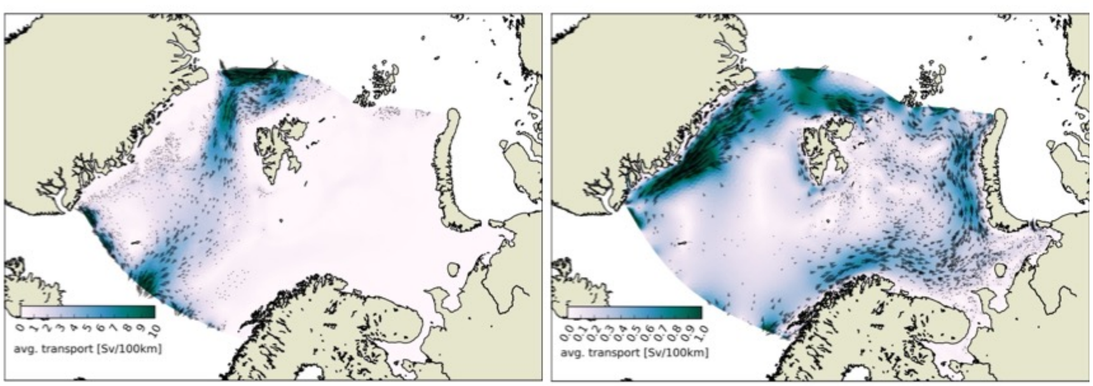


Figure 2.3 Monthly averaged transports in the upper 20 layers (right) and the lower 30 layers (left), scaled in Sv per 100 km horizontal length.

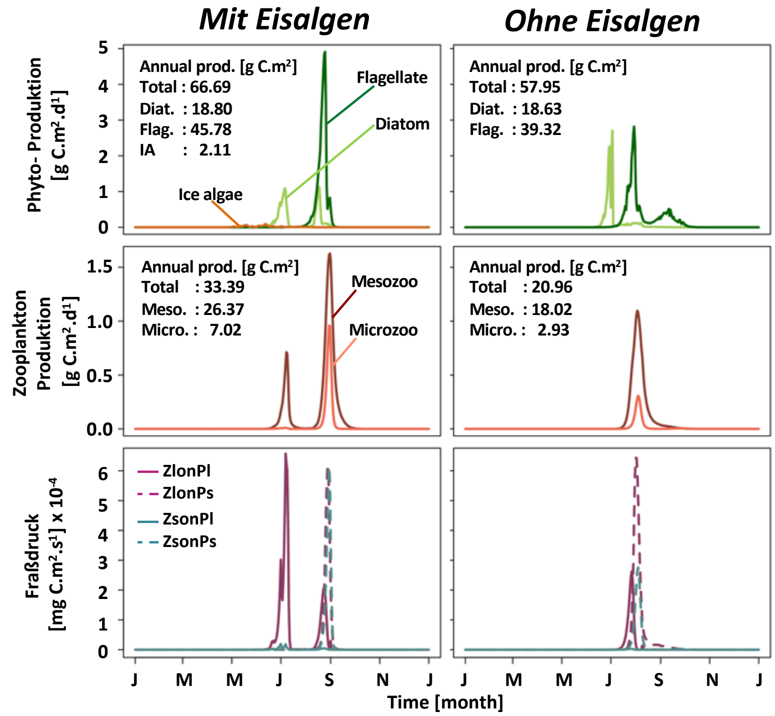
3 Model development of end-to-end ecosystem models

In Work Package 3, the necessary enhancements were made to the ecosystem models to allow proper simulation of the Arctic ecosystem.

Implementation of sea ice biogeochemistry in the model system.

One of the most important developments in the project was the model description of biogeochemical processes in sea ice. Although sea ice algae contribute a rather small fraction of the total primary production in Arctic ecosystems, they play an important role in food web dynamics. To better understand the ecosystem response to warming and sea ice decline, a proper representation of sea ice phenology and linkage with the pelagic and benthic systems is needed. Therefore, the extension of the biogeochemical models to include a sympagic system in the model formulation was successfully implemented during the project. The implementation in ECOSMOII[2] and its relevance to the Barents Sea ecosystem has been described in detail in Benkort et al. (2020)[9]. The new parameterization for sea ice biogeochemistry includes four nutrients (NO_3, NH_4, PO_4, and SiO_2), a functional group for sea ice algae and a detritus pool, and exchange with the uppermost ocean layer. The project investigated the effects of the linkage between the three systems (sympagic, pelagic, and benthic) on ecosystem dynamics, the contribution of ice algae to total primary production, and the effects of changing ice cover on Arctic ecosystem dynamics. To address the scientific and technical challenges associated with the coupling, the model was implemented in a 1D application of the General Ocean Turbulence Model (GOTM). Results show that the model realistically simulated the seasonal pattern of sympagic components when compared to current knowledge of the Barents Sea[10]. Our results show that the sympagic system influences the timing and amplitude of pelagic primary and secondary production in the water column (Fig. 3.1). We have also shown that sea ice algae production early in the year increases the initial biomass of pelagic diatoms and leads to an increase in zooplankton production.

In the context, we also conducted multi-year simulations to investigate the importance of sea ice and its ecosystem on overall primary production in the Barents Sea (Fig. 3.2). As in previously described studies [11], we found a clear relationship between primary production and the onset of sea ice melt. However, our simulations also showed that the highest primary production does not occur at all in an ice-free ocean, but in years with thin ice cover and early ice melt. This result indicates that primary production in the Barents Sea will not necessarily increase under the coming ice-free conditions, but may even decrease locally, especially in regions with seasonal sea ice dynamics.



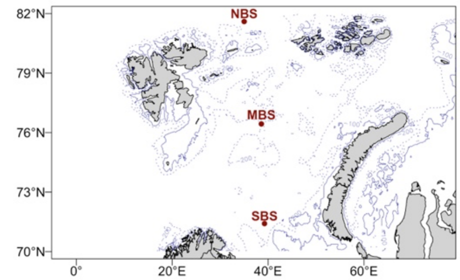


Figure 3.1 Simulated time series at point MBS for primary production, secondary production, and frass rates of meso- (Zl) and micro- (Zs) zooplankton on diatoms (Pl) and flagellates (Ps) with and without consideration of sea ice biogeochemistry (see Benkort et al. 2020).

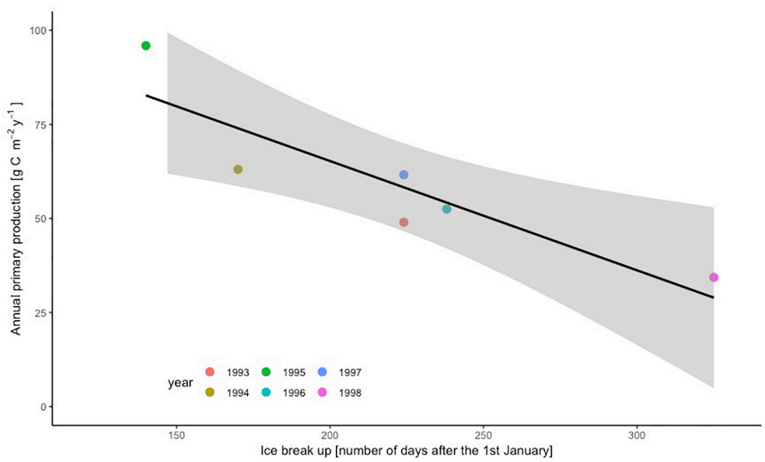


Figure 3.2 Relationship between annual primary production and timing of ice breakup for the 7 years simulated at the central Barents Sea station. Values (p = 0.0159, R2 adjusted = 0.75). (see Benkort et al. 2020).

Development and testing of static and dynamic representations of time-dependent distribution (vertical and horizontal) of plankton and fish functional groups for application in both model systems.

The objective here is to develop mathematical functions that produce a similar distribution of fish biomass in the model systems SCHISM-ECOSMO and STRATH E2E as seen in the acoustic data (provided by UStA).

In both model systems, the vertical distribution of fish functional groups is implemented indirectly in the model system. While food availability in each horizontal grid cell determines the production of fish biomass in the same, the integrated fish biomass is vertically redistributed based on the relative vertical distribution of prey groups at each time step. Food availability is thus the only variable that determines the vertical distribution of fish biomass.

Since large-scale fish migration patterns are mainly relevant in the Norwegian Sea[12] , the horizontal migration of the pelagic fish group was first implemented in a coarse-scale model setup of the entire North Atlantic using the physical model HYCOM (Hybrid Coordinate Ocean Model) [13]. Future work will examine whether the implementation must necessarily be considered for the SCHISM-ECOSMO E2E setup for the Barents Sea and Fram Strait as well. Unfortunately, due to some delays in the model development, we were not able to test the migration in SCHISM-ECOSMO E2E during the project.

Simulations of long-term changes in the North Atlantic and Arctic Oceans were performed using the model system. Figure 3.3 shows the spatial distribution of the migrating (pelagic) fish group over the course of a simulation year. Fish migration is parameterized as a function of predator-prey ratio to account for both food availability and competition. Over the course of the year, this results in a northward migration of the fish group following the zooplankton bloom, particularly along the Norwegian coast (Fig. 3.3), which is consistent with observed migration patterns of the pelagic fish group in the region [14].

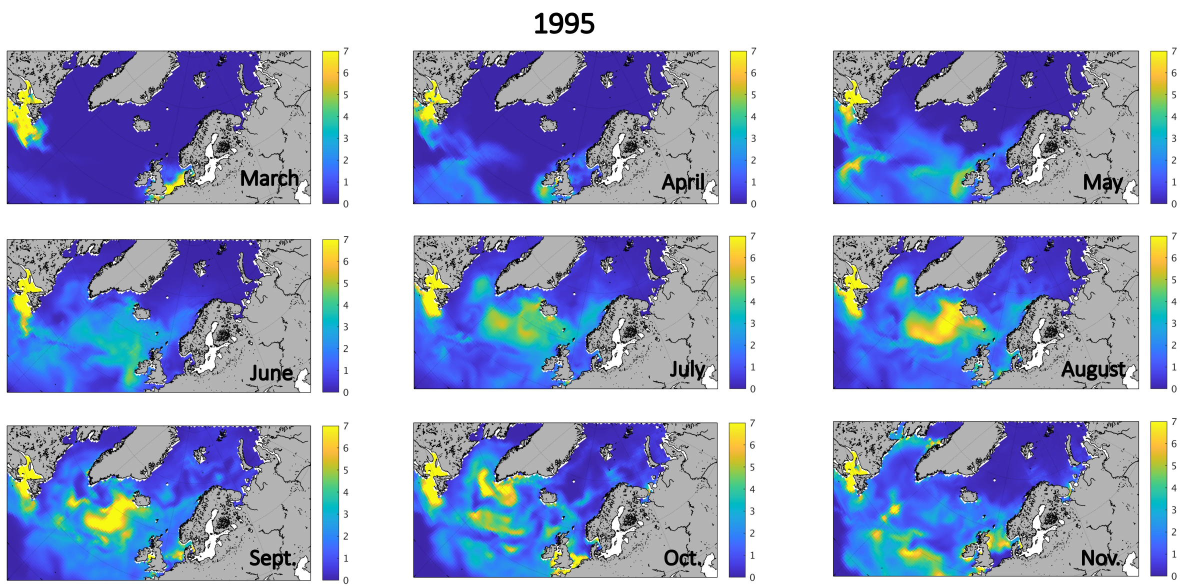


Figure 3.3 Monthly mean vertically integrated pelagic fish biomass (gC/m-2) in the model for the year 1995. Simulation: 1981-2009 (plus 10 years spinup).

Implementation of SCHISM-ECOSMO in the Barents Sea/Arctic Ocean region.

The SCHISM-ECOSMO-POLAR model system (including sea ice biogeochemistry) has been implemented in the Barents Sea/Fram Strait region and generally shows very good performance with respect to ecosystem productivity and distribution of nutrients. Model validation with corresponding observational data on chlorophyll, nutrients. Observational data on nutrients are available through the ICES database (ices.dk).

The simulations showed that the coupled model provides reasonable and realistic spatial and seasonal dynamics of the sea ice biogeochemistry component over the Barents Sea and Fram Strait. The results of total sea ice algal production (Fig. 3.4) are consistent with known patterns in the region, and show comparable results to previous modeling studies [15] .

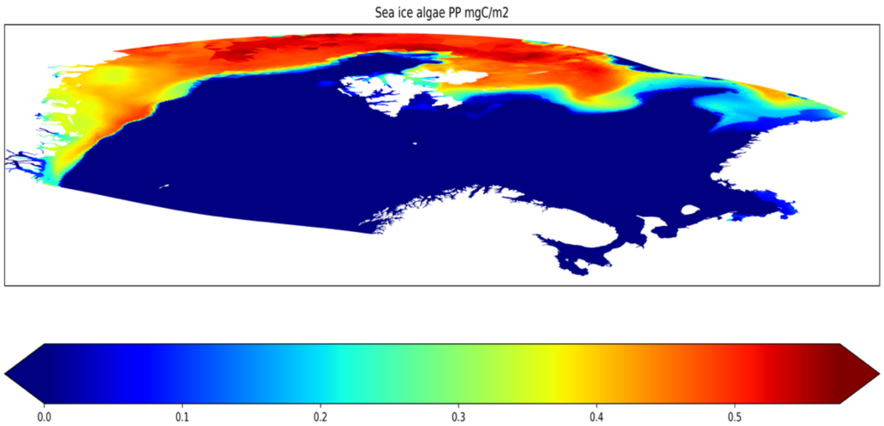


Figure 3.4 Annual ice algae production in g C m-2 y-1 for the year 1991.

The spatial and seasonal distribution of pelagic phytoplankton and zooplankton blooms also show realistic expected patterns (Figs. 3.5 & 3.6).
The results show a latitudinal dependence of the timing and amplitude of the pelagic phytoplankton (Fig. 3.5) and zooplankton (Fig. 3.6) biomass. Wherein the bloom in the southern Barents Sea begins in April and extends northward throughout the season. In this process, the zooplankton bloom starts about one month later than the phytoplankton bloom. Production follows the typical limiting patterns in the region, which are primarily determined by light availability and seasonal stratification of the water column.

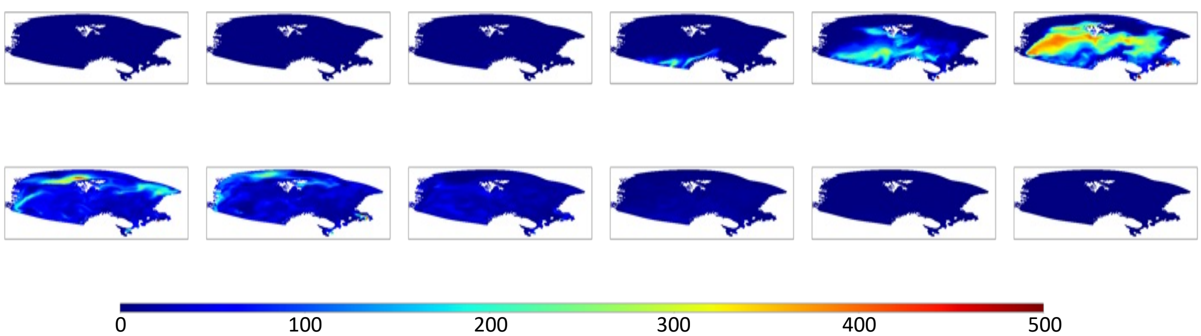


Figure 3.5 Monthly mean surface phytoplankton biomass (mg C m-3). Simulated year is 1991.

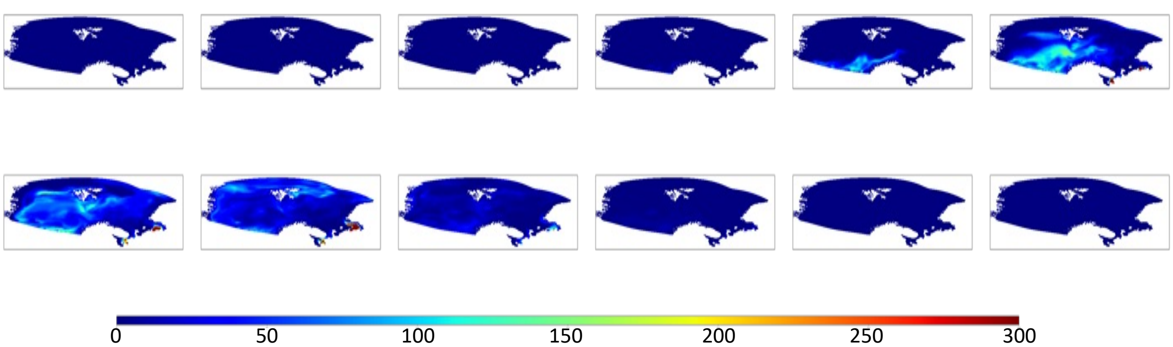


Figure 3.6 Monthly mean surface zooplankton biomass (mg C m-3). Simulated year is 1991.

4 Decadal Hindcast Simulation

1d GOTM-ECOSMO

Decadal hindcast simulations were first performed using the 1d GOTM-ECOSMO model system and the model results were compared with those from StrathE2E and observations (Fig. 4.1). This involved applying the 1d model system to different locations in the Barents Sea, statistically averaging the results, and comparing them to observations of chlorophyll in the Barents Sea. The results for the period 2011-2019 were published as part of the CAO special issue of AMBIO[16].

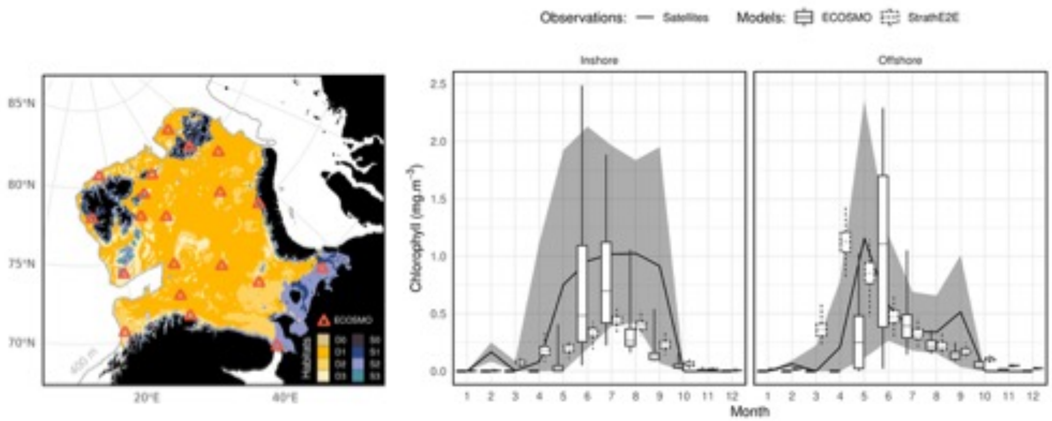


Figure 4.1 (Figure from Heath et al. 2022) Phytoplankton chlorophyll comparison between model outputs and observations for 2010s climatology. Box plots show median and interquartile range. The shaded area shows the interquartile range for satellite observations (https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=OCEANCOLOUR_ARC_CHL_L4_REP_OBSERVATIONS_009_088), with the median as the solid line. The range bars for the ECOSMO results represent the spatial variability between model sites (left panel) within each zone. For StrathE2EPolar, the range bars represent credible intervals of model output due to parameter uncertainty.

3d SCHISM-ECOSMO-Polar

To further investigate the changes in spatial variability, especially with reference to changes in sea ice cover and the role of ice algae, decadal simulations were performed using SCHISM-ECOSMO-Polar. Figures 4.2 & 4.3 show the simulation results for annual primary and secondary production for 1991-1999. The results show strong interannual as well as spatial variability. The Atlantic waters along the Norwegian coast and west of the Svalbard archipelago show the highest production. A comparison to satellite-based estimates of primary production in the region[17] shows that the model reproduces primary production patterns well, both qualitatively and quantitatively. However, production in the eastern Barents Sea still appears underrepresented. However, comparison to satellite observations here is limited because satellite products are subject to uncertainty due to the algorithms used and are related to differences in absorption and backscatter properties of phytoplankton and concentrations of colored dissolved organic matter (CDOM) and minerals[18]. As a result, the estimates are often flawed, especially in coastal areas with high riverine inputs. In some of the simulated years, we observe stronger primary production in the southern Barents Sea, which is related to a stronger inflow of Atlantic water masses into the Barents Sea (1991, 1993, 1998, 1999). This situation is likely to become more frequent in the future with the continuously increasing influence of Atlantic water masses in the Barents Sea (Arctic Atlantification)[19]. In the north, sea ice limits primary production. In recent simulation years (1997-1999), we observe a north-westward increase in primary production in sea ice associated with an opening of sea ice. Secondary production, which ultimately determines the distribution of zooplankton, largely follows the distribution of primary production (Fig. 4.3).

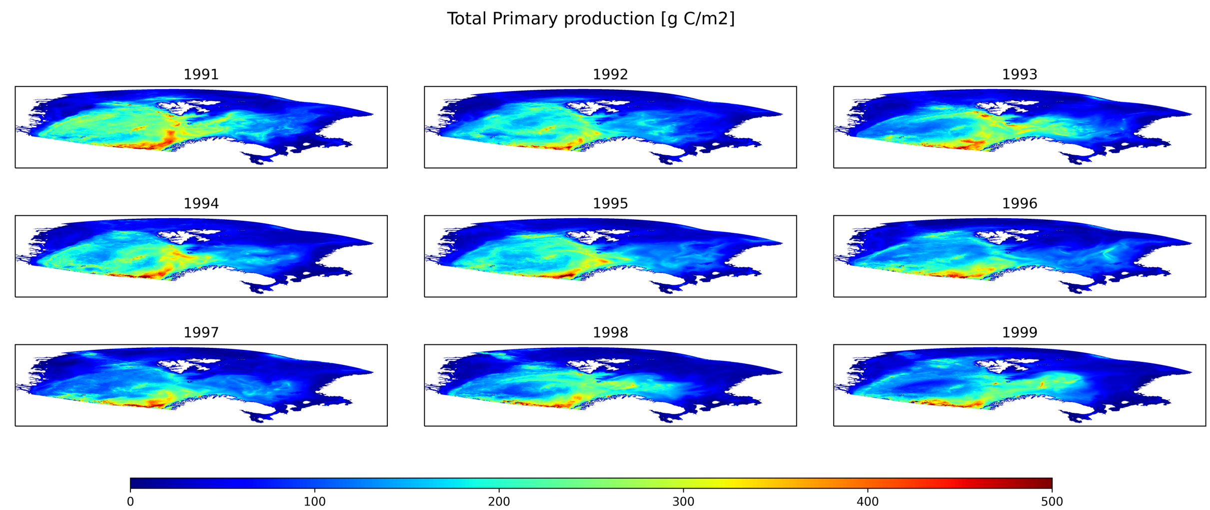


Figure 4.2 Annual primary production simulated with SCHISM-ECOSMO-Polar

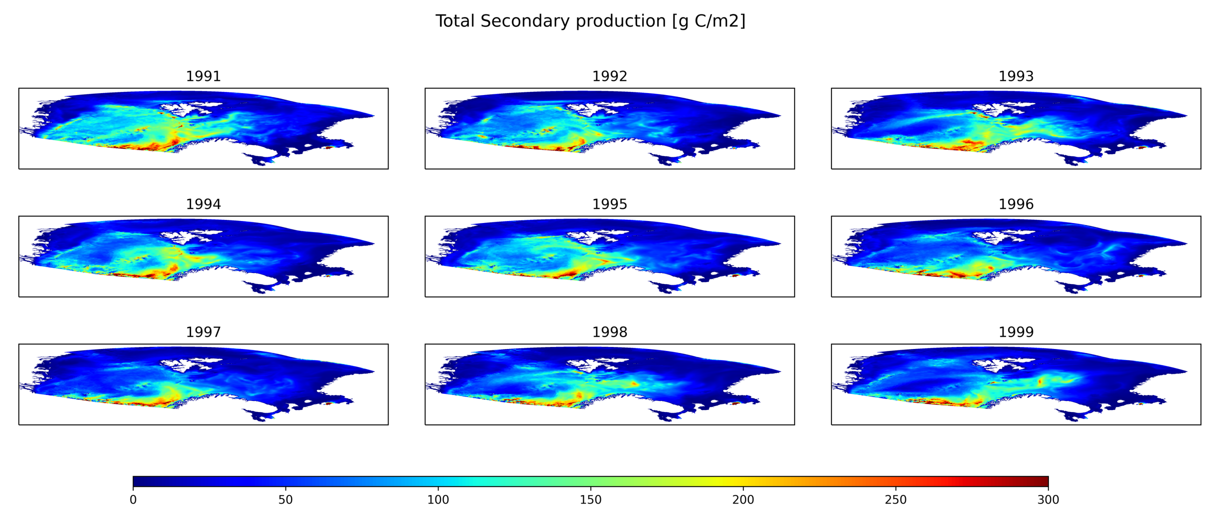


Abbildung 4.3 Jährliche Sekundärproduktion simuliert mir SCHISM-ECOSMO-Polar.

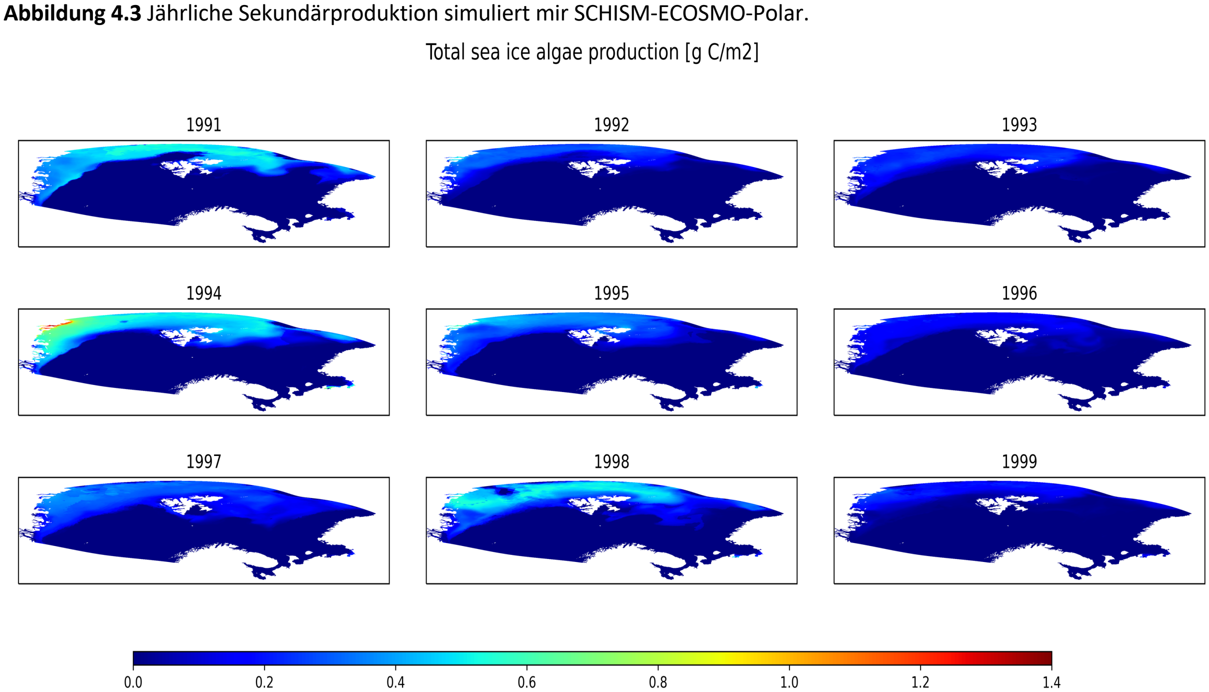


Abbildung 4.4 Annual sea ice algae production simulated with SCHISM-ECOSMO-Polar.

Sensitivity of production distribution to sea ice bloom.
To investigate the role of sea ice production on the spatial distribution of pelagic primary production, we calculated an analogous sensitivity scenario with SCHISM-ECOSMO-Polar in which sea ice production was not considered. The results show the relevance of sea ice biogeochemistry especially for primary production along the ice edge (Fig. 4.5). In general, a spatial redistribution of production occurs. Under the ice, ice algae lead to a decrease in pelagic primary production as a result of increased light limitation due to shading effects. However, directly at the ice edge where sea ice melts, part of the ice algae released in the water column contributes positively to pelagic primary production, leading to a local increase in pelagic production (see May figure).

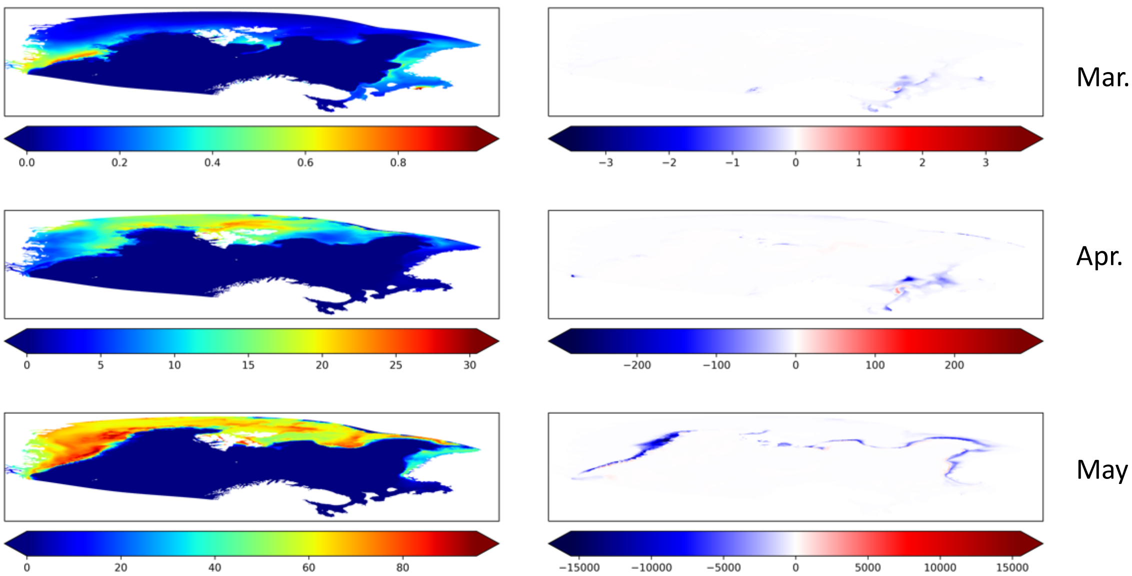


Figure 4.5 Monthly sea ice algae production simulated with SCHISM-ECOSMO-Polar (left) and difference in primary production with and without consideration of sea ice biogeochemistry.

3d HYCOM-ECOSMO E2E
Furthermore, multidecadal hindcast simulations were performed using the HYCOM-ECOSMO E2E model system to investigate environmental influences on fish distribution. An initial comparison with observed interannual variability (Fig. 4.6) [20] shows that the model can represent some of the variability. However, in the 1990s, the results show variability that is different from the observations. One possible reason for this here is that variable fishery mortality was not included in the simulation. A first comparison to the fish biomass calculated by StrathE2E for the period 2010-2019 also shows that both models calculate the biomass in the same order of magnitude[16].

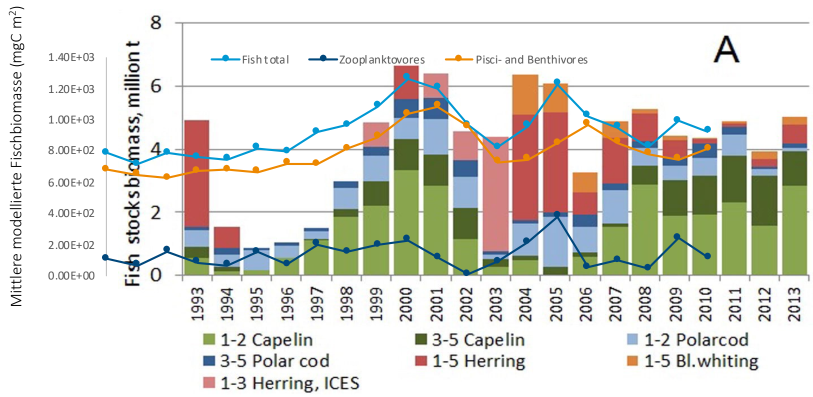


Figure 4.6 Annual averaged simulated fish biomass for the two fish groups (1. Zooplanktivore; 2. Pisci- and Bentivore) and total fish biomass in the Barents Sea. In addition, for comparison of interannual variability, the observed fish biomass from 26. The units in the observations are not one-to-one comparable to the units in the simulated fish biomass, so only a qualitative comparison is possible here.

5 Future scenarios - ecosystem response to environmental change.

Simulations cover the period 2040-2049 and were performed consistently with simulations for the period 2010-2019 for both ECOSMO-E2E-POLAR and StrathE2EPolar models[16]. The forcing data for the future projections were extracted from the simulations using NEMO-MEDUSA for the ocean and prepared for use with in both models. The first year of the 2040 simulation marks the beginning of nearly year-round ice-free conditions in the region, based on the available NEMO-MEDUSA Scenario[21] (IPCC RCP8.5). Here, the selected scenario is one that assumes very high CO2 emissions, making it one of the most extreme future scenarios. For both models, the environmental data relevant to these runs were taken from the NEMO-MEDUSA results. Since no projections of nutrient inputs from rivers or atmospheric deposition rates of nutrients are, to our knowledge, available for the region these were held constant. Future fishing scenarios were the subject of the scenario experiments with the status quo of fishing activities and gear characteristics for 2011-2019 assumed as the reference. For the atmospheric forcing data for SCHISM-ECOSMO-POLAR, the data (consistent with the Nemo-Medusa simulations) were extracted from the simulation using HadGEM2-ES RCP8.5 [22].

The planned IPCC scenarios with the fully coupled SCHISM-ECOSMO-POLAR model could not be finally run and analysed due to delays in model development during the project lifetime, but will be discussed in a further publication after completion. The main reasons for the delays were the unexpected departure of key personnel in the second year of the project and the increased work pressure resulting from the changes during the pandemic.

Comparative simulations of the two models and fisheries scenarios.

For the comparative model simulations, the ECOSMO-Polar was run in a 1d setup for different locations in the Barents Sea area and the results were averaged and thus made comparable to the results of the box model StrathE2E-Polar. Comparing the two time periods, the results show significant ecosystem changes for all ecosystem groups considered (Fig. 5.1), which are related to both sea ice retreat and changes in nutrient availability. Most representative, however, is the overall decrease in sea ice algae. From the simulations with StrathE2EPolar, there is also a significant influence of changing environmental conditions on the different fish groups as a consequence of both bottom-up and top-down effects. The main conclusion is that productivity and maximum sustainable yield (MSY) of demersal fishes in the Barents Sea are likely to increase, leading to additional feeding pressure on planktivorous fishes, which in turn has implications for higher trophic levels. These changes are driven by loss of sea ice, which affects both habitat, migration, and feeding of high trophic levels, as well as increased primary production due to light penetration into the ocean. The results are illustrated in Figure 5.1 and were also published in Heath et al. (2022).

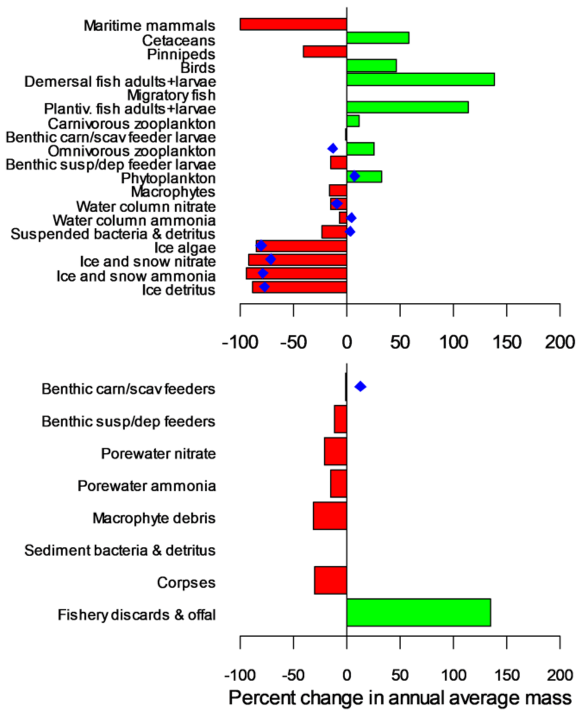


Figure 5.1. (Figure from Heath et al. 2022) Differences in average annual modeled biomasses of food web components between the 2040s and 2010s. Red and green refer to StrathE2EPolar results. Blue symbols denote results from ECOSMO-Polar (with a more constrained food web). Green bars and symbols on the right indicate a larger value of the respective variable in the 2040s than in the 2010s, and vice versa, for red bars and symbols on the left indicate a reduction of the value in the projections.

Publications

Benkort, D., Daewel, U., Heath, M., and Schrum, C. 2020. On the Role of Biogeochemical Coupling Between Sympagic and Pelagic Ecosystem Compartments for Primary and Secondary Production in the Barents Sea. https://www.frontiersin.org/article/10.3389/fenvs.2020.548013.

Heath, M. R., Benkort, D., Brierley, A. S., Daewel, U., Hofmeister, R., Laverick, J. H., Proud, R., et al. 2020. HOW IS CLIMATE CHANGE AFFECTING MARINE LIFE IN THE ARCTIC ? Frontiers for Young Minds.

Heath, M. R., Benkort, D., Brierley, A. S., Daewel, U., Laverick, J. H., Proud, R., and Speirs, D. C. 2022. Ecosystem approach to harvesting in the Arctic: Walking the tightrope between exploitation and conservation in the Barents Sea. Ambio, 51: 456–470.

Szeligowska, M., Benkort, D., Trudnowska, E., and Błachowiak-Samołyk, K. 2022. How Do Dark Streams of Arctic Glacial Meltwater Affect Plankton? Frontiers for Young Minds, 10.

ICES. 2021. Working Group on Integrative, Physical-biological and Ecosystem Modelling (WGIPEM). ICES Scientific Reports. 3:73. 62 pp. https://doi.org/10.17895/ices.pub.8231

Planed Publications

Benkort, D., Daewel, U., Hofmeister, R. and Schrum, C. in prep. Past and Future ecosystem changes in the Barents Sea and Fram Strait area.

Daewel, U, Samuelsen, A., Schrum, C., Yumruktepe, Ç. in prep. Potential implications of environmental changes on fisch productivity in the in the North Atlantic/Arctic Ocean.

Conference participations

Benkort, D., Daewel, U., Hofmeister, R., Schrum, C. (2019) Implementing sea-ice algae into the biogeochemical model ECOSMO-E2E. Poster presentation, *CAO – annual meeting*, 01/2019, *in person*

Benkort, D., Daewel, U., Hofmeister, R. (2019) Biogeochemical modelling of the Arctic system: role of the sea-ice and pelagic systems linkage on the primary production. Talk presentation, *WGIPEM – Annual meeting*, 03/2019, *in person*

Benkort, D., Daewel, U., Hofmeister, R., Schrum, C. (2019) Biogeochemical modelling of the Arctic system: role of the sea-ice and pelagic systems linkage on the primary production. Pico-presentation, EGU – General assembly, 01/2019, *in person*

Benkort, D., Daewel, U., Hofmeister, R., Schrum, C. (2019) Biogeochemical linkage of the sea-ice and pelagic systems and its role on the Arctic ecosystem dynamic. Talk presentation, *IGS – Sea Ice Symposium*, 08/2019, *in person*

Benkort, D., Daewel, U., Hofmeister, R., Schrum, C. (2020) Role of biogeochemical coupling between sympagic, pelagic and benthic ecosystem for primary and secondary production. Poster presentation, *CAO – annual meeting*, 01/2020, *in person*

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