



Nordic Council
of Ministers

Effects of climate change on future environment and marine life in the Nordic sea areas



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Foreword

This document is the main report from the project NorScen - Nordiske klimaScenarier (Nordic climate Scenarios) funded by The Nordic Council of Ministers (NCM) programme Marine Management and Climate. Main target groups are the Nordic Council of Ministers, national ministries and directorates, other researchers and the Nordic population.

The United Nations' Intergovernmental Panel on Climate Change (IPCC) published over the years 2019–2023 a range of comprehensive reports within its 6th assessment cycle (AR6). IPCC AR6 contains an enormous amount of high-quality information and has better coverage of marine aspects and higher regional resolution than earlier IPCC assessments. Still, the Nordic sea areas (Baltic, North, Norwegian, Iceland, Greenland, and Barents seas) are not treated as a unit or resolved well into individual seas. It is particularly challenging that the state-of-the-art global climate models used to simulate future climate and climate effects under different emission do not have sufficient resolution to provide a good basis for decision-making on a Nordic scale. This is additionally problematic because our sea areas have characteristics that distinguish them from many others and may make them especially vulnerable to future climate change.

The NCM sees a need to increase our understanding of the effects of future climate change specifically on the Nordic sea areas and has asked for regional analyses and assessments. NorScen aims to address the request. In our first report we gave an up-to-date overview of knowledge of the present status and expected future development of climate impacts on physical ocean properties, organisms and ecosystems in the seas around the Nordic countries. This current report presents the main results of the project. By producing, presenting and discussing the results of detailed model data for future values of physical, biogeochemical, and ecological variables across the sea areas of the Nordic countries, the project aims to enhance understanding of climate change impacts, facilitate economic and societal adaptation, and provide a robust knowledge base for decision-makers. We have chosen to be quite comprehensive in our reporting, striving to make our results publicly available. Nonetheless, we acknowledge that not all decision-makers and managers may have the time or interest to study the full report and therefore also provide a concise summary.

The authors, research scientists from Norway, Sweden and Denmark, wish to thank colleagues from within and outside the project for helpful discussions and ideas.

Oslo, March 10th, 2025

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Summary

The IPCC's Sixth Assessment Report highlights that climate change is more severe than previously understood, with profound implications for marine systems. The ocean, which has historically buffered climate change, is now starting to experience significant alterations in its physical properties and biogeochemistry, including changes in sea temperature, sea level, ice coverage, current patterns, and chemical composition. These transformations are expected to push many marine species and ecosystems beyond their adaptive capacities, with potentially widespread consequences. The seas of the Nordic region are characterized by expected rapid climate development and unique marine environments, which may be especially vulnerable to climate change. Thus, for the Nordic countries understanding the impacts is crucial for preparing marine-based industries and maintaining the region's environmental leadership.

From a Nordic perspective it is particularly challenging that the state-of-the-art global climate models used to simulate future climate and climate effects under different emission scenarios (Coupled Model Intercomparison Project Phase 6, CMIP6) do not have sufficient resolution to provide a good basis for decision-making on our regional scale. The Nordic Council of Ministers (NCM) took an initiative towards diminishing the gaps between available and wanted information, thus aiming to increase our understanding of the effects of future climate change specifically on the Nordic sea areas. Through the program *Marine Management and Climate* and specifically the call *Climate change in Nordic sea areas towards 2100*, NCM has asked for regional analyses and assessments.

Our project NorScen - Nordic climate Scenarios - answers to work package 1 of this call. By producing detailed model data for future values of physical, biogeochemical, and ecological variables across the Nordic sea areas, the project has throughout strived to enhance understanding of climate change impacts, facilitate economic and societal adaptation, and provide a robust knowledge base for decision-makers.

Although well integrated, the work was carried out ocean by ocean in parallel, allowing to build upon models already set up for the area. These large models take years to develop so it's highly important to build upon existing systems. The focus is on downscaling from global to regionally resolved information, running model simulations for both historical periods and future (IPCC) scenarios. Based on the resulting physical values, we have produced data fields on historical and future values also for biogeochemical and ecological variables. Geographically and scale-wise we cover comprehensively and on different scales, from the Danish Limfjord and the Baltic Sea via the North Sea to the Norwegian- and Barents seas. The core of the report is structured according to geographical area, as is most of this

summary. The report only briefly touches upon the methods/models applied, focusing more on describing, presenting, and discussing the main results. Still, although the typical reader of this report is not a scientist with technical expertise in the field, we have chosen to retain a certain level of complexity, especially some of the figures relating to model validation and comparison are aimed at those with more in-depth interest in the topic. Nevertheless, the figure captions and main text should be helpful to everyone. For even more thorough and detailed presentation, large parts of the material presented here is recently, or will soon be, published in scientific papers, which we refer to.

SMHI applied the ocean model NEMO-SCOB to the North Sea and Baltic Sea. Downscaled physical and biogeochemical fields were produced for the historical period 1951–2014 and future IPCC scenarios SSP1-2.6 (low emission, high mitigation) and SSP3-7.0 (high emission, low mitigation). Under the high-emission SSP3-7.0 scenario, surface temperatures are projected to increase by 2.5–3°C in the Baltic Sea and 1–2 °C in the North Sea by the end of the 21st century, with a more modest increase of around 1 °C in the Baltic Sea and less than 0.5 °C in the North Sea under the lower-emission SSP1-2.6 scenario.

Significant changes are also found for other parameters, including a general decrease in salinity, particularly in the Baltic Sea's bottom water, and a substantial reduction in ice cover. For the SSP3-7.0 scenario, ice will largely remain only in the Gulf of Bothnia and Gulf of Finland, with the central Bothnian Sea expected to be ice-free in most future years. The time evolution of sea surface temperature and salinity reveals multidecadal variability, with the long-term climate trend being more pronounced in the SSP3-7.0 scenario and markedly larger temperature increases in the Baltic Sea compared to the North Sea.

Complex changes in nutrient dynamics across the Baltic Sea and North Sea are projected, with dissolved inorganic nitrogen (DIN) and phosphorus (DIP) concentrations showing varied patterns depending on location and emission scenario. Under most conditions, nutrient loads are projected to decrease, particularly in the SSP1-2.6 low-emission scenario, with notable reductions in coastal areas. However, some regions, like the Gulf of Bothnia and along the North Sea coast of Scotland, show slight increases in nutrient concentrations, likely due to changes in riverine nutrient inputs and increased runoff.

These nutrient load changes are expected to significantly impact marine ecosystem processes, including primary production, phytoplankton concentrations, and bottom oxygen conditions. The SSP1-2.6 scenario generally projects an improvement in water quality, with reduced primary production and enhanced bottom oxygen levels. The higher-emission SSP3-7.0 scenario suggests less favourable conditions with higher runoff and increased eutrophication, though still potentially better than current conditions. Importantly and in accordance with

earlier work on the Baltic Sea, we conclude that the impacts of nutrient load changes are more significant than those of climate change, with an overall expectation of future decreased eutrophication and improved water quality in the Baltic.

Aarhus University examined the future conditions in Limfjorden, northern Denmark, with the high-resolution FlexSem model set up in a 3D coupled hydrodynamic-biogeochemical model. Future development within the three climate scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5 are explored and compared with historical values for the period 2009–2018. Limfjorden is a shallow fjord stretching from the North Sea to the Kattegat, characterized by seasonal oxygen depletion, saline waters in the west and brackish in the east. This is the most important area for mussel fishing and -farming in Denmark but is negatively impacted by agricultural runoff.

All three climate scenarios project decreasing salinity and increasing water temperatures. The most significant changes are, as can be expected, in the SSP5-8.5 scenario, showing potential water temperature rises up to 5 °C and strong water column stratification for 2090–2099.

The accuracy of FlexSem for Limfjorden with regards to biogeochemical variables was rigorously validated with seasonal measurements. FlexSem quite accurately reproduces seasonal variations in nutrients, phytoplankton, and oxygen concentrations, but has some limitations in representing short-term variations. The most severe ecosystem changes are found for the SSP5-8.5 scenario and the latest time period 2090–2099. Within this scenario there is significant oxygen depletion and reduced benthic mussel biomass by 2090–2099. Also when Water Management Plans (Miljø-og-Fødevareministeriet 2016) are implemented, climate change prevents ecological improvement, with increased temperature and stratification hampering oxygen supply. The biomass of benthic mussels is reduced in all three scenarios. On the other hand, mussel farming in the water column, which is less hampered by oxygen depletion than the bottom, is expected to expand significantly in all scenarios.

IMR have studied climate scenarios for the Norwegian- and Barents Seas by downscaling with the NEMO-NAA10km model. This is a regional ocean modelling configuration designed to study ocean processes and climate impacts. Two climate models are presently used to force Nemo-NAA10km in climate downscaling mode, NorESM2 and EC-Earth. An important long-term contribution is that in NorScen we developed an enhanced method for handling river runoff in climate downscaling simulations by re-routing two-dimensional climate model runoff fields to the Nemo-NAA10km grid. Monthly runoff fields from 1950–2100 that preserve inter-annual variability while maintaining consistency with original hindcast simulation inputs were created.

Biogeochemistry is modelled with NORWECOM.E2E, a comprehensive biogeochemical model system that includes a nutrient–phytoplankton–zooplankton–detritus (NPZD) module with two types of phytoplankton and zooplankton. In this study NORWECOM.E2E was run offline using 5-day mean values from the NEMO-NAA10km physical ocean fields and NorESM2 atmospheric fields.

The new Nemo-NAA10km version with improved runoff distributions shows more moderate changes in surface salinities and sea surface temperatures compared to the old version, particularly in the Barents, Kara, and Norwegian seas, with less extreme variations and a generally shallower mixed layer depth in the subpolar region. In the main text of the report, we show example maps of future sea surface salinity and temperature and mixed layer depth from the new enhanced model runs. Also, time series and trends for projected values of these variables under different scenarios for open ocean and coastal regions in the Norwegian Sea and Barents Sea are shown, so are similar figures for net primary production (NPP) and gross secondary production (GSP). NPP is currently highest in coastal and ice-free regions, with minimal changes across emission scenarios until mid-century, after which SSP5-8.5 shows a significant increase in the Arctic part of the Barents Sea, doubling NPP by century's end. GSP follows similar trends, with a general increase across all areas, most pronounced in the Arctic part of the Barents Sea under the high-emissions SSP5-8.5 scenario.

The frequency and intensity of marine heat waves (MHWs) in Nordic waters is increasing, with the Barents Sea experiencing a 62% increase in annual MHW frequency since 2004. Further, projections by other authors suggest that the North Sea and Norwegian Sea could see 20–30 times higher MHW probability in a 3.5 °C warming scenario. Our ongoing research characterises historical MHW events, distinguishing between surface and near-bottom MHWs. We find increasing trends in frequency and intensity, with notable variations in different marine regions.

The Norwegian and Barents Seas Atlantis model (NoBa Atlantis) is a comprehensive ecosystem model with 53 species and functional groups, representing commercial species individually and smaller groups collectively. The model uses a three-dimensional grid to represent the ecosystem, with each grid cell representing a specific area of the sea. The model incorporates temperature sensitivity through a knife-shaped approach affecting movement, spawning, and growth rates, and requires daily input of physical parameters. To address uncertainty in phytoplankton and zooplankton responses to climate change, our researchers conducted nine perturbation simulations across three emission scenarios, varying growth rates based on projections from NORWECOM.E2E.

Species responses to the projected higher temperatures vary widely, mainly based on their temperature tolerance. Prawns and mesopelagic fish are climate winners,

while capelin and Greenland halibut are losers. Polar cod showed, rather surprisingly, no clear response due to uncertain links between recruitment and sea ice. Seven species had positive responses, with differences becoming evident after 2065. Haddock showed strong responses due to recruitment variability. Prawns thrived in warmer shallow waters, despite some areas exceeding their tolerance. Twelve species responded negatively to higher temperatures. Contrary to earlier projections this includes Atlantic cod, declines found by our NoBa Atlantis analyses are linked to reduced prey, capelin and zooplankton, availability.

Additional funding allowed us to arrange a workshop on *Economic consequences of climate change towards 2100 for fisheries and aquaculture in the Nordic region*.

The workshop brought together a multidisciplinary expert group of resource economists, fisheries oceanographers, and biologists, and one representative from the fishing industry. A broad range of topics were discussed and a comprehensive account included as part of this report. This is structured as follows: Expected developments, challenges and adaptation strategies for both fisheries and aquaculture under climate change, followed by a comprehensive chapter on Fisheries by ocean region, and Aquaculture. Fishery and aquaculture may have completely different development paths and issues in the future. Fisheries will likely in many areas be challenged by negative impacts of climate change. If fisheries are strongly reduced, aquaculture may be subsidised to sustain settlement along the coast, but to thrive the aquaculture industry must be flexible. Technological advancements and economic drivers are crucial for the future. Already now the industries face challenges with high costs, rising demands for sustainable practices, and competition for land and sea space. While some issues may be solved in the relatively near future (like change of fuel), others may intensify. In addition, and especially in Norway, both the fisheries and aquaculture industries must expect debates on the balance between the nation's future role as a food producer or primarily a technology developer and supplier.

Abbreviations

AMAP	Arctic Monitoring and Assessment Programme, a Working Groups of the Arctic Council
AR5	IPCC's Fifth Assessment Report
AR6	IPCC's Sixth Assessment Report
BACC	Assessment of Climate Change for the Baltic Sea Basin
BSAP	Baltic Sea Action Plan
Chlorophyll- <i>a</i>	The primary photosynthetic pigment found in plants, algae, and cyanobacteria
CMIP	Coupled Model Intercomparison Project. Massive multi-model runs at the heart of IPCC assessments. There are several generations, we refer to CMIP3, CMIP5, CMIP6 (most recent finalised), and CMIP7 (ongoing)
CNRM-CM6-1	French CMIP6 global climate model used for climate change projections and research
DIN	Dissolved inorganic nitrogen
DIP	Dissolved inorganic phosphorus
EC-Earth	European Community Earth System Model, a coupled earth system model
EEZs	Countrys' Exclusive Economic Zone
E-HYPE	European HYdrological Predictions for the Environment is a hydrological model used to simulate water flow and nutrient transport across Europe.
ERA5	High resolution atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF).
EURO-Cordex	Coordinated regional climate downscaling experiment focused on Europe.

FlexSem	Flexible Spatial Ecosystem Model, a marine ecosystem modelling approach
GSP	Gross secondary production.
HCLIM	High-resolution Climate Model developed for regional climate downscaling
HELCOM	The Baltic Marine Environment Protection Commission
HIROMB- BOOS- HIRLAM (HBH)	Advanced regional coupled ocean-atmosphere modeling system primarily used for marine and coastal environment studies in the Baltic Sea region
ICES	International Council for the Exploration of the Seas
IPCC	The United Nations' Intergovernmental Panel on Climate Change
MHW	Marine heat wave
NCM	The Nordic Council of Ministers
NEMO- NA10km	A regional ocean model that covers the area from the North Atlantic to the Arctic
NEMO-SCOB	An ocean model coupled to the Swedish Coastal and Ocean Biogeochemical model, that covers the North Sea, the Skagerrak-Kattegat transition zone and the Baltic Sea.
NoBa Atlantis	The Nordic and Barents Seas Atlantis model (NoBa Atlantis)
NorESM	Norwegian Earth System Model, a coupled global earth system model
NorScen	Nordic climate Scenarios, the NCM funded project behind this report
NORWECOM.e2e	NORWegian ECOlogical Model system end-to-end. A marine ecosystem model.
NOSCCA	North Sea Region Climate Change Assessment
NPP	Net primary production
NPZD	Nutrient-Phytoplankton-Zooplankton-Detritus model

OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
Pelagic	Residing in free water masses (as opposed to demersal, benthic...)
Psu	Practical salinity units - dimensionless unit for salinity
RAS	Recirculating Aquaculture Systems
SSP1-2.6	SSPs, Shared Socioeconomic Pathways, are scenarios of projected socioeconomic global changes up to 2100 adopted by IPCC. SSP1-2.6 is a low emission scenario labelled "Sustainability (Taking the Green Road)"
SSP2-4.5	Intermediate IPCC scenario labelled "Middle of the Road"
SSP3-7.0	High emission scenario labelled "A Rocky Road"
SSP5-8.5	Extremely high emission scenario labelled "Fossil-fuelled Development"
SSP	Sea Surface Pressure
SST	Sea Surface Temperature
TAC	Total Allowable Catch

1. Introduction

In its Sixth Assessment Report (AR6), the United Nations' Intergovernmental Panel on Climate Change (IPCC) accentuates that climate change is even greater and clearer than previously assumed and that the effects on humans and nature will be extensive (IPCC 2022). Further, IPCC (2019), states that the ocean so far has acted as a buffer against climate change, but climate change now alters the ocean in many ways and consequences for nature and humanity are sweeping and severe. The changes affect physical properties of the ocean (including sea temperature, sea level, ice coverage, current patterns, mixed layer depth) and biogeochemistry (oxygen and nutrient levels, pH, and more). Many marine species and ecosystems will face environmental conditions outside what they are adapted to, and future impacts are expected to be pronounced.

To prepare the Nordic countries significant marine based industries (including aquaculture, fisheries, transportation, tourism and much more) for the unavoidable changes and maintain the region's leading role in climate and environmental policy, it is essential to have the best possible knowledge base about future climate changes and their effects on our marine areas. This report focuses on The Baltic Sea, North Sea, Norwegian Sea, and Barents Sea (Fig. 1). Note that when we refer to "the Nordic sea area" or similar this covers all these seas, sometimes also including The Iceland- and Greenland Sea, although these two seas generally are less discussed.

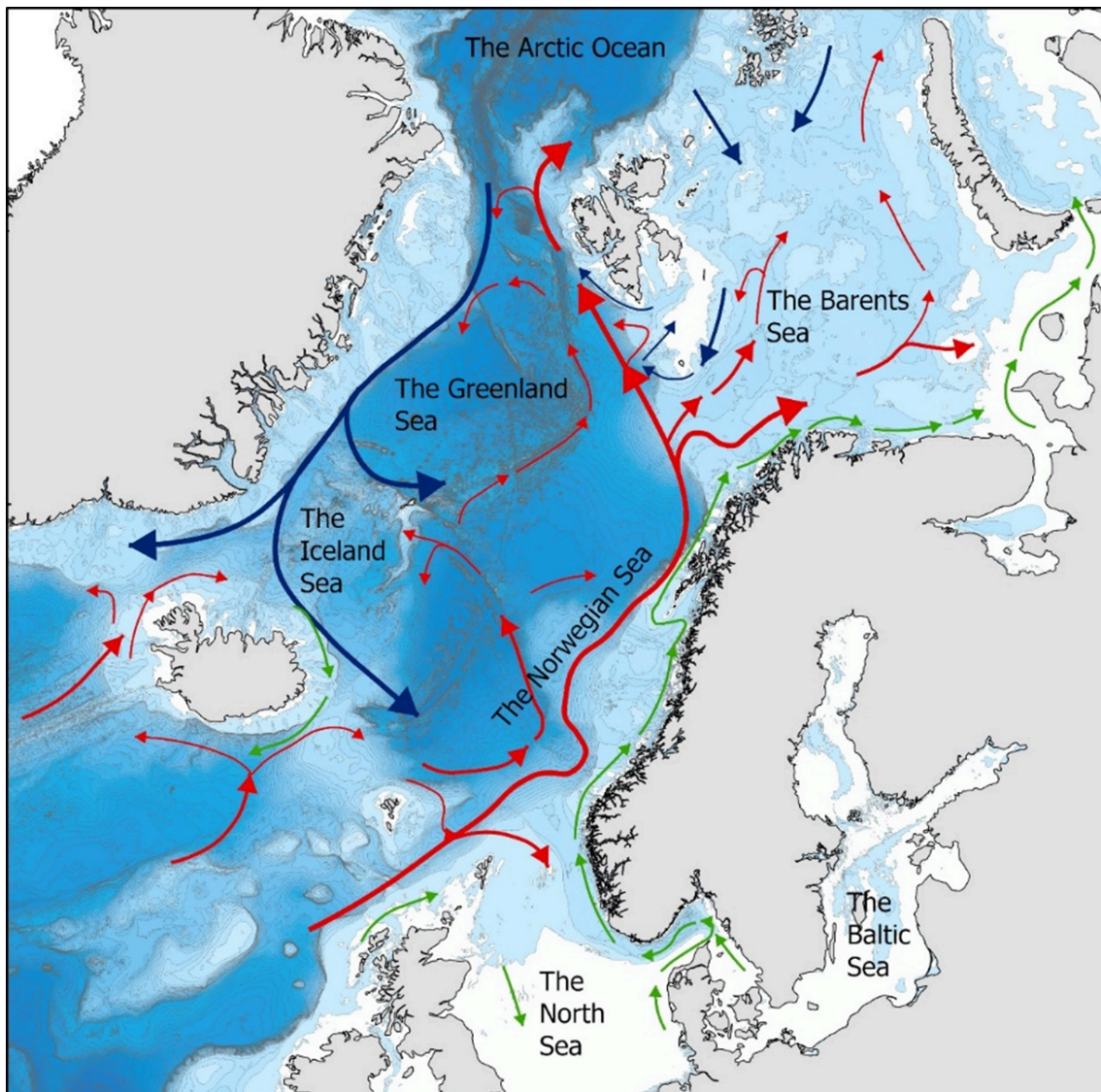


Figure 1. The main ocean regions covered in this report and dominating currents. Red arrows show warm close-to-surface (Atlantic) ocean currents, blue arrows cold deeper ocean currents, and green arrows coastal currents. Graphics by Per Arne Horneland, IMR.

This is especially the case since these seas have characteristics that distinguish them from many others and may make them especially vulnerable to future climate change (Table 1). The Nordic countries are wealthy and well organised, but still the high rate of the projected development of climate change in our region may make it extra difficult for states, society and the affected industries to adjust and implement adaptive measures.

Table 1. Key characteristics and expected consequences of climate change for the seas examined.

Region	Key characteristics
Baltic Sea	The Baltic Sea is a shallow, near-enclosed sea with low salinity and limited water exchange, making it prone to eutrophication. The health of key fisheries (cod, herring, sprat) is tied to the sea's unique environmental conditions and face challenges from overfishing, pollution, and habitat degradation. Climate change is expected to further increase surface temperatures, shorten ice cover period, and lower the salinity and oxygen levels further. Human uses include fishing, maritime transportation, tourism, and offshore wind farms.
North Sea	The North Sea is a shallow semi-enclosed northeastern arm of the Atlantic Ocean, with significant oil and natural gas reserves, as well as busy shipping lanes and historically rich fishing grounds. Consequently, the North Sea has an extensive total burden from many other human impacts, including eutrophication, habitat damage and intense fishing, in addition to climate change.
Norwegian Sea	The Norwegian Sea is a deep, open ocean region. Despite the northerly location, most of the area is ice-free year-round due to the warm Atlantic current. Large quantities of phyto- (plant) and zooplankton are produced here. This allows the free water masses of the Norwegian Sea (and neighbouring Iceland- and Greenland seas) to be the habitat of large fish stocks, in particular of herring, mackerel and blue whiting. Their distribution is highly temperature dependent. Ocean acidification has advanced faster here than the global average.
Barents Sea	The Barents Sea is a comparatively shallow shelf sea. While the southwestern part is heavily influenced by relatively warm Atlantic water masses, the northern and eastern parts are essentially of Arctic nature. The Barents Sea is home to several abundant and commercially harvested fish stocks, notably the "skrei" cod. With climate change some of the largest changes on the planet are expected in the northern Barents Sea, associated with the amplified temperature increase resulting in a fundamental change from a seasonally ice-covered to a (nearly) permanently open ocean system. Maritime transport and tourism is increasing.

Although IPCC AR6 contains an enormous amount of information and has better regional resolution than earlier IPCC assessments, it is difficult to scale down to more detailed local information. From a Nordic perspective it is particularly challenging that the state-of-the-art global climate models used to simulate future climate and climate effects under different emission scenarios (Coupled Model Intercomparison Project Phase 6, CMIP6) do not have sufficient resolution to provide a good basis for decision-making on our regional scale.

Comprehensive regional overviews and evaluations of expected climate change impacts on some Nordic sea areas exist, e.g., the books "Second Assessment of Climate Change for the Baltic Sea Basin" (BACC II Author Team 2015), and "North Sea Region Climate Change Assessment" (NOSCCA; Quante and Colijn 2016). These are still good sources of background knowledge, but climate models are rapidly developing, and these books do not capture this and especially not the knowledge gained from CMIP6 and derived information. Climate change is also an overarching theme in the work of HELCOM (helcom.fi), see, e.g., the very recent report Climate Change in the Baltic Sea (2024), and OSPAR (ospar.org).

The Nordic Council of Ministers (NCM) sees a need to fill such gaps and increase our understanding of the effects of future climate change specifically on the Nordic sea areas. Through the program Marine Management and Climate and specifically the call Climate change in Nordic sea areas towards 2100 NCM and has asked for regional analyses and assessments. NorScen answers to work package 1 of this call. As an important part of our proposal and contract certain Deliverables were agreed upon. The degree of compliance between ordered and actual deliveries of the project is detailed in Table 2.

Table 2. Degree of compliance between ordered and actual deliveries.

Description of Deliveries and Activities	Comment /Deviation
Report with overview of previously published and ongoing works on identified and expected future effects of climate change on marine environment and ecosystems in Nordic sea areas	Delivered as NorScen first report with content as described. Somewhat delayed, but this in agreement with NCM coordinator
Downscaled physical model fields from simulations for the period 1950–2014 with the regional ocean model NEMO-NAA10km. NEMO-NAA10km covers the North Atlantic from 40 degrees N, the North Sea, Nordic Seas and the Arctic Ocean. For the Baltic Sea and North Sea, corresponding results from an ocean model with 3.7 km resolution. For Limfjorden, Denmark, high-resolution model results from the FlexSem model for the period 2009–2018 will be delivered	Done and described in this report, with some deviation. Applies to Deliverable 2, 3, and 4. For the Norwegian and Barents Seas an updated version of NEMO-NAA10km and NORWECOM.E2E were successfully applied and results produced for historical period and the scenarios SSP1-2.6 (low emissions), SSP2-4.5 (intermediate), and SSP5-8.5 (very high). Due to unexplained unexpected temperature values in the SSP3-7.0 (high) run, we do not report for this scenario
Downscaled physical model fields from simulations of IPCC scenarios SSP1-2.6, SSP2-4.5 and SSP3-7.0 with NEMO-NAA10km and corresponding results for other sea areas. For computational reasons, results will need to be delivered for specific periods ("time-slices"), not the entire period up to 2100	For the North Sea and Baltic Sea downscaled fields were successfully produced with the ocean model NEMO-SCOBI. Due to severely late delivery of atmospheric forcing from external source downscaling was done for historical period 1951–2014 and future scenarios SSP1-2.6 and SSP3-7.0
Model fields from the coupled physical-chemical-biological model system NORWECOM.E2E for historical and future simulations as above. The physical model fields from 1. and 2. will be used as a basis for the NORWECOM.E2E runs, the latter will be set up for a smaller area. For the Baltic Sea-North Sea, corresponding model fields from the physical-biogeochemical model NEMO-Nordic-Scobi will be delivered	For Limfjorden highly resolved physical and biogeochemical were produced by the FlexSem model according to plan for historical period and scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5. Due to the late delivery described above alternative input fields had to be and were found, but SSP3-7.0 was left out

Model fields from the ecosystem model NoBa Atlantis for corresponding historical and future simulations as in No. 3 and 4. NoBa will use the same physical model fields as NORWECOM.E2E, but will additionally take into account various harvesting regimes for commercial species in the system (for example mackerel, herring and cod)	Done. Reported here. Of particular interest are the projected differences in response to ocean warming between SSP2-4.5 and SSP5-8.5 as compared to SSP1-2.6
Report/article describing results of analyses based on the future scenarios above. The results from the simulations will be analysed with respect to variation and trends in relevant physical and biogeochemical variables for selected habitats and sea basins to study climate effects on different marine ecosystem species. This analysis will include detailed studies of how sensitive various species and relevant populations are to changes in temperature, oxygen, acidification, primary and secondary production, and sea ice extent	Done, reported here
Overall assessment of climate change effects on marine ecosystems in Nordic sea areas	Done, brief evaluations/assessment based on our model projections included in this report. For a more comprehensive review please see report from the NorMECC project
Final report	Delivered
Additional Activity undertaken and reported here. Possible due to additional NCM funding	A workshop on <i>Economic consequences of climate change towards 2100 for fisheries and aquaculture in the Nordic region</i> was arranged
Additional Activity reported here	Work on Marine Heatwaves conducted at IMR within another project

The first NorScen report briefly summarised the present knowledge of the observed and expected future impacts of climate change on marine environment and ecosystems in the Nordic region (Ottersen et al. 2023). The present report documents the core of the work within NorScen, focusing on downscaling from global to regionally resolved information. We have produced model data fields for the most important physical variables on spatial scales suitable for understanding our sea and coastal areas. To achieve this, we have run regional model simulations for both historical periods and future (IPCC) scenarios to downscale information from global climate models. Based on these physical values, we by means of already developed and proven model systems, have produced data fields on historical and future values also for biogeochemical and ecological variables. Geographically and scale-wise we cover comprehensively and on different scales, from the Danish Limfjord and the Baltic Sea via the North Sea to the Norwegian- and Barents seas. The core of the report is structured according to geographical area, for each we provide information on the methods/models applied, describe and present results, and discuss them. In addition to the Summary given, we also provide an overall assessment of the effects of climate change on the marine environment and ecosystems in the Nordic region. While NorScen and this report provides enhanced knowledge specifically on climate change and its impacts, climate knowledge is an important basis also for assessing the effects of other impacts such as eutrophication and fisheries, as the future of the seas around the Nordic countries and the life in them is a combined effect of many influences.

Through generous additional funding from NCM we were able to arrange a workshop focusing on future economic and societal impacts of climate change on the marine fisheries and aquaculture sectors in the Nordic region. To facilitate this, we brought together a broad group of people working at the interface of natural sciences and societal impacts, including resource economists. The outcomes of the discussions during the meeting and afterwards are reported here.

2. Assessment of climate change effects on Nordic marine ecosystems

2.1 Ecosystem impacts for the North Sea and Baltic Sea

Marine ecosystems in the Baltic Sea have adapted to the brackish environment for thousands of years and are sensitive to hydrographic and biogeochemical changes. These long-term climate changes come on top of other pressures from pollution, shipping, fishing etc. In a recent study (Wåhlström et al. 2022) it was shown that the climate change impact (from temperature increase, salinity decrease, and ice cover decrease) on marine ecosystems in Swedish waters was of similar magnitude as the combined impacts of all present human pressures on the marine environment. Climate change will result in novel environmental conditions that will change ecosystem composition (Blenckner et al. 2021), modify biodiversity, and change the risks of invasive species entering the region. Cod is an example of a species which depends on specific salinity and oxygen conditions for reproduction and is also an example of a species where nutrient remediation measures can help to increase climate resilience (Wåhlström et al. 2020).

The scenarios we have modelled and provided data on will have several near-future appliances. They will be used to perform habitat modelling and species distribution modelling (Fredriksson et al. 2024) for present and "door knocking" marine invasive species. In addition to habitat modelling, currents will be used to study existing and changing connectivity and advective spread of invasive species. The habitat modelling and dispersal understanding will in turn facilitate the possibility to initiate control activities at the introduction of an invasive species or very early in the invasion curve and thereby decrease the rate of growth and expansion of the invasive species. The dispersal patterns and connectivity of invasive species are, however, influenced by factors beyond national borders (e.g., water currents, rising temperatures, salinity). It is therefore crucial to adopt a regional approach to develop effective mitigation strategies. Here this common understanding through scenarios and a broader regional perspective as well as bi-lateral initiatives are essential to ensure timely, precise, and cost-effective actions. Besides initiating bi-lateral and regional control, the understanding will also locally guide municipalities responsible e.g. for shielding Marine Protected Areas.

2.2 Ecosystem impacts in the Limfjord

Climate change is expected to increase the water temperature in the Limfjord by up to 5 °C in the worst-case scenario (SSP5-8.5). In addition, salinity is reduced due to increased runoff and thus the stratification of the water column becomes stronger in all scenarios. In the two most optimistic future scenarios (SSP1-2.6, SSP2-4.5), the expected improvements in bottom oxygen and Chl *a* concentration during implementation of Water Management Plans were counteracted by changes in physics (warming, stronger stratification). Therefore, it will be necessary to increase nutrient reductions in the Water Management Plans to achieve good ecological status under the influence of climate change. In the worst-case future scenario (SSP5-8.5), the oxygen depletion in the Limfjord will increase with negative consequences especially for benthic mussels. Mussel farming in the water column was intensified in all scenarios and showed a high potential for harvesting, while benthic mussels suffered from reduced food supply and oxygen depletion (Maar et al. 2024).

Due to climate change and increasing demands for a more sustainable production of mussels, it is likely that mussel farming will become the primary source of mussels in the industry in the future rather than dredging of mussels in the wild. The applied modelling scenarios can be used to inform managers, mussel farmers, fishermen and the local population about future mussel harvesting options, potential changes in ecosystem health and to find solutions to adapt to climate change impacts.

2.3 Ecosystem impacts in the Barents and Norwegian Seas

For both the Barents and Norwegian seas pronounced changes are expected to arise from climate change. The degree, and in some cases also the direction of change, is however, highly different between scenarios. The most significant ecological impacts from climate change are, also in these regions, through higher sea temperatures. Temperature changes will decrease both ice cover and thickness, and also mixed layer depth, in most cases decreasing it. This and other effects of temperature change will likely alter nutrient mixing and availability. In the Barents Sea, our results show that change in mixed layer depth is a main driver for changes in net primary production (NPP). For the Norwegian Sea, an initial strong decrease in mixed layer depth until 2030 is particularly notable in our results. Caution should be shown to the latter though, as we cannot rule out that this is an erroneous effect of model initialization artifacts.

The projected alterations in primary and gross secondary production (GSP) will affect fish stocks, some negatively and some positively, and thus alter ecosystem dynamics in many ways. Projected increase in GSP in the Barents Sea might positively impact fish recruitment and cause fish species like Atlantic cod and haddock to expand their distribution northwards and eastwards. In the Norwegian Sea our results show significant decrease in both NPP and GSP, especially in coastal areas. This may potentially negatively impact recruitment to important fish stocks there, like Norwegian spring-spawning herring.

We have not projected future development of marine heat waves (MHWs), but with general temperature increase, MHWs are expected to become more frequent, longer lasting and, more intense (although the actual values depend on the base period on which MHWs are calculated). Relatively little work has been done on MHWs in the Nordic sea area, but recent and ongoing research point to increasing number and severity of both surface and near-bottom events over large parts of the region.

The projections conducted with the NoBA Atlantis model are the first with an end-to-end ecosystem model using downscaled regional physical forcing. They project significantly different results from global models, showing that some local species respond positively to increased temperatures, although with high uncertainties connected to functional responses and temperature tolerances. It should be noted that different approaches have yielded quite different results. The negative response in cod and capelin, the lack of response in the pelagic species in the Norwegian sea, and the unclear response of the polar cod found in the NoBa Atlantis projections contrast with the findings in other expert based studies in the region (Kjesbu et al. 2021; Sandø et al. 2024). This highlights the complexity and uncertainty in long-term projections for higher trophic levels, like fish stocks. In Nilsen et al. (2024) important processes such as density-dependent movement-recruitment relationships (e.g. for the pelagic fish stocks in the Norwegian/Barents sea, and the polar cod), the lack of knowledge for some of the species, the lack of adaptation, and the importance of indirect and direct trophic interactions are discussed. The results of the study point towards a need for both modelling and empirical studies to go more in depth in some of these challenges, and to improve our possibility to provide, e.g., fisheries managers with projections that can be used for adaptations of fisheries to climate change. Models like Atlantis can also be used to detect and explain potential 'surprises' driven by indirect and direct predator-prey interactions, which may not necessarily be clear from expert-based studies founded on single-species information.

3. Future scenarios for the North Sea and Baltic Sea

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3.1 Methods for downscaling physical and biogeochemical fields

The downscaling of global earth system model climate projections to the North Sea and Baltic Sea was performed with the ocean model NEMO-SCOBI (Ruvalcaba-Baroni et al. 2024). The model has a regular grid with horizontal resolution of about 3.7 km and a vertical resolution of 3 m at the surface, decreasing to 22 m in the deepest parts of the domain (Norwegian trench). The Swedish Coastal Ocean and Biogeochemical model (SCOBI) is the biogeochemical component in NEMO-SCOBI (Ruvalcaba Baroni et al. 2024; Almroth-Rosell et al. 2015; Eilola et al. 2009). The SCOBI model includes 13 pelagic variables: dissolved oxygen, nitrate, ammonia, phosphate, mineral-bound inorganic phosphorus, dissolved silicate, three phytoplankton groups (diatoms, flagellates and others, and cyanobacteria), zooplankton and finally detritus pools of nitrogen, phosphorus and amorphous biogenic silica. The sediment includes four state variables of nitrogen, silicon, organic phosphorus and inorganic phosphorus. Hydrogen sulphide concentrations are represented by 'negative oxygen' equivalents as described in Fonselius (1962).

Our regional downscalings are driven at the boundaries by the global climate model CNRM-CM6-1 (Voldoire et al. 2019). More specifically using its contribution to CMIP6 (O'Neill et al. 2016). The atmospheric forcing is not taken directly from the coarse global model, but instead first downscaled using the regional atmospheric model HCLIM (Belušić et al. 2020) to a horizontal resolution of 0.11 degrees to better capture local and regional winds and precipitation. These downscaled atmospheric runs are part of the EURO-Cordex project (Jacob et al. 2020) that provides regional atmospheric downscaling for Europe. The temporal resolution of our atmospheric forcing is hourly.

Three different scenarios were downscaled. The first is the historical period 1951–2014, where greenhouse gases, aerosols and other climate forcing parameters are kept close to those observed during the period. The two other scenarios are two different climate scenarios for the period 2015–2100, following two different shared

socioeconomic pathways (SSPs), namely SSP1-2.6 and SSP3-7.0. SSP1-2.6 assumes a low emission, high mitigation future, while SSP3-7.0 corresponds to a high emission, low mitigation scenario. The number after the dash gives the radiative forcing in these runs in watts per m^2 compared to a preindustrial background. A higher value implies greater warming.

Open boundary conditions for the ocean model are taken directly from the global climate model CNRM-CM6-1 for the respective scenarios. The variables used for forcing are salinity and temperature, sea surface height and barotropic currents. These variables were available only as monthly means, suggesting that high frequency variability at the boundaries will be muted in our simulations.

The daily runoff data from 1951 to 2100 was produced using dedicated CMIP6 simulations with the Hydrological Predictions for the Environment model, specifically the European application version 3.1.8 (E-HYPE; Donnelly et al. 2016), forced by the same climate model projections described above. These values were later modified by a factor of 0.88 after comparison with datasets from the North Sea (ICG-EMO database of European rivers; Lenhart et al. 2010) and from the Baltic Sea (Gustafsson et al. 2012), during the historical period of 1951–2014. The same scaling factor was assumed for the future period. A similar approach was used to estimate the nutrient loads from rivers, which include nitrate, ammonium, phosphate, silica and bioavailable detrital nitrogen and phosphate. For the historical period, E-HYPE nutrient loads (both CMIP6 scenarios) were yearly and basin wise adjusted, to the available observational data in the Baltic Sea (Gustafsson et al. 2012) and North Sea (ICG-EMO database of European rivers; Lenhart et al. 2010). Future river loads (after 2015) assume a constant scaling factor, which is the average of the yearly scaling factors computed between observations and E-HYPE model for a recent period (2006–2017). The method implies the underlying assumption of existing similar conditions of land use and E-HYPE performance in the recent period and in the future. As E-HYPE output does not include silica properties, future concentrations were obtained by assuming a climatology concentration computed for the historical period. The differences between the average for the historical reference period 1985–2014 (black) and the nutrient loads, runoff and river nutrient concentration are shown with time in Figs. 2 and 3.

Atmospheric deposition for the historical period is based on a monthly data set at different basins of the Baltic Sea, provided by the Baltic NEST Institute (Savchuk et al. 2018). For the North Sea region, the study assumes that the nutrient atmosphere's deposition is the same as in the Baltic Proper area. The data set was used directly as forcing in the historical period and used to compute a monthly climatology of the recent years (2006–2017) that was assumed for the future period. Details on the data sets and methods are also described in Ruvalcaba-Baroni et al. (2024).

Total N Riverine input change (future-present)

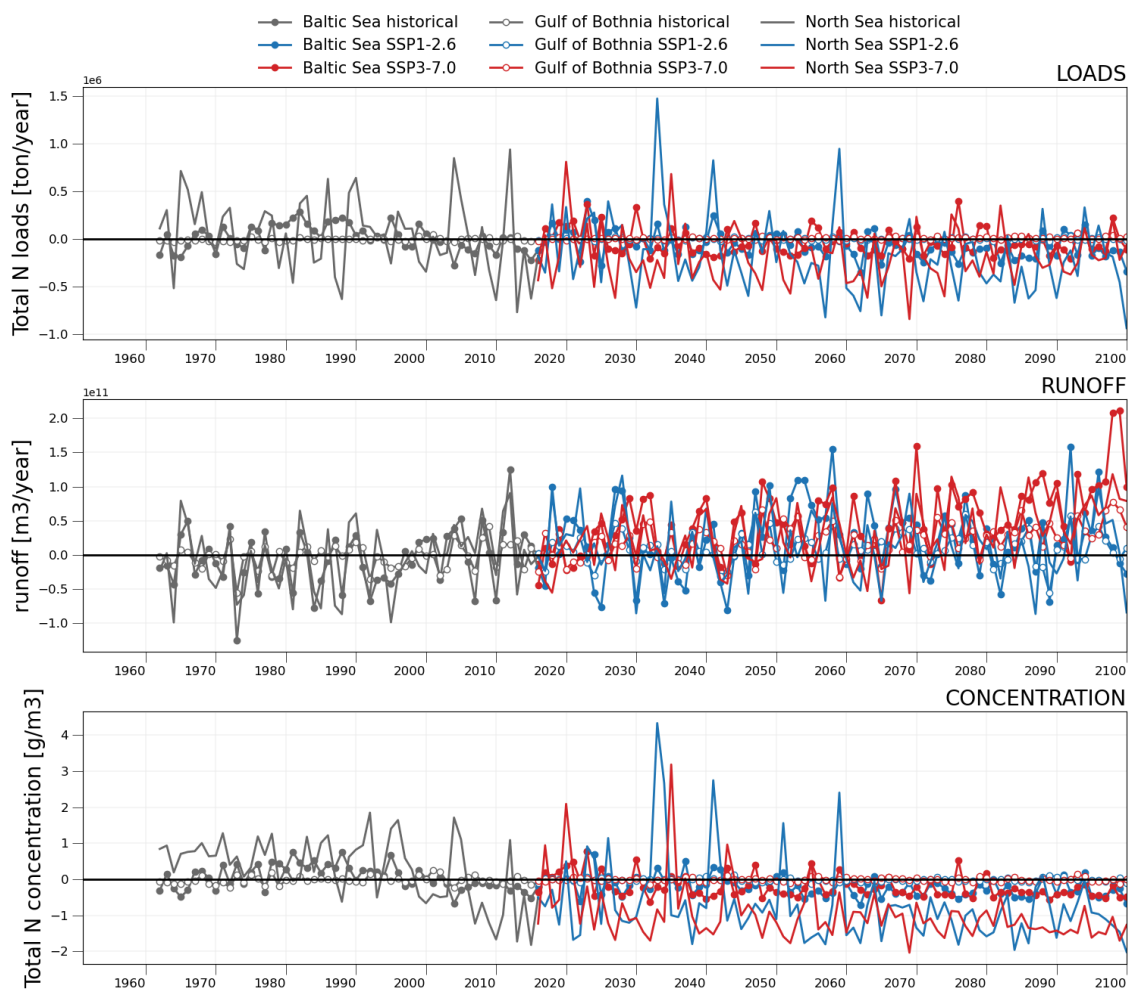


Figure 2. Nitrogen riverine input shown as regionally averaged time series of the differences between the historical period 1985–2014 (grey) and future developments with time. Development of nitrogen loads (top), runoff (middle) and river concentrations (bottom) with time for scenario SSP 1-2.6 (blue) and SSP3-7.0 (red) in the Baltic Sea (filled circles), Gulf of Bothnia (white circles), and North Sea (line).

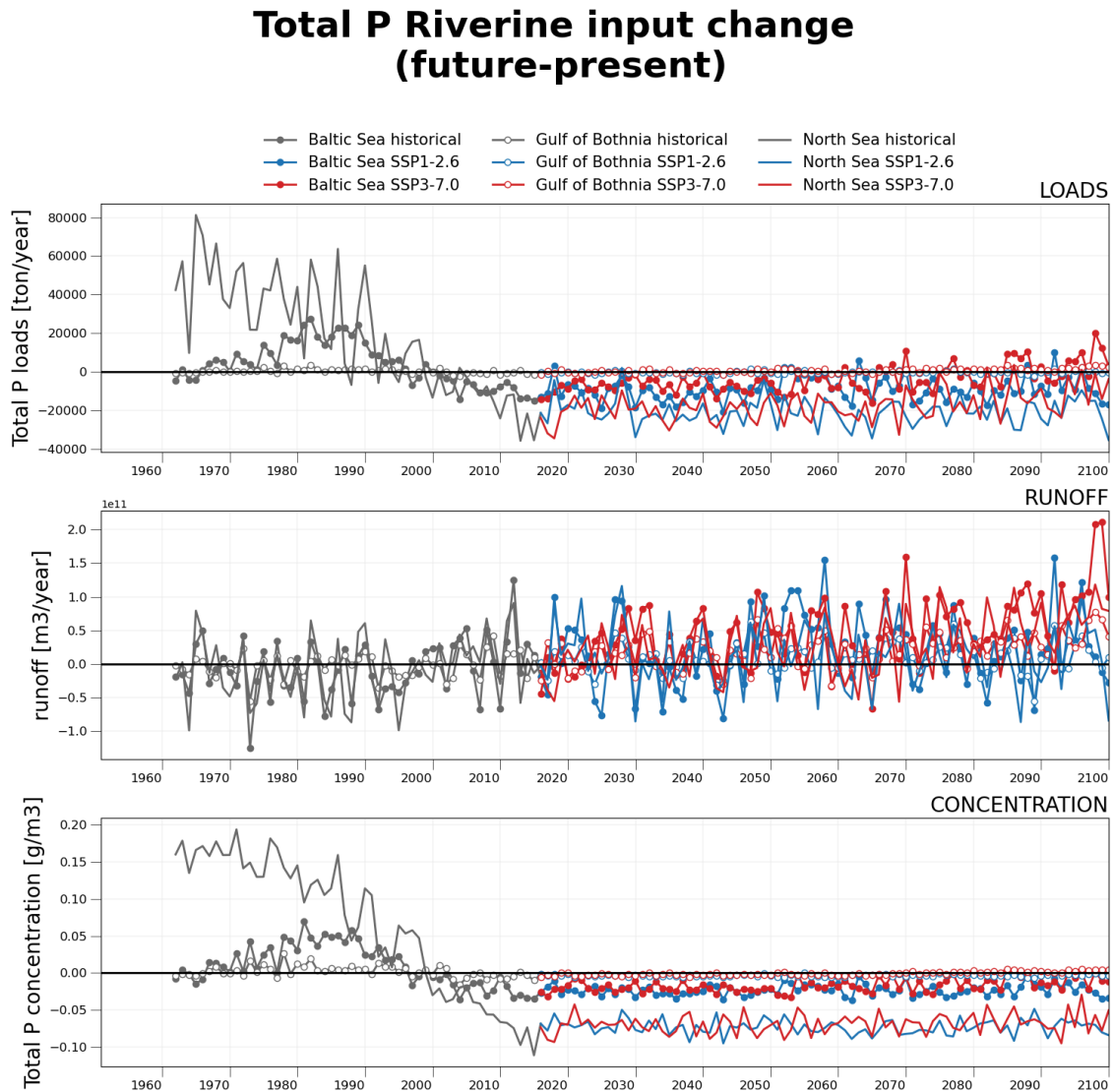


Figure 3. Phosphorus riverine input shown as regionally averaged time series of the differences between the historical period 1985–2014 (grey) and future developments with time. Development of nitrogen loads (top), runoff (middle) and river concentrations (bottom) with time for scenario SSP1-2.6 (blue) and SSP3-7.0 (red) in the Baltic Sea (filled circles), Gulf of Bothnia (white circles), and North Sea (line).

3.2 Downscaled physics and biogeochemistry in the North Sea and Baltic Sea

This section presents the downscaling of CMIP6 runs for one global model downscaled with one regional ocean model. These results add to the large ensemble of earlier CMIP3 and CMIP5 projections for the region, summarized, e.g., in the EN CLIME fact sheet *Climate Change in the Baltic Sea* (2021) for the Baltic Sea and in Quante and Colijn (2016) for the North Sea, and will be seen as a complement to those rather than independent results. The reason for this is the large variability in results and conclusions caused by natural variability as well as global and regional climate model uncertainties. These results should therefore be seen as the first step towards building a larger CMIP6 ensemble for the region.

3.2.1 Downscaled physical fields

For scenario SSP3-7.0, the surface temperatures increase with 2.5–3 °C in the Baltic Sea and 1–2 °C in the North Sea from the most recent 30-year period to the last 30-year period of the 21st century (Fig. 4). For scenario SSP1-2.6 the increase is smaller with about 1 °C in the Baltic Sea and < 0.5 °C in the North Sea, and in some regions near the outer boundaries the temperatures decrease rather than increase. The changes are generally smaller in the bottom water than in the surface water, except for the decreasing temperatures in the North Sea that are larger in the bottom water than in the surface water. The changes in the Baltic Sea are within the range of changes reported earlier, e.g., *Climate Change in the Baltic Sea* (2021), considering that the CMIP6 reference period is later than those of the earlier CMIPs.

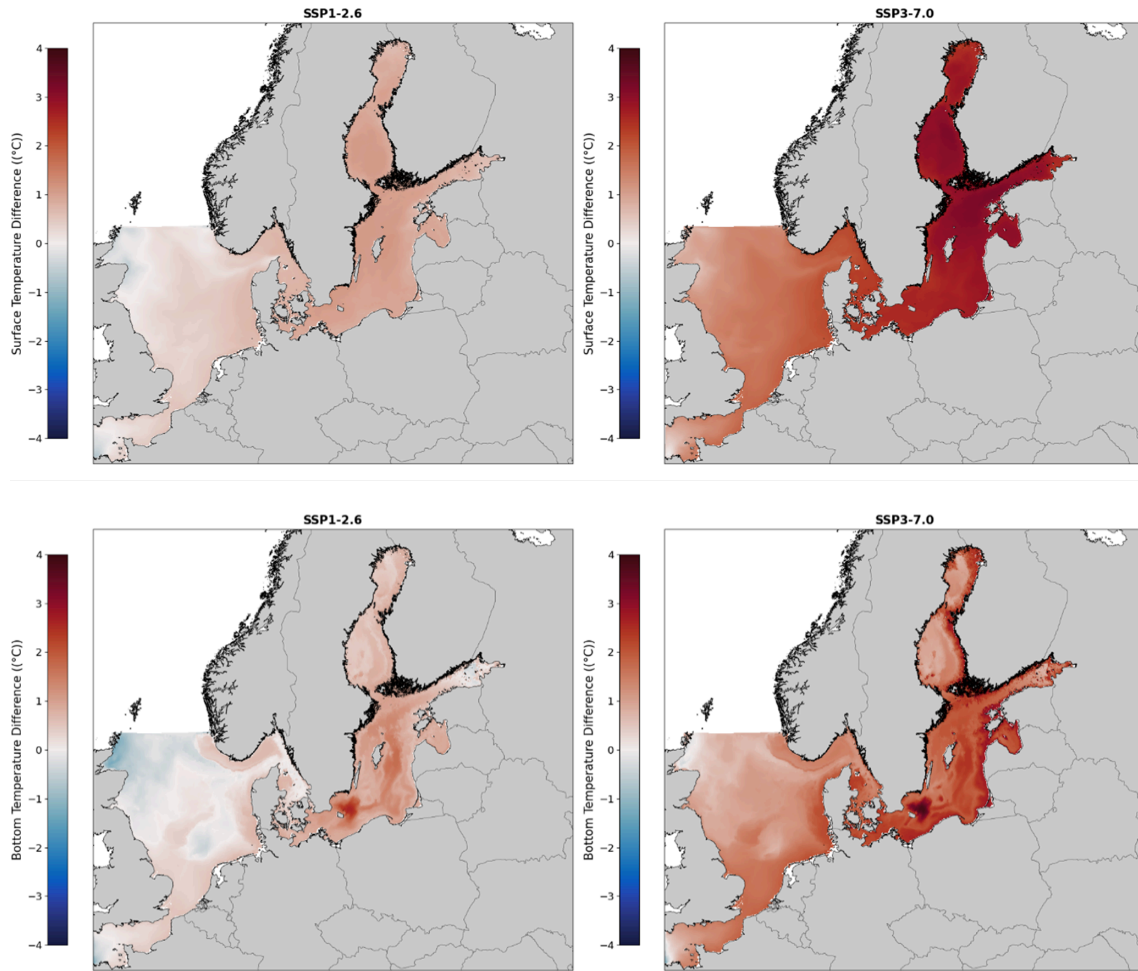


Figure 4. Surface (top row) and bottom (bottom row) temperature differences between the periods 1985–2014 and 2070–2099 for the scenarios SSP1-2.6 (left) and SSP3-7.0 (right).

The salinities show a general decrease (Fig. 5), most in the Baltic Sea bottom water with about 2 g/kg for the SSP3-7.0 scenario, and somewhat smaller decreases for the SSP1-2.6 scenario, Baltic surface waters and North Sea bottom and surface waters. In the central surface waters of the Skagerrak, there are increasing salinities, which are largest for the SSP1-2.6 scenario. This must be associated with a strengthening of the gradient between coastal and central Skagerrak salinities. Decreasing salinities are also found in earlier assessments for both the Baltic Sea (*Climate Change in the Baltic Sea* 2021) and North Sea (Quante and Colijn 2016). For the Baltic Sea, the results are sensitive to the assumption of no sea level rise, which would increase the salinities in the Baltic Sea due to larger inflows of saline water. The present result therefore probably represents an overestimate of the salinity decrease in the Baltic Sea.

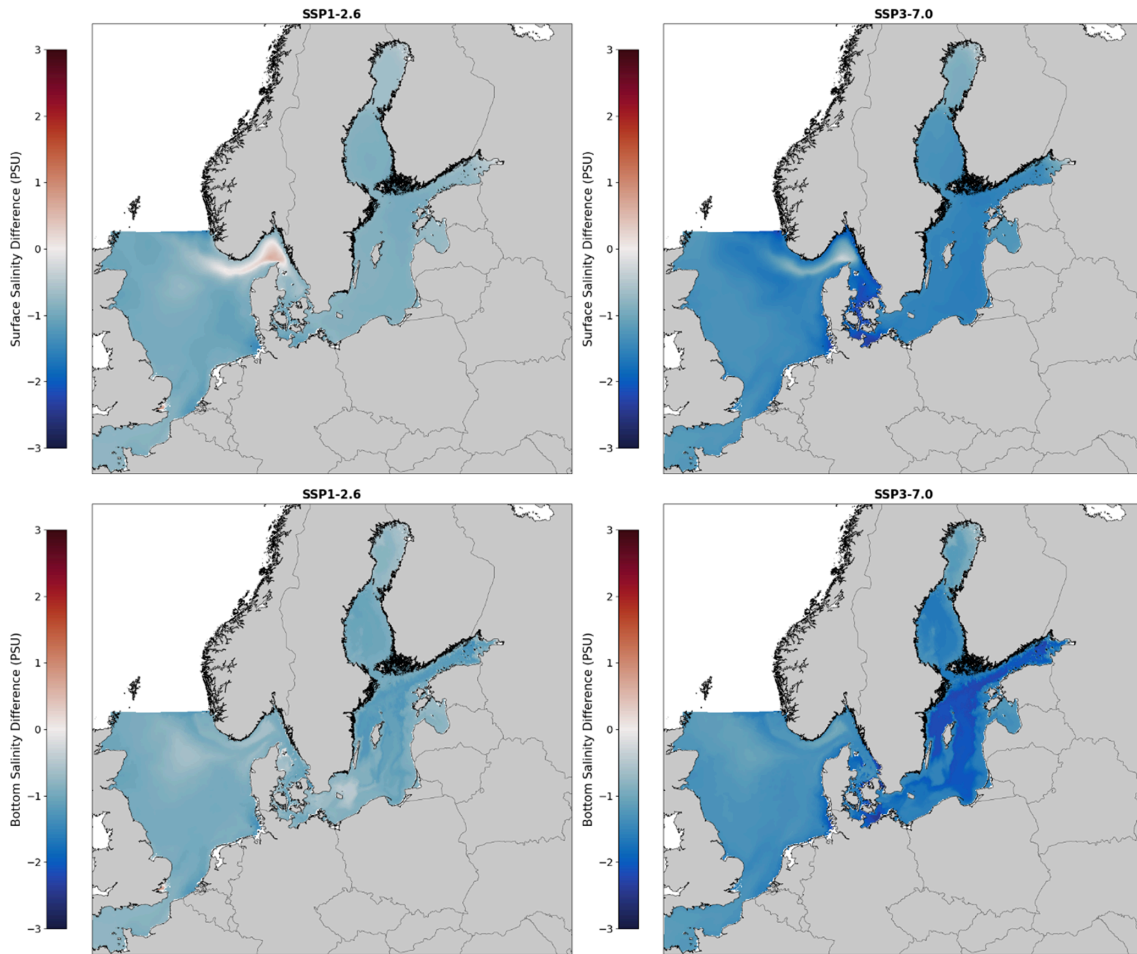


Figure 5. Surface (top row) and bottom (bottom row) salinity differences between the periods 1985–2014 and 2070–2099 for the scenarios SSP1-2.6 (left) and SSP3-7.0 (right).

The ice cover (Fig. 6) is decreasing for both scenarios, but most for SSP3-7.0, where ice will mainly be present only in the Gulf of Bothnia and Gulf of Finland, and where the central parts of the Bothnian sea will be ice free most years in the future period.

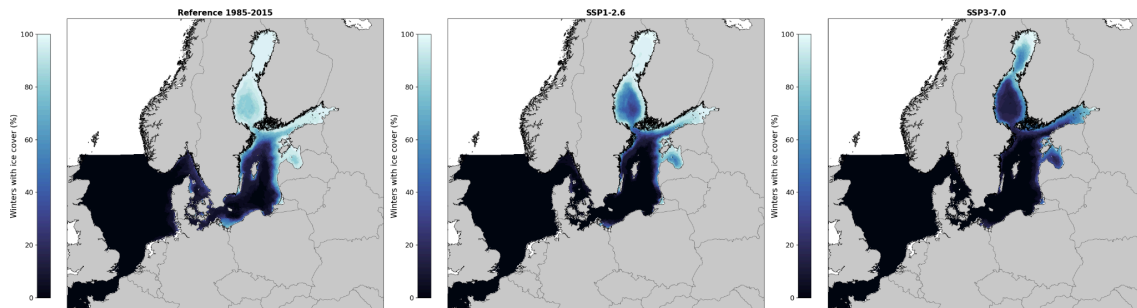


Figure 6. Percentage of winters with ice cover for historical period (1985–2014, left panel), and future period (2070–2099) for SSP1-2.6 (central panel), and SSP3-7.0 (right panel).

The time evolution of sea surface temperature and sea surface salinity for the North Sea, the Kattegat, and the Baltic Sea (Fig. 7) show the same changes as illustrated in Figs. 4 and 5, but they also show the multidecadal variability, which dominates the SSP1-2.6 signal for sea surface temperature, whereas the long-term climate trend is clearer in the SSP3-7.0 temperatures and for both scenarios for sea surface salinity. For sea surface temperature the increase is noticeably larger in the Baltic Sea than in the North Sea.

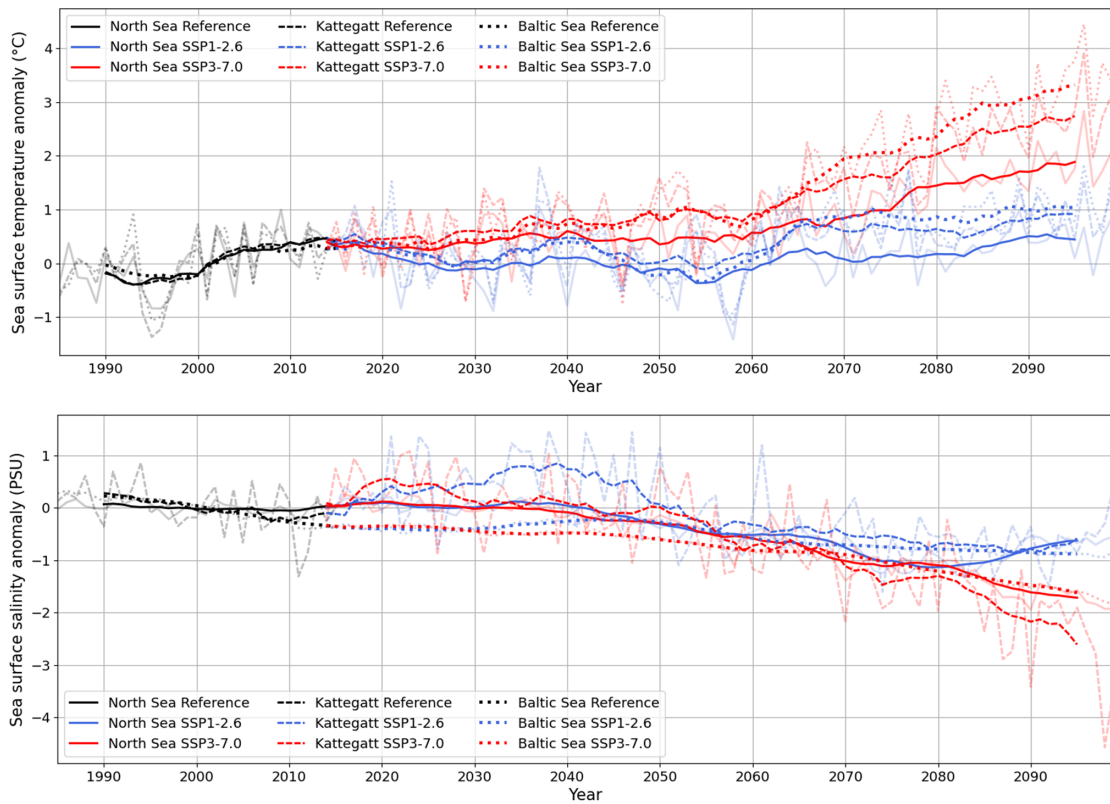


Figure 7. Sea surface temperature (upper panel) and sea surface salinity (lower panel) changes. Regionally averaged time series of the differences relative to the historical period 1985–2014 for the scenarios SSP1-2.6 (blue) and SSP3-7.0 (red) in the three regions North Sea (solid), Kattegatt (dashed) and Baltic Sea (dotted). Transparent lines represent the annual mean, whereas the bold lines show a 10-year running mean.

3.2.2 Downscaled biogeochemical fields

The difference between the future (2070–2099) and historical period (1985–2014) surface average winter dissolved inorganic nitrogen (DIN), shows a decrease in a large part of the coastal areas in the Baltic Sea and North Sea. However, in the Gulf of Bothnia, along the Scotland coast, southern England and to a small extent also along the eastern coast of southern Sweden, DIN increases (Fig. 8, top). This pattern suggests a strong influence of the riverine nutrients input and consequently its main assumptions. In most areas, E-HYPE future adjusted projections indicate an increase in runoff and generally a decrease in nutrient loads and nutrient concentration (Figs. 2 and 3). Exceptions are the discharges in the Gulf of Bothnia (Figs. 2 and 3) and Scotland (not shown), where future river loads show a slight increase, where DIN increase is detected. As scenario SSP 3-7.0 projects a higher runoff increase, the pattern is enhanced and the winter DIN concentration differences between future and present are higher. Spatially, the changes in averaged winter DIN concentrations are relatively more important in the Kattegat (decrease) than in the North Sea (decrease) and in the Baltic Sea (increase), as shown in Fig. 8 (bottom) through the whole simulation period. Similar results are found for winter dissolved inorganic phosphorus (DIP) concentrations (Fig. 9 bottom). There is a projected decrease in most of the Baltic Sea and coastal areas with some exceptions that likely result from the influence of the increased riverine phosphorus input, e.g. Gulf of Bothnia (shown in Fig. 3) and Gulf of Riga (not shown).

In general, the nutrient loads are projected to decrease in the future scenarios, with less decrease in the SSP3-7.0 scenario compared to the SSP1-2.6 scenario (or slight increase), which is also reflected in the nutrient concentration changes. Thus, the decrease in dissolved phosphate in the Kattegat area, the Baltic Sea and in the North Sea are larger in the SSP1-2.6 scenario (Fig. 9 top). The decreases are found along the southern North Sea coastline, the Kattegat area and the Baltic proper (Fig. 8 bottom).

Changes in the riverine nutrient loads and runoff will imply changes in biogeochemical processes, namely in the primary production and phytoplankton concentration (Figs. 10 and 11), and ultimately in bottom oxygen conditions (Figs. 12 and 13). In a general view, the system is highly dominated by the riverine loads. In the above identified areas where nitrogen and phosphate concentrations were projected to decrease, chlorophyll concentrations are projected to be reduced (Figs. 10 and 11) and bottom oxygen concentrations to increase (Figs. 12 and 13).

In summary, the results show the importance of riverine nutrient loads in the Baltic Sea and North Sea biogeochemical variables dynamics. In general, the scenario SSP1-2.6 conditions project an overall improvement in water quality state and

eutrophication conditions in the study area. Nutrient loads from rivers are reduced, primary production is reduced, and bottom oxygen conditions improve in most of the areas. Scenario SSP3-7.0, in turn, corresponds to a worse scenario by projecting less decreased riverine loads, but higher runoff, which leads to higher primary production and eutrophication processes in the system. However, this scenario does not seem to be worse than the current conditions and will even project an improvement of the ecosystem dynamics in terms of primary production and eutrophication problems.

The results of the present study agree with previous studies conducted in the Baltic Sea area (Saraiva et al. 2019a, b) where conclusions indicate that for most of the included future scenarios (within the previous CMIP5 ensemble) the overall water quality state of the Baltic Sea is expected to improve, as long-lasting consequence of on-going nutrient load reductions since the 1980s. The impact of warming climate may amplify the effects of eutrophication and primary production. However, effects of changing climate, within the range of considered greenhouse gas emission scenarios, are smaller than effects of considered nutrient load changes. Generally, water quality conditions are expected to improve.

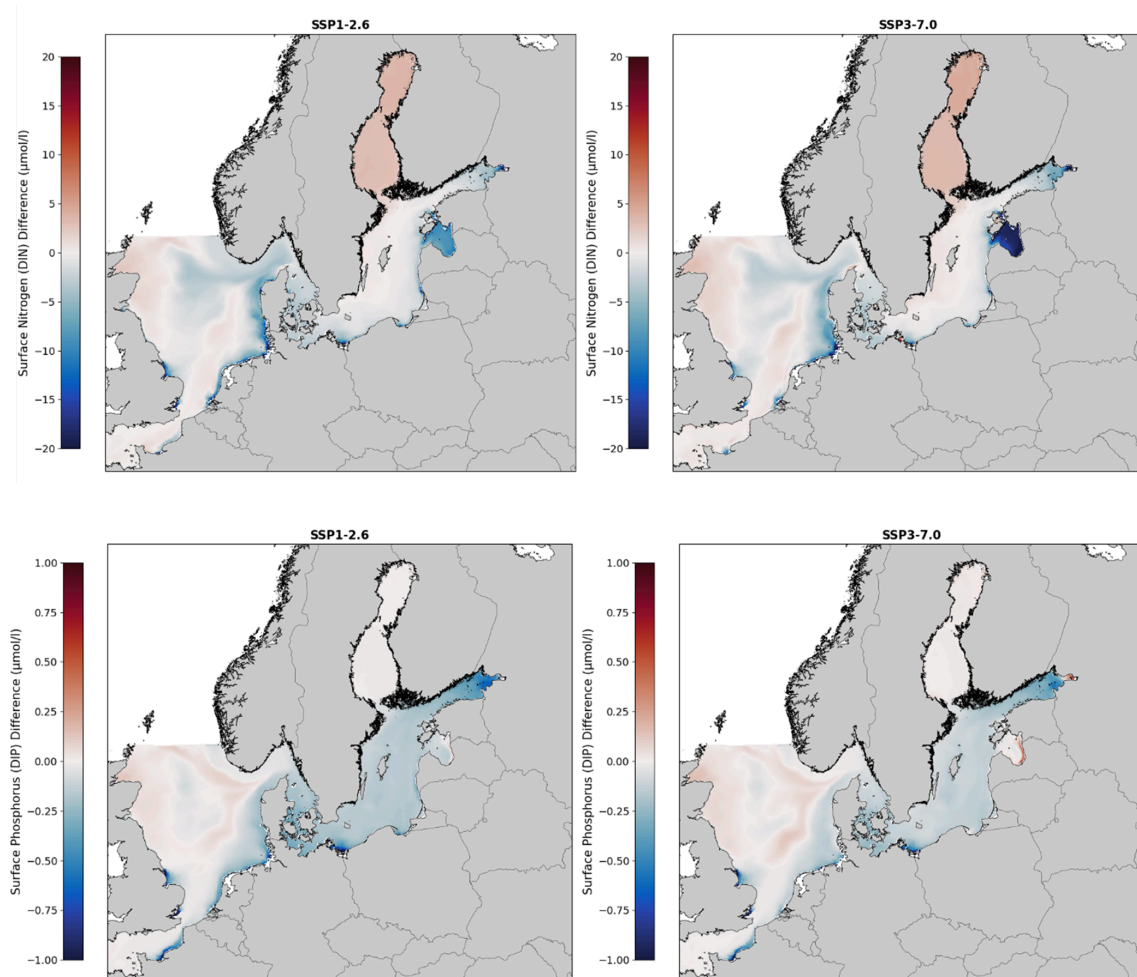


Figure 8. Winter surface Dissolved Inorganic Nitrogen concentration, DIN (top row) and winter Dissolved Inorganic Phosphorus concentration, DIP (bottom row): differences between average present conditions (1985–2014) and future scenarios (2070–2099) SSP1-2.6 (left) and SSP3-7.0 (right).

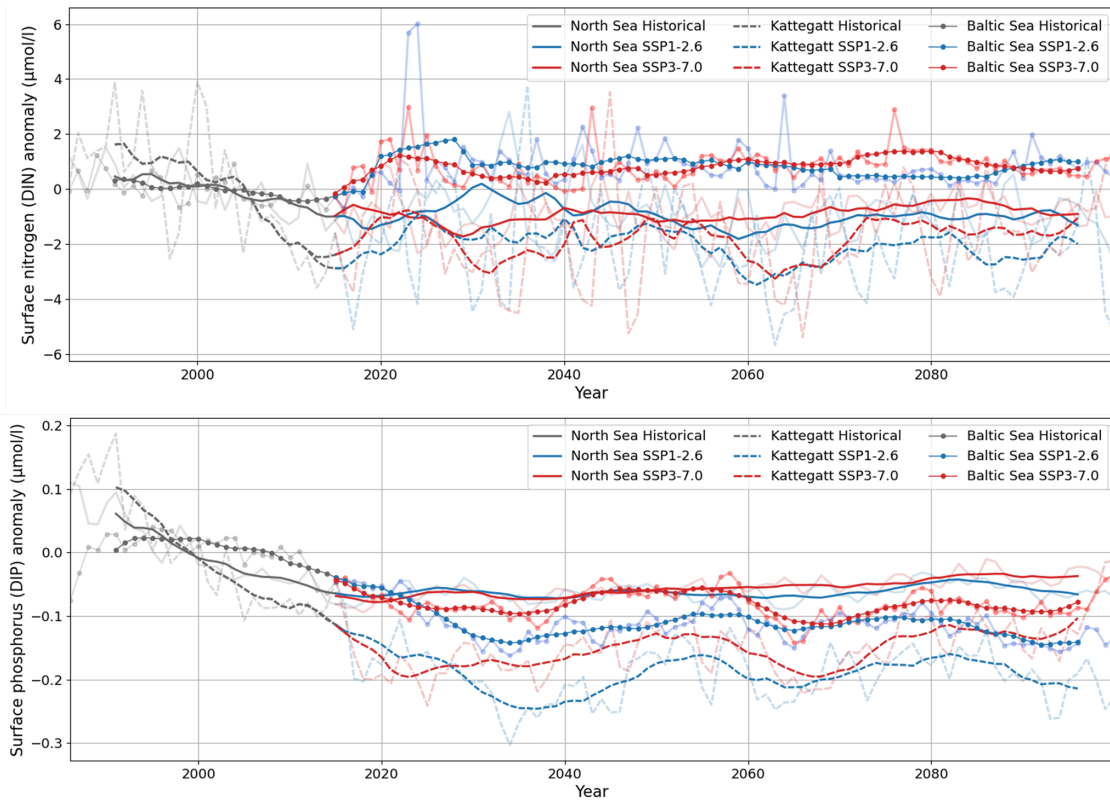


Figure 9. Winter dissolved inorganic nitrogen (DIN) (top bar) and dissolved inorganic phosphorus (DIP) concentration changes: Regionally averaged time series of the differences relative to the historical period 1985–2014 for the scenarios SSP1-2.6 (blue) and SSP3-7.0 (red) in the three regions North Sea (solid), Kattegatt (dashed) and Baltic Sea (dotted). Transparent lines represent the annual mean, whereas the bold lines show a 10-year running mean.

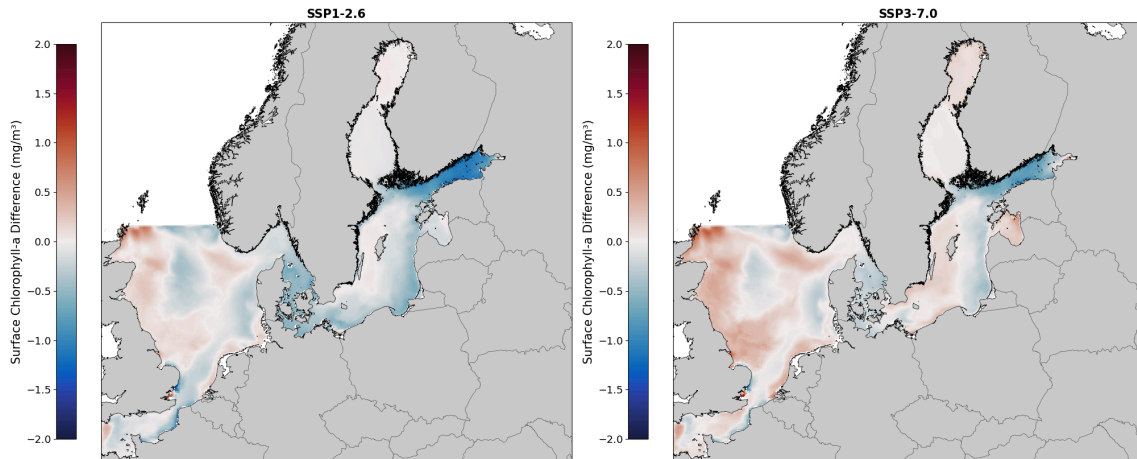


Figure 10. Surface chlorophyll-a concentration: differences between average current conditions (1985–2014) and future scenarios (2070–2099) SSP1-2.6 (left) and SSP3-7.0 (right).

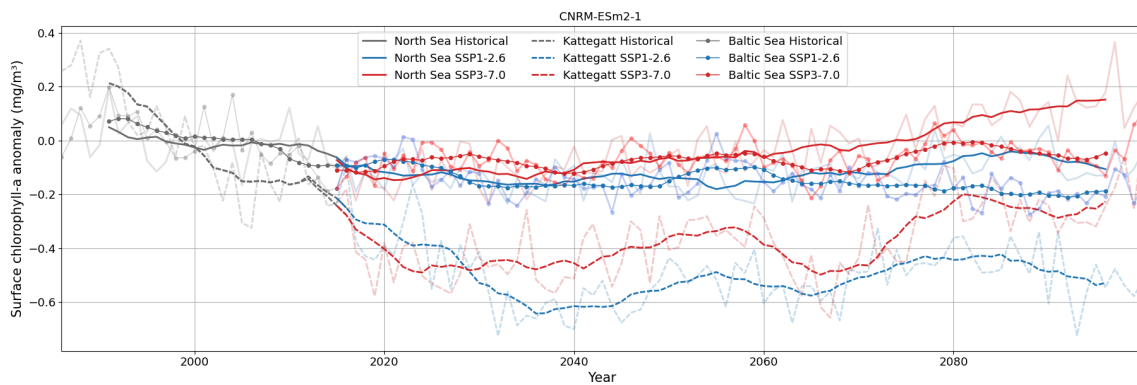


Figure 11. Surface chlorophyll-a concentration changes: Regionally averaged time series of the differences relative to the historical period 1985–2014 for the scenarios SSP1-2.6 (blue) and SSP3-7.0 (red) in the three regions North Sea (solid), Kattegatt (dashed) and Baltic Sea (dotted). Transparent lines represent the annual mean, whereas the bold lines show a 10-year running mean.

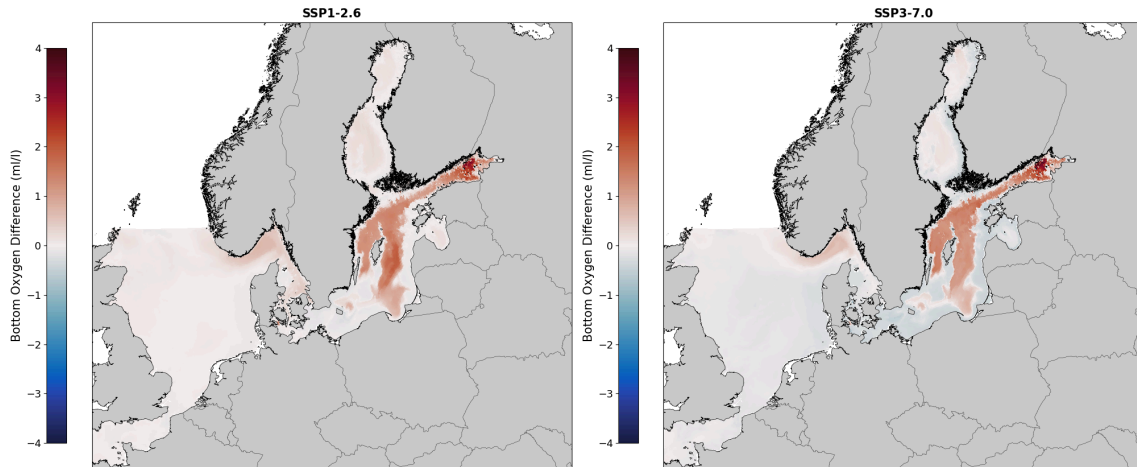


Figure 12. Bottom oxygen concentration: differences between the periods 1985–2014 and 2070–2099 for the scenarios SSP1-2.6 (left) and SSP3-7.0 (right).

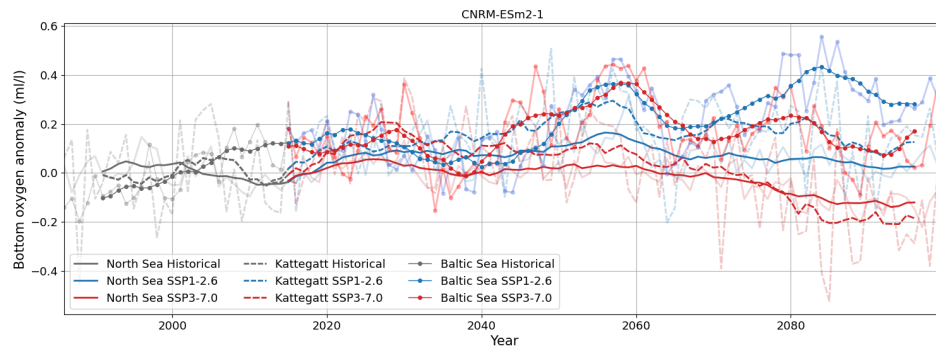


Figure 13. Bottom oxygen concentration changes: Regionally averaged time series of the differences relative to the historical period 1985–2014 for the scenarios SSP1-2.6 (blue) and SSP3-7.0 (red) in the three regions North Sea (solid), Kattegat (dashed) and Baltic Sea (dotted). Transparent lines represent the annual mean, whereas the bold lines show a 10-year running mean.

4. Modelling historical and future conditions in Limfjorden

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4.1 Description of Limfjorden

Limfjorden is a shallow fjord with an average depth of 4.8 meters, consisting of several smaller basins connected by narrow straits (Fig. 14). It is located in the northern part of Denmark, with connections to the North Sea to the west and the fresher Kattegat to the east. Therefore, the salinity in the fjord varies from 32–34 psu in the west to 19–24 psu in the east (Fig. 14). Additionally, there is low salinity in basins with high freshwater inflow. The main current flows from west to east, modified by wind direction and a weak tidal signal (Schourup-Kristensen et al. 2021). Limfjorden has high concentrations of nutrients with seasonal oxygen depletion (hypoxia) in the inner basins and a high population of blue mussels (Maar et al. 2023a, Schourup-Kristensen et al. 2023). The system receives nutrients from freshwater sources, as the catchment area is dominated by agriculture, and the fjord is therefore in poor ecological condition according to the EU Water Framework Directive. Limfjorden is the most important area for mussel fishing and -farming in Denmark. Mussel dredging is currently the most important type of fishing, as the fish stocks in the fjord collapsed in the 1990s. Since then, mussel catches have fallen from about 122 Kt wet weight in 2001 to 20 Kt wet weight in 2022 (data from the Danish Fisheries Agency). However, mussel harvests from commercial farms have increased from very low numbers in 2009–2017 to 8.4 Kt wet weight in 2022 due to higher technological expertise and good profitability. The number has not increased in very recent years though, due to a temporary ban on new permits. Still, the number of applications is about the same as the number of current farms, so when the government approves new permits, growth is expected. Additionally, Limfjorden is an important area for tourism and recreational activities.

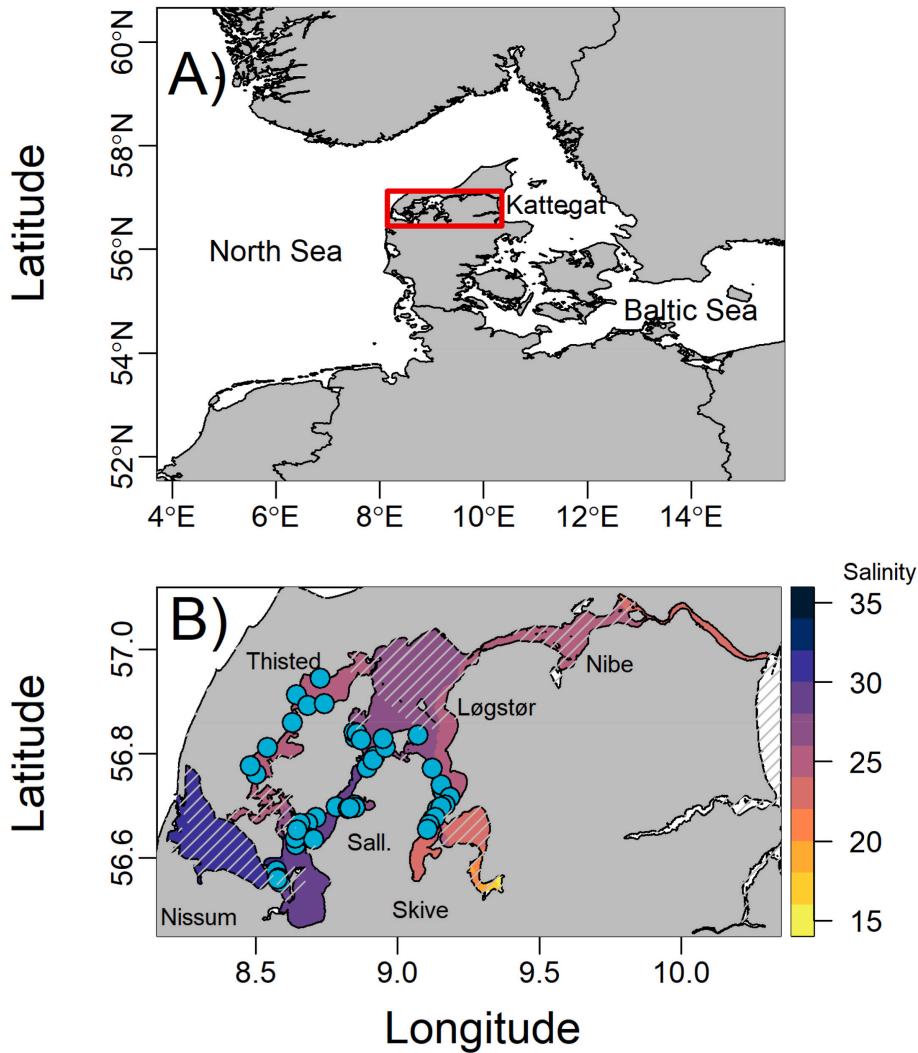


Figure 14. A) Limfjorden (red box) is located in the northern part of Denmark between the North Sea and Kattegat and B) modelled surface salinity (color bar), mussel farms (cyan points), and names of the main basins; Nissum Broad (Nissum), Sallingsund (Sall.), Thisted Broad (Thisted), Løgstør Broad (Løgstør), Skive Fjord (Skive), and Nibe Broad (Nibe). Grey hatched lines are the Natura 2000 areas where mussel farming is not allowed. From Maar et al. (2024).

4.2 FlexSem model for Limfjorden

The FlexSem model has been set up in a 3D coupled hydrodynamic-biogeochemical model for Limfjorden (Larsen et al. 2020, Maar et al. 2024). The model used an unstructured grid with 6,686 elements covering a total area of 1,502 km² (Fig. 15). The size of the elements varied from 143 m to 1,773 m with an average of 474 m. The vertical resolution was 1.5 m in the flexible surface layer, followed by nine 1 m depth layers and three 5 m layers, with a maximum water depth of 30 m. The

hydrodynamic model solved the Navier-Stokes equations for velocities and the advection-diffusion equations for the transport of tracers (e.g., heat, salinity, nutrients). The turbulent part of the hydrodynamic solution was modelled using a k-epsilon model in the vertical and a Smagorinsky model in the horizontal. A surface radiation model calculated heat transfer through the sea surface and changed the water temperature.

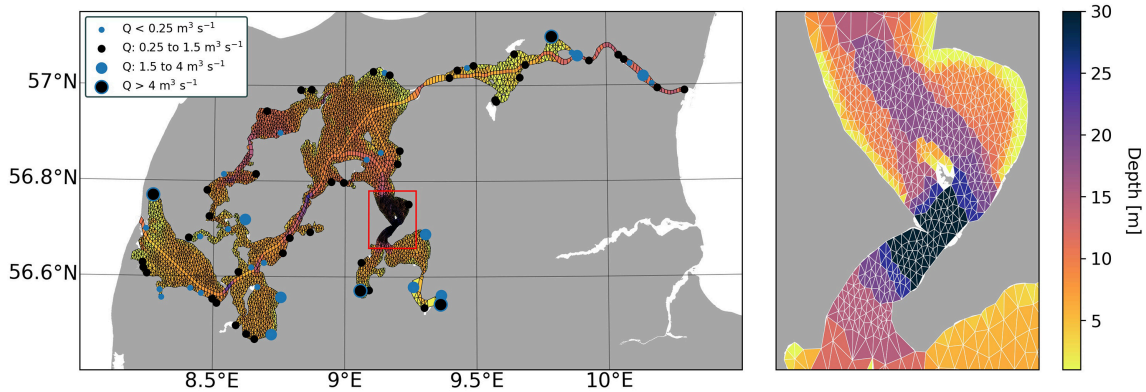


Figure 15. The FlexSem model setup for Limfjorden shows water depth (colour scale), elements (grey polygons), and freshwater sources categorized by size (blue/black circles). The panel on the right is a close-up of the area within the red square on the left. From Schourup-Kristensen et al. (2021).

The hydrodynamic model was fully coupled to a biogeochemical model, which includes a water phase model, coupled to a sediment model and a mussel model (Maar et al. 2023a, 2024). The model describes the state and changes in nutrients (nitrate, ammonium, phosphate), phytoplankton (picoplankton, flagellates, diatoms), micro- and mesozooplankton, detritus, oxygen, bottom-dwelling mussels, small animals in the sediment, and sediment pools of nutrients over time and space (Fig. 16). The described processes include nutrient uptake, growth, grazing, mortality, respiration, nutrient excretion, sedimentation, resuspension, detritus decomposition, nitrification, denitrification, diffusion between the water column and sediment, and nutrient regeneration. The mussel model is a dynamic energy budget model that describes the ecophysiological growth of mussels in a mussel farm and feedback mechanisms to the ecosystem (Fig. 16).

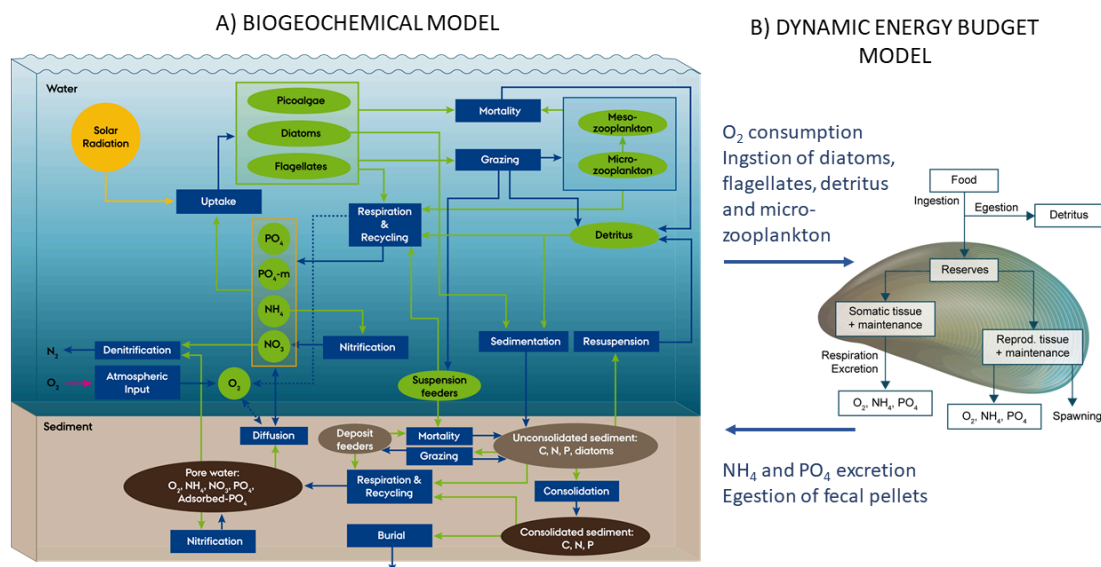


Figure 16. Conceptual model diagram of the biogeochemical model applied in FlexSem for Limfjorden. The blue background represents the water column and the brown background the sediment. The green and brown ovals show the state variables in the water column and sediment, respectively, and the blue boxes represent ecosystem processes. The biogeochemical model is two-way coupled to a dynamic energy budget mussel model. Extended from Schourup-Kristensen et al. (2023).

The reference scenario in Limfjorden used historical data (2009 to 2018) for atmospheric pressures, open boundary conditions, and freshwater runoff. Atmospheric data were taken from the EC-Earth CMIP6 simulations, as they showed the best quality in the study area (Kristiansen & Butenschön 2023). Limfjorden has two open boundaries, one towards the North Sea and one towards Kattegat. Values for salinity, temperature, water level, and current speeds at the two open boundaries were provided by the HIROMB-BOOS-HIRLAM model (Murawski et al. 2021). Boundary values for nutrients, Chl *a* (distributed in the three phytoplankton groups), and oxygen were obtained from monitoring data (<https://odaforalle.au.dk/>). Runoff (diffuse and point sources) and nutrient input (TN=total nitrogen and TP=total phosphorous) were obtained from the SWAT catchment model with 79 sources with daily resolution (Molina-Navarro et al. 2017). There were 14 active commercial mussel farms, which represents the average mussel production in the reference period.

IPCC works with a set of different scenarios for future greenhouse gas emissions and thus the future climate of the planet. In this study, EC-Earth CMIP6 simulations were used, as the downscaled CMIP7 products were not yet available

when the study was conducted. The three climate scenarios used (SSP1-2.6, SSP2-4.5, and SSP5-8.5) are named after different socio-economic developments (SSP) and the level of radiative forcing in the year 2100 of 2.6, 4.5, and 8.5 W/m², respectively (Table 3). SSP1-2.6 is largely consistent with the maximum atmospheric CO₂ concentration required under the Paris Agreement, which aims to “significantly reduce global greenhouse gas emissions to limit the global temperature increase this century to 2 °C while pursuing efforts to limit the increase even further to 1.5 °C.”

Greenhouse gas emissions are partially higher in SSP2-4.5, while they continue to rise throughout the whole 21st century in SSP5-8.5. The scenarios were conducted for the periods 2051–2060 and 2090–2099. There was a spin-up period of 10 years to achieve semi-stable conditions for the water column and sediment. A statistical downscaling of several sea models for the North Sea was used to create monthly average values for temperature, salinity, Chl *a*, and oxygen for boundary data in the scenarios (Kristiansen & Butenschön 2023), while all other variables remained unchanged from the reference period. The SWAT catchment model made future runs under the three scenarios to calculate future runoff and nutrient load.

In the SSP1-2.6 and SSP2-4.5 scenarios, it was also assumed that reductions in land-based nutrient loads were implemented according to the Danish water plans (36% reduction of the current N load, no P reduction required) (Danish Ministry of Environment and Food 2016). In the SSP5-8.5 scenario, it was assumed that the national water plans were not implemented due to the growth of the agricultural sector with little regard for environmental impacts (Table 3). We assumed that mussel production would be intensified (52 commercial mussel farms) to meet the global market demand for protein foods with a low CO₂ footprint in all scenarios after consultation with stakeholders in the EU FutureMARES project.

Table 3. Overview of model reference period and future scenarios with time periods, number of mussel farms, degree of reduction of nitrogen supply, implementation of water plans, and emission level.

Scenario	Period Years	Number of commercial mussel farms	Reduction of N supply	Implementation of water plans	Emission levels
Reference	2009– 2018	14	-	Reference period	Reference period
SSP1- 2.6	2051– 2060 2090– 2099	52	36%	Water plans implemented	Low
SSP2- 4.5	2051– 2060 2090– 2099	52	36%	Water plans implemented	Intermediate
SSP5- 8.5	2051– 2060 2090– 2099	52	0%	No water plans implemented	High (worst case)

4.3 Downscaled physical model fields for Limfjorden

4.3.1 Historical

The shallow Limfjord is characterized by a salinity of approximately 32–34 psu in the western part, connected to the North Sea, and lowest in the innermost part of the fjord where there is high runoff (20 psu, Fig. 17). Surface temperatures also show a gradient with slightly warmer water towards the west and cooler water towards the east and in the innermost part (Fig. 18).

Before the model is applied for the future, it is important to verify that it works well for present and historical times. For model verification we apply so-called Taylor diagrams, which indicate correlation coefficient, bias, and the normalized standard deviation, nSD, between the model and observation-based data. Results with a high correlation, low bias, and an nSD within $1 \pm 25\%$ show the best representation

of the measurement data. Comparison with measurements in the reference period shows good agreement both seasonally, between years, and spatially between stations for both salinity and temperature (Figs. 17 and 18).

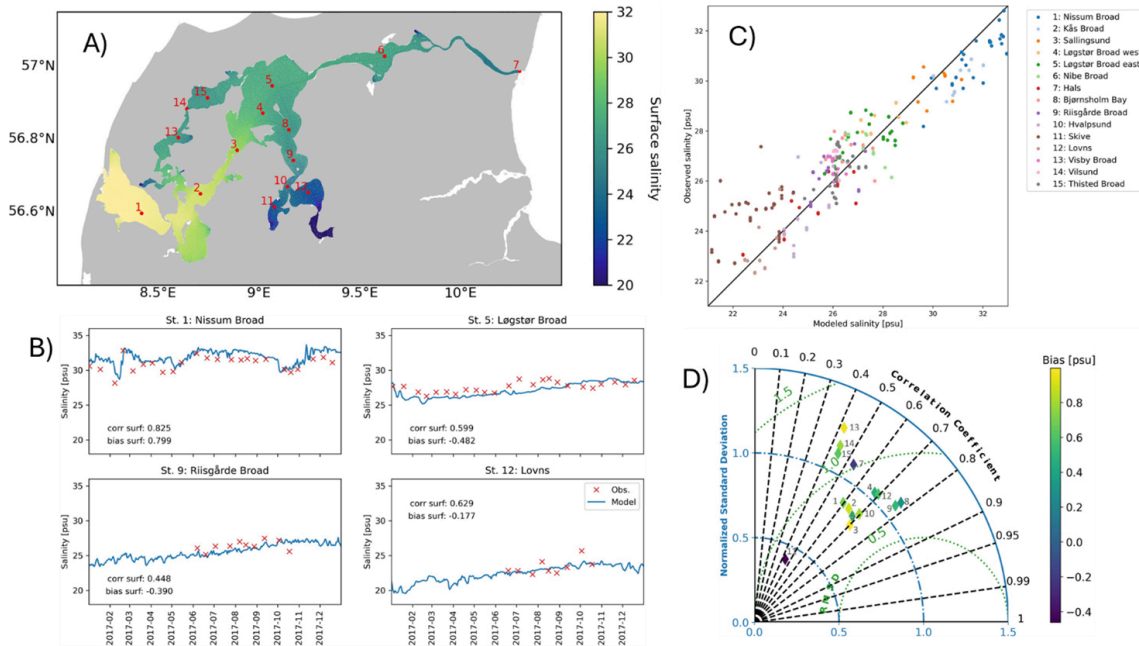


Figure 17. Salinity in Limfjorden. Modelled A) and measured B) values and model validation (C, D). A) Modelled average salinity, B) time series for selected stations in 2017, C) correlation between model and measurements for all stations, D) Taylor diagram showing correlation coefficient, bias (colour scale), and the normalized standard deviation between model and data. Compiled from Schourup-Kristensen et al. (2021).

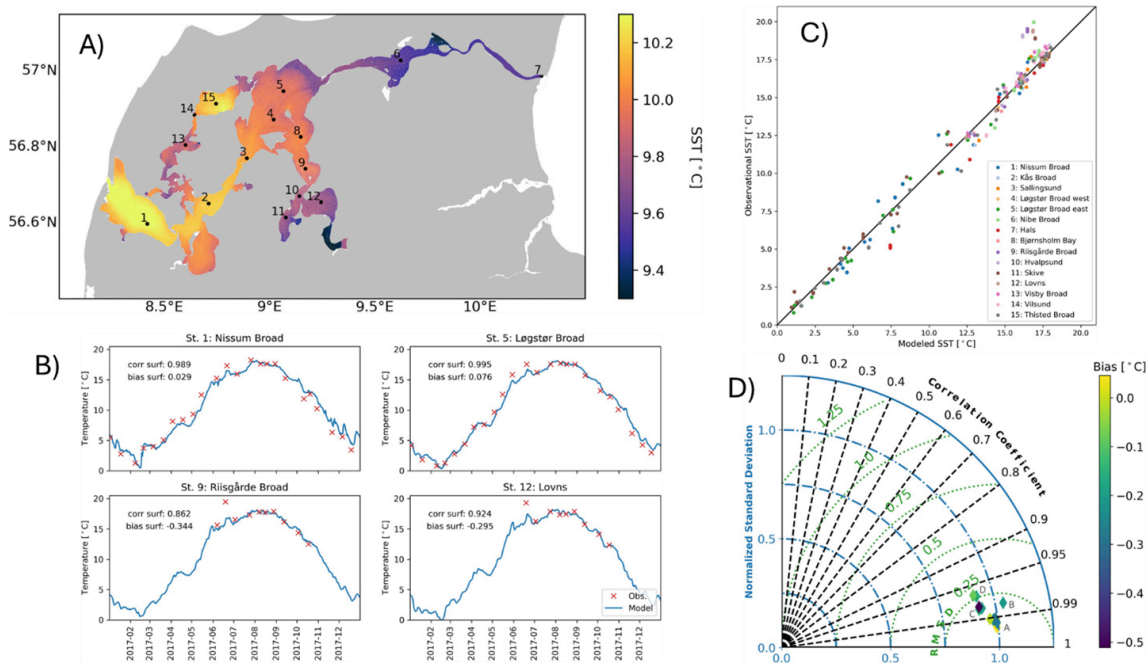


Figure 18. Temperature in Limfjorden. Modelled A) and measured B) values and model validation (C, D). A) Modelled average salinity, B) time series for selected stations in 2017, C) correlation between model and measurements for all stations, D) Taylor diagram showing correlation coefficient, bias (colour scale), and the normalized standard deviation between model and data. Compiled from Schourup-Kristensen et al. (2021).

4.3.2 Scenarios

Climate scenarios for Limfjorden generally show the greatest change in physics for SSP5-8.5 and the latest period from 2090–2099 (Figs. 19 and 20). Salinity will decrease in all three scenarios by up to 2.2 psu in SSP5-8.5 due to greater runoff from land for the period 2090–2099 (Fig. 19). Water temperature will increase by 1–2 °C in SSP1-2.6 and SSP2-4.5, while it will rise by up to 5 °C in SSP5-8.5 in the last period (Fig. 20). The stratification of the water column is expressed by a PEA index, which indicates how much energy is required to mix it. A high index thus indicates strong stratification of the water column. In the most optimistic scenario, SSP1-2.6, there is only a small change in stratification in the future, while in the other two scenarios, stronger stratification is seen, especially in SSP5-8.5 for the last period (Figs. 19 and 20).

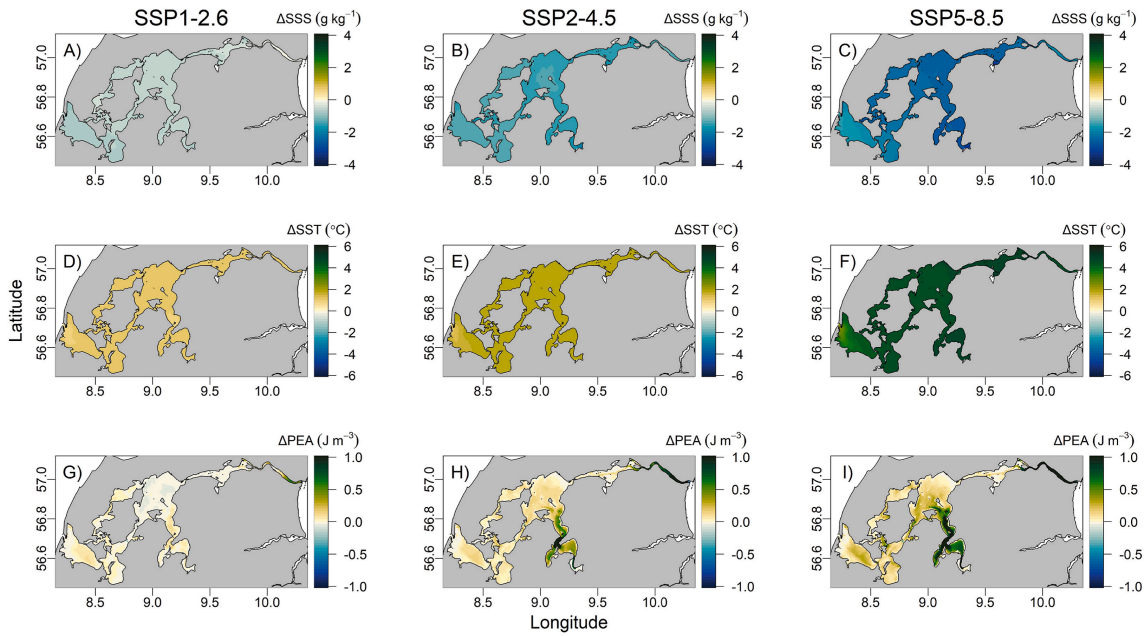


Figure 19. Changes in surface salinity (first row), surface temperature (second row), and stratification index (PEA, third row) in the three scenarios for the period 2090–2099 relative to the reference period. From Maar et al. (2024).

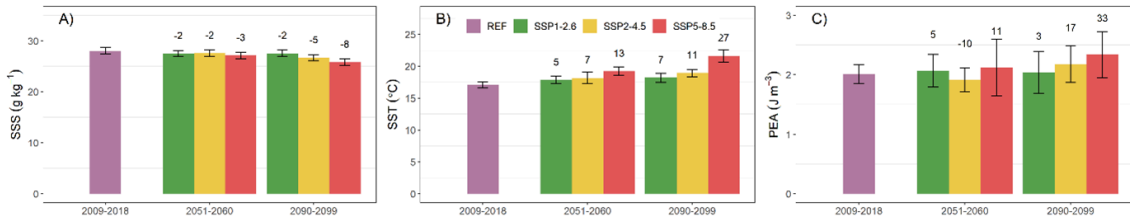


Figure 20. Average (±std) reference values (purple bar) and future changes in the three scenarios (green, yellow, red) for A) surface salinity (SSS), B) surface temperature (SST), and C) stratification Index (PEA) for the two time periods 2051–2060 and 2090–2099. Values above the bars are the percentage change relative to the reference period.

4.4 Downscaled physical-chemical-biological fields for Limfjorden

4.4.1 Historical

Results from the biogeochemical model during the reference period were compared with seasonal measurements from the ODA database. The seasonal variation of dissolved inorganic nutrients from the biogeochemical model during the reference period were compared with seasonal measurements from the ODA database. The seasonal variation of Dissolved Inorganic Nitrogen (DIN) is relatively large (Fig. 21A). In summer, the concentration is low at all stations, while the concentration increases during autumn and early winter. The model follows the seasonal cycle of the observations, although the model shows less short-term variation. Phosphate is also depleted in spring, but in mid-summer the surface concentration of phosphate increases again at all stations due to oxygen starvation-induced release from the sediment. The seasonal cycle of phosphate is well represented in the model, although there are occasionally higher summer values than seen in measurements (Fig. 21B).

The spring phytoplankton bloom, which takes place from February to April, is represented by the model in terms of timing and size (Fig. 21C). The subsequent low summer Chlorophyll *a* concentration and the autumn bloom in the Skive fjord are also represented in the model. During autumn and winter, the fjord has blooms of mixotrophic organisms in some years that are not represented by the functional plankton groups in the model.

The bottom oxygen concentration reaches a maximum in early spring when the water is mixed due to strong winds, the water temperature is low and biological consumption is reduced (Fig. 21D). After the spring bloom of phytoplankton and the accompanying transport of biological material to the sediment, the oxygen concentration decreases and reaches a minimum in late summer. The model reproduces the general trend of the seasonal cycle. However, the short-term variation is not fully represented by the model.

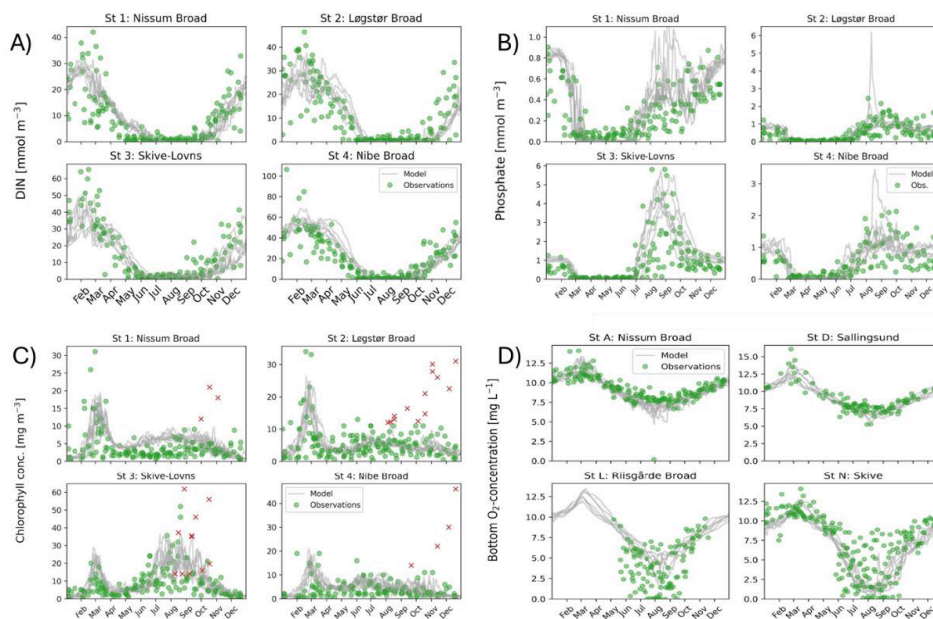


Figure 21. Comparison of model and measurements over time for A) DIN ($\text{NO}_3 + \text{NH}_4$) concentration, B) phosphate concentration, C) Chl *a* concentration, and D) bottom oxygen concentration for the reference period for four selected stations. The grey lines are modelled values and the green circles measurements for each of the 10 years. The red crosses in C) are mixotrophic species not described in the model.

The model validation was also here summarised in Taylor plots for DIN, PO_4 , Chl *a* and oxygen using the time series from 2011 to 2017. For closer examination of these plots, we refer to scientific papers by M. Maar and others, here a summary of the validation results. The modelled DIN has correlations higher than 0.80 at all stations, and nSD is within 1.00 ± 0.25 . The highest deviation is in the location Nibe Bredning, where the modelled values are on average underestimated. These errors are due to winter values, which are largely controlled by freshwater inflow. PO_4 has correlations around 0.70 at all stations. Phosphate concentration is overestimated (high nSD and deviation) at some stations in the model, possibly due to localised oxygen depletion in the model inducing a release of phosphate from the sediment.

The modelled Chl concentrations capture the seasonal cycle well with correlations around 0.50 except for Nibe Bredning due to minor short-term variability in the model in summer. Chl *a* is slightly overestimated at stations 1, 3 and 4 and nSD is within 1.00 ± 0.25 .

The statistics between modelled and observed oxygen concentration are best for stations with a full seasonal cycle of observations (St. A, B, C, I and N, F), while stations with only observed summer values have lower correlation and nSD due to the lack of seasonal variation in the model.

4.4.2 Scenarios

Climate scenarios for the Limfjord generally show greatest change in the ecosystem for SSP5-8.5 and the latest time period from 2090–2099 (Figs. 22 and 23). The greatest development of oxygen depletion is in the worst-case scenario SSP5-8.5, while there are no major changes in oxygen concentration for the less severe scenarios SSP1-2.6 and SSP2-4.5 (Figs. 22 A-C, Fig. 23B). Chl *a* concentration decreases slightly in the two lowest scenarios because the implementation of the Water Management Plans means that there is less nutrients available for algae growth (Figs. 22D-F). Overall, oxygen conditions and Chl *a* levels do not improve enough to achieve a better ecological status even with the implementation of the Water Management Plans (Fig. 23). This is because climate change in the form of increased temperature increases turnover and increased stratification prevents the supply of oxygen to the bottom water.

In the scenario SSP5-8.5, where the Water Management Plans nutrient reduction is not implemented, Chl *a* concentration is overall unchanged, but with a spatial redistribution (Fig. 23C). The biomass of benthic mussels is reduced <15% in the two optimistic scenarios due to lower food concentrations (Chl *a*), but the biomass is reduced more drastically (20–36%) in the worst-case scenario SSP5-8.5 due to the poorer oxygen conditions (Figs. 22 G-I, Fig. 23D).

The harvest of farmed mussels in the water column is expected to increase significantly in all scenarios as more mussel farms are established than in the reference period. Furthermore, farmed mussels are not significantly hampered by climate change induced oxygen depletion, as they are located at the top of the water column with good oxygen conditions and better access to food than at the bottom.

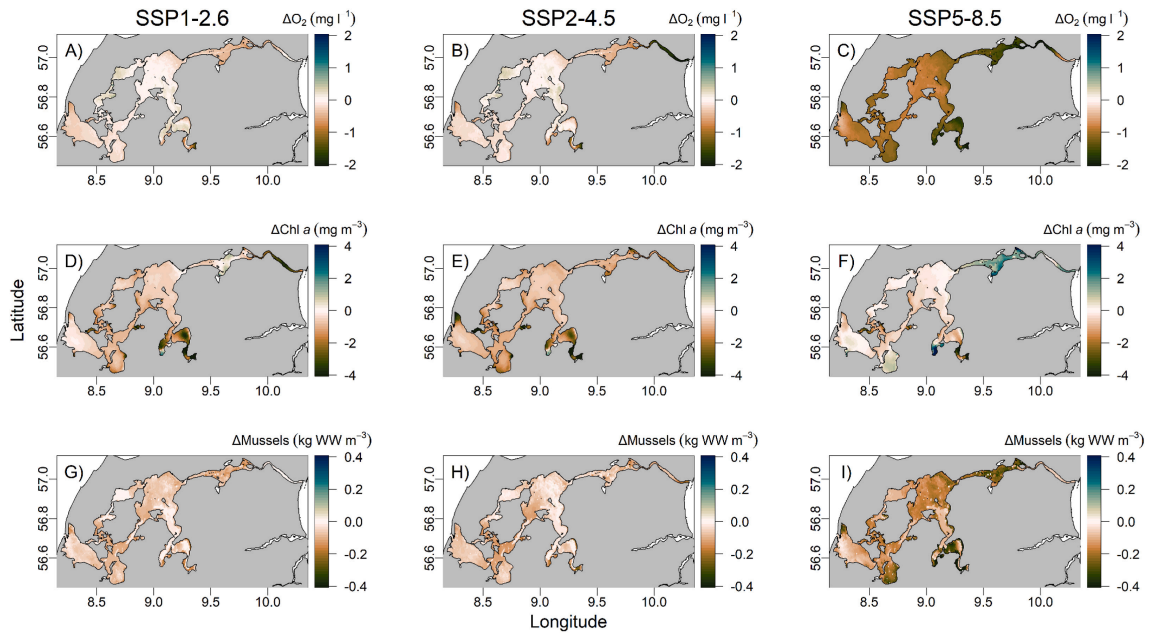


Figure 22. Changes in bottom oxygen (first row), surface Chl-a (second row) and mussel biomass (third row) in the three scenarios for the period 2090–2099. From Maar et al (2024).

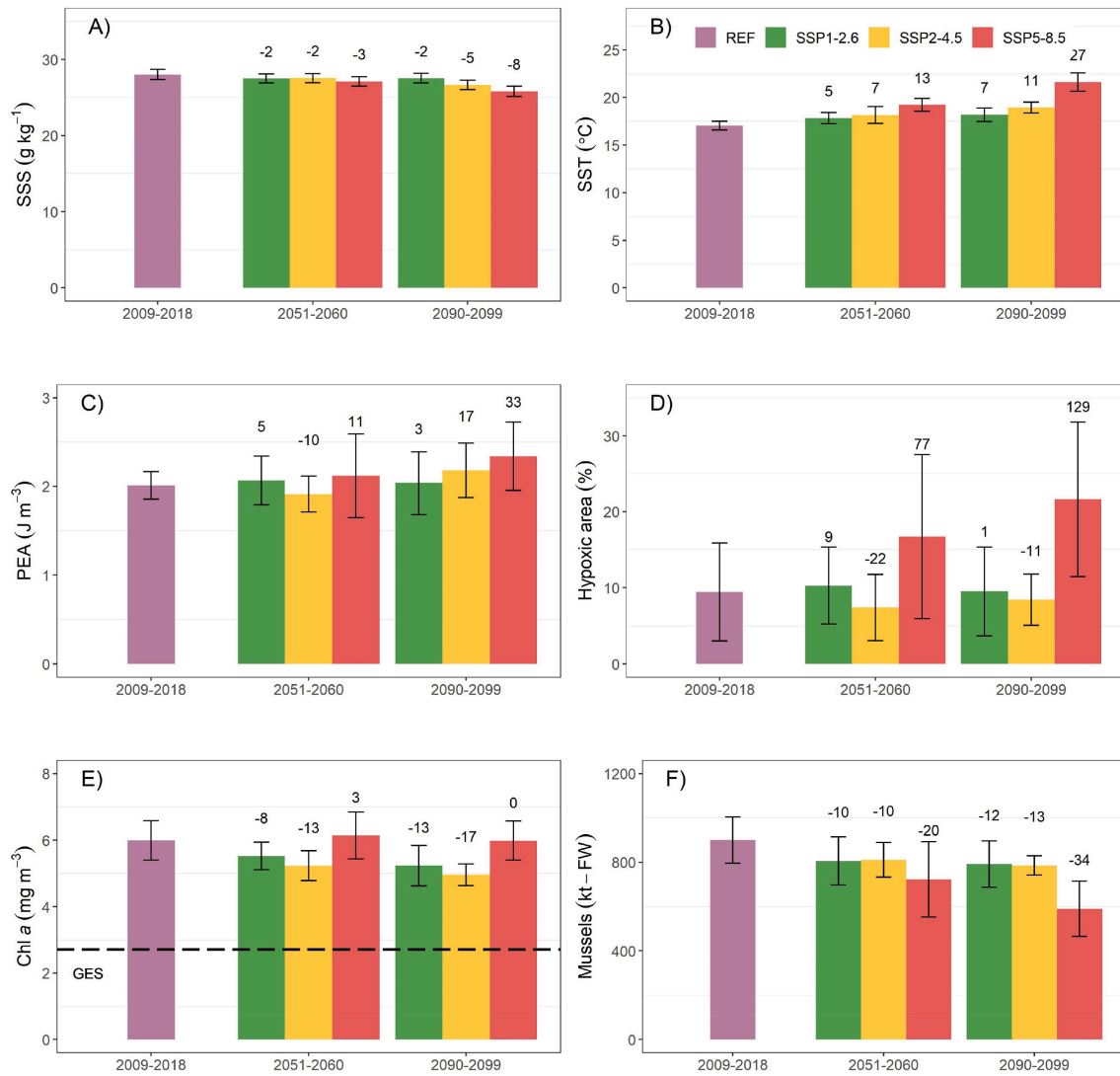


Figure 23. Summer (June to September) means ($\pm$ SD) of A) sea surface salinity (SSS), B) sea surface temperature (SST), C) stratification index (PEA), D) hypoxic area ($<4 \text{ mg l}^{-1}$) as percentage of total area, E) surface Chl a concentration, and F) benthic mussel biomass for the reference period (2009–2018) and the three scenarios and the two time-slices 2051–2060 and 2090–2099. The values above the columns are the percentage deviations from the reference period. The horizontal dashed line in E) indicates the thresholds for a good ecological status (GES).

5. Climate scenarios for the Norwegian and Barents Seas

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5.1 Methods – downscaling with the NEMO-NAA10km model

5.1.1 The ocean model

We here describe the work on and results from the climate downscaling simulations performed by IMR within the NorScen project. For this work to be understood, we first present the framework within which the development was done. This is related to the development of the Nemo-NAA10km ocean model, in climate downscaling mode. Nemo-NAA10km is an ocean modelling configuration based on the NEMO ocean engine, which development started in 2018 at IMR (Hordoir et al. 2022). Nemo-NAA10km is not a climate model and works in forced mode. Its purpose is to study ocean processes and climate impacts, especially surface processes such as mixed layer depth, which are important for primary production. Nemo-NAA10km has been used in several articles which goal is to estimate the impact of climate related changes on biogeochemical systems (Nilsen et al., 2023) and is being used to understand changes of transport towards the Barents Sea through the Barents Sea Opening (Jahanmard et al. 2024). Nemo-NAA10km is forced through its boundary conditions, either with the atmosphere at the surface of the ocean, or with the ocean at the open boundary conditions of the domain. The latest open boundary conditions are located at the latitude of southern Spain in the Atlantic Ocean, and in the Northern Pacific Ocean (Fig. 24). The coastal boundaries of Nemo-NAA10km are also forced as they provide freshwater in the form of river runoff to the ocean model. When used in hindcast mode, the atmospheric data to Nemo-NAA10km comes from the ERA5 reanalysis of Hersbach et al. (2020), while the open boundary conditions come from the GLORYS ocean reanalysis (<http://marine.copernicus.eu>). In hindcast simulations we assume the river runoff to be climatological, which means that it has seasonal variations, but no interannual variability. It is extracted from a database based on observations and statistics from Dai and Trenberth (2002).

The goal of our climate downscaling is to run Nemo-NAA10km based on forcing extracted from climate models, instead of re-analysis. When switching to climate downscaling mode, these three forcing components, atmospheric data, ocean boundary conditions and river runoff forcing, need to be adapted from the climate models. Two climate models are presently used to force Nemo-NAA10km in climate downscaling mode, NorESM2 and EC-Earth, to provide a wider range of possible results.

5.1.2 Enhanced river runoff

Runoff from rivers, either a few large ones or accumulated from many smaller, is important input to the climate downscaling simulations. Within NorScen we aimed at providing enhanced river runoff fields that are as accurate as possible and that follow the inter-annual variability of the climate model runoff to the downscaling simulations. This is quite challenging and work demanding. An earlier attempt, based on output from the NorESM2 climate model, provided unrealistic river runoff.

River runoff outputs of climate models are two-dimensional fields, which for every coastal point of the ocean component of a climate model provide a runoff value to the ocean. Each point corresponds to a drainage area outlet, but the representation of drainage areas varies between grid and models. Meanwhile, it is impossible to represent river runoff as two-dimensional fields, as they are on one hand discrete distributions, and on the other hand runoff conservation is essential which does not permit any spatial interpolation to enable comparison. A method is needed to perform this comparison.

To perform this task, the runoff of the climate model is re-routed to the Nemo-NAA10km, this means that for a given runoff point of the climate model, the runoff is re-routed towards the closest coastal point of the Nemo-NAA10km grid. River outflow locations can differ from one model to another, but integrating the river runoff along a coastline, should lead to the same accumulated value. Therefore, our strategy is to integrate along a coastline that spawns the entire coast of the Nemo-NAA10km grid.

This algorithm, once applied to the runoff fields of the NorESM2 and EC-Earth climate models, allowed for the creation of monthly runoff fields, for each year of the period 1950–2100. These fields follow the inter-annual variability of each climate model original runoff fields, while being bias corrected and consistent with the original runoff inputs of the Nemo-NAA10km hindcast simulations. A somewhat more detailed description of correction algorithms for river runoff and precipitation fields from climate models is given in Appendix 1.

5.1.3 The biogeochemical model

The biogeochemical model used in the present study is the NORWegian ECOlogical Model system end-to-end, NORWECOM.E2E (Aksnes et al. 1995; Skogen et al. 1995; Skogen and Søiland 1998). NORWECOM.E2E is a coupled physical–chemical–biological model system originally used to study primary production, nutrient budgets and dispersion of particles such as fish larvae and pollution. The model system consists of an NPZD (Nutrient-Phytoplankton-Zooplankton-Detritus) model, several individual based models (e.g., Hjøllø et al. 2012), and modules for ocean acidification (Skogen et al. 2014) and contaminants. In the present study, only the NPZD and the ocean acidification modules have been used. The model has two different types of phytoplankton (diatoms and flagellates) together with two types of zooplankton (micro- and mesozooplankton). The model has previously been validated by comparison with field data in the Nordic region and the Barents Sea (Hjøllø et al. 2012; Sandø et al. 2021; Skaret et al. 2014; Skogen et al. 2007, 2014, 2018). The model has been run in offline mode using 5 days mean values of the physical ocean fields (velocities, salinity, temperature, sea surface height, and sea ice) from the NEMO-NAA10km together with atmospheric fields from NorESM2. The horizontal grid used by the biogeochemical model is a sub-area of the original NEMO-NAA10km grid (Fig. 24) covering the Barents and Nordic Seas.

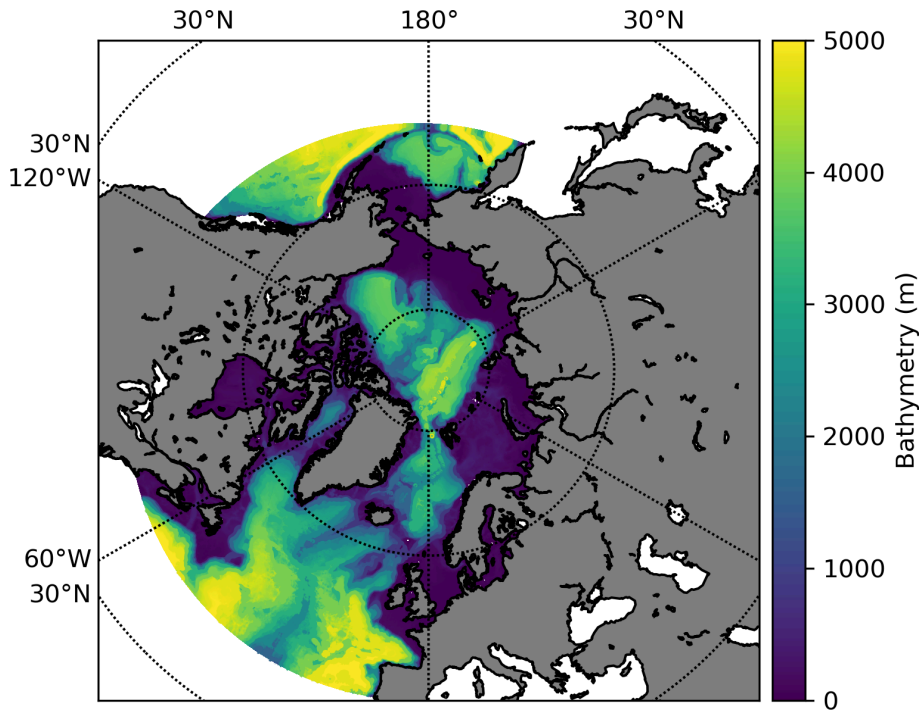


Figure 24. Domain and bathymetry (in m) of the Nemo-NAA10km configuration.

5.2 Results from dynamical modelling of the Norwegian and Barents seas

5.2.1 Downscaled projections of physical variables

A new version of the NEMO-NAA10km model was developed for NorScen. This version, including updated downscaling with improved runoff distributions is hereafter referred to as NEMO-NAA10km-new. In the following we show time series and trends from the new NEMO-NAA10km-new runs for open ocean and coastal regions in the Norwegian Sea and Barents Sea. In addition, we have split the open Barents Sea in to an "Atlantic" and "Arctic" compartment as the environment and ecosystems are quite different (Fig. 25).

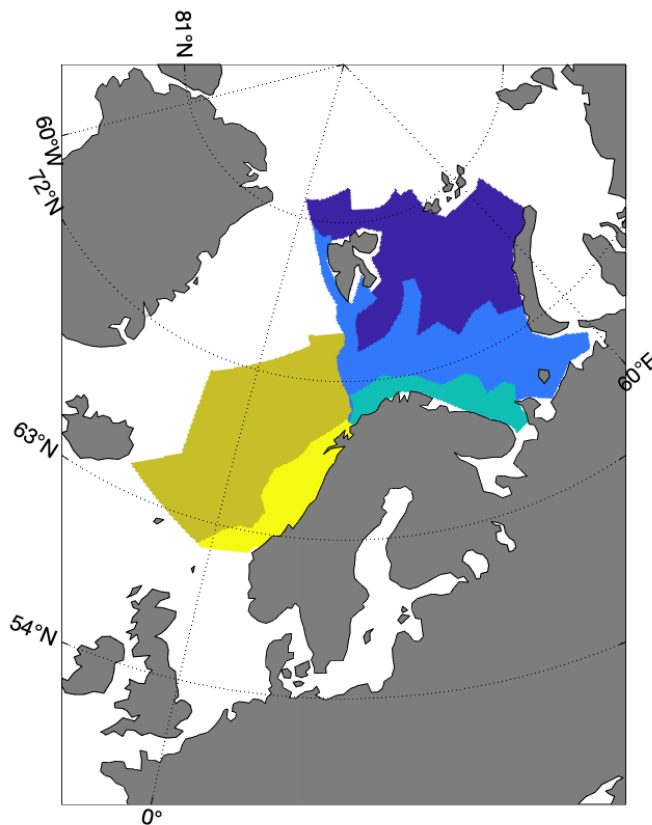


Figure 25. The regions in the Norwegian Sea and Barents Sea that we apply our analyses too. Dark blue – Barents Sea Arctic; lighter blue - Barents Sea Atlantic; blue-green – Barents Sea coast; greyish yellow – Norwegian Sea Open; clear yellow – Norwegian Sea Coast.

Figs. 26–28 show updated downscaling results from NEMO-NAA10km-new for temperature, salinity, and mixed layer depth, respectively. The temperature development is quite different between the three scenarios. This is similar, but not identical, to what shown in Sandø et al. (2024), based upon the previous NEMO-NAA10km version. The SSP1-2.6 scenario has weak, negative temperature trends in most areas, except in the Norwegian Sea Open, while SSP2-4.5 and SSP5-8.5 have positive trends in all areas with strongest temperature increase in SP5-8.5. The smoothed time series, which represent variations on a decadal to multidecadal time scale, also indicate that the temperature has strong decadal to multidecadal variability (Fig. 26).

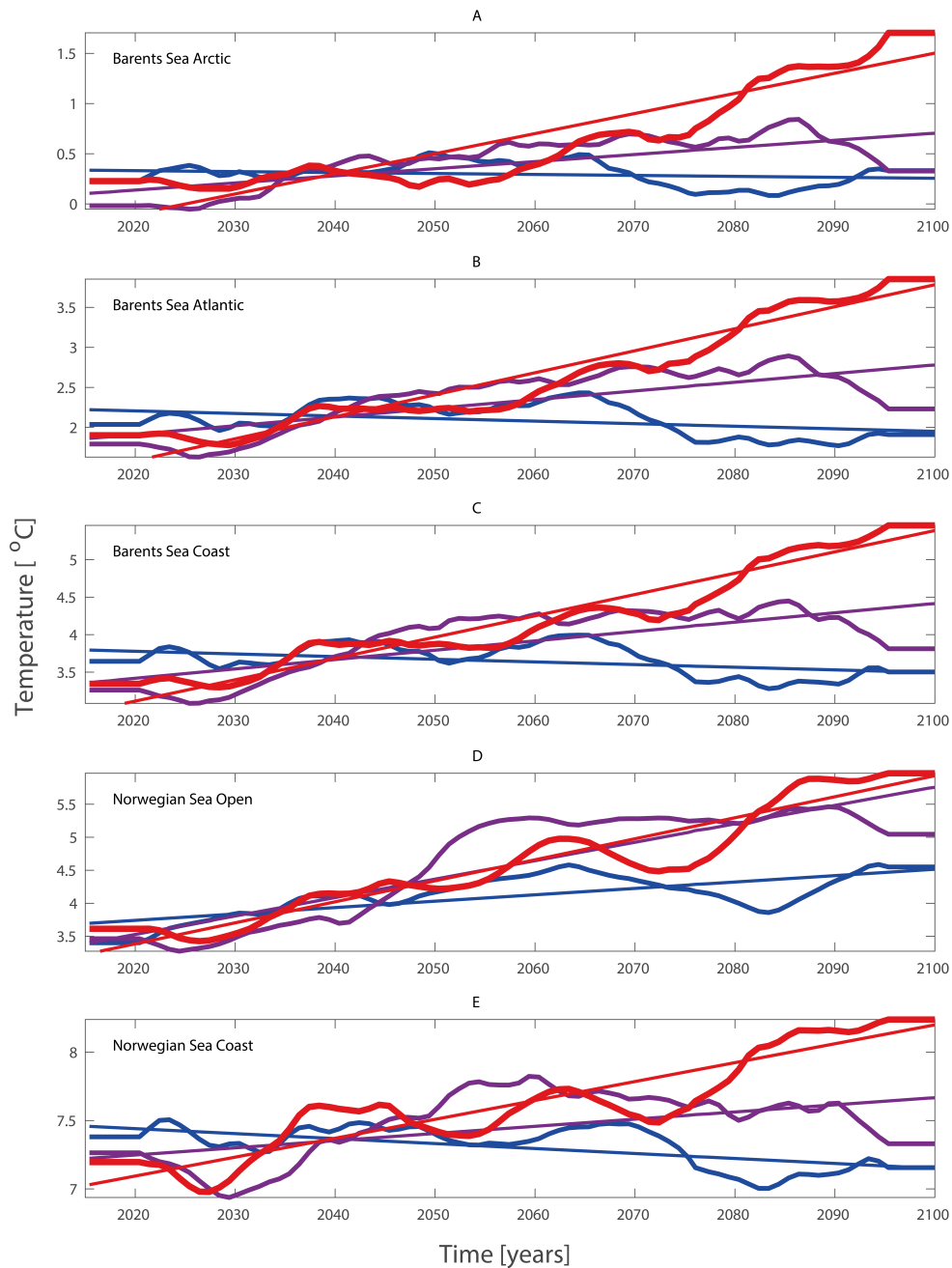


Figure 26. Projected annually averaged ocean temperature (°C) at 50–200 m for the period 2015–2100 in various ocean basins and corresponding coastal regions. From upper to lower: Barents Sea Arctic, Barents Sea Atlantic, Barents Sea Coast, Norwegian Sea Open, and Norwegian Sea Coast. Coloured time series indicate the scenarios SSP1-2.6 (blue), SSP2-4.5 (purple), and SSP5-8.5 (red), and corresponding straight lines their trends.

The salinity trends at 50–200 m are positive for all areas and scenarios and are therefore less mutually different (Fig. 27). Fig. 28 shows that the different temperature and salinity trends also impact the mixed layer depth differently with almost neutral to negative trends in the coastal areas, and mostly strong positive trends in the open ocean areas, at least for SSP5-8.5.

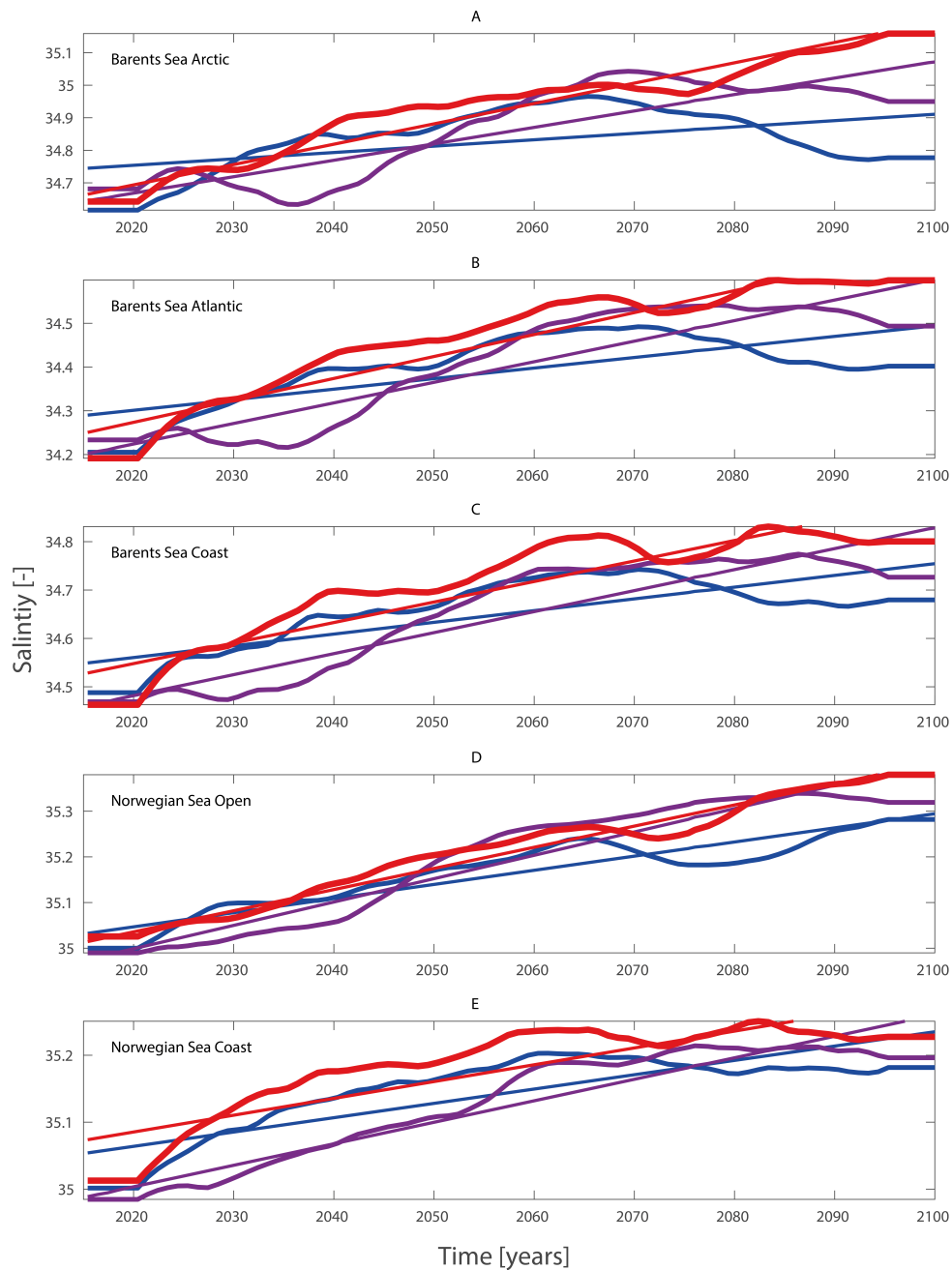


Figure 27. Projected annually averaged ocean salinity (unitless) at 50–200 m for the period 2015–2100 in various ocean basins and corresponding coastal regions. From upper to lower: Barents Sea Arctic, Barents Sea Atlantic, Barents Sea Coast, Norwegian Sea Open, and Norwegian Sea Coast. Colored time series indicate the scenarios SSP1-2.6 (blue), SSP2-4.5 (purple), and SSP5-8.5 (red), and corresponding straight lines their trends.

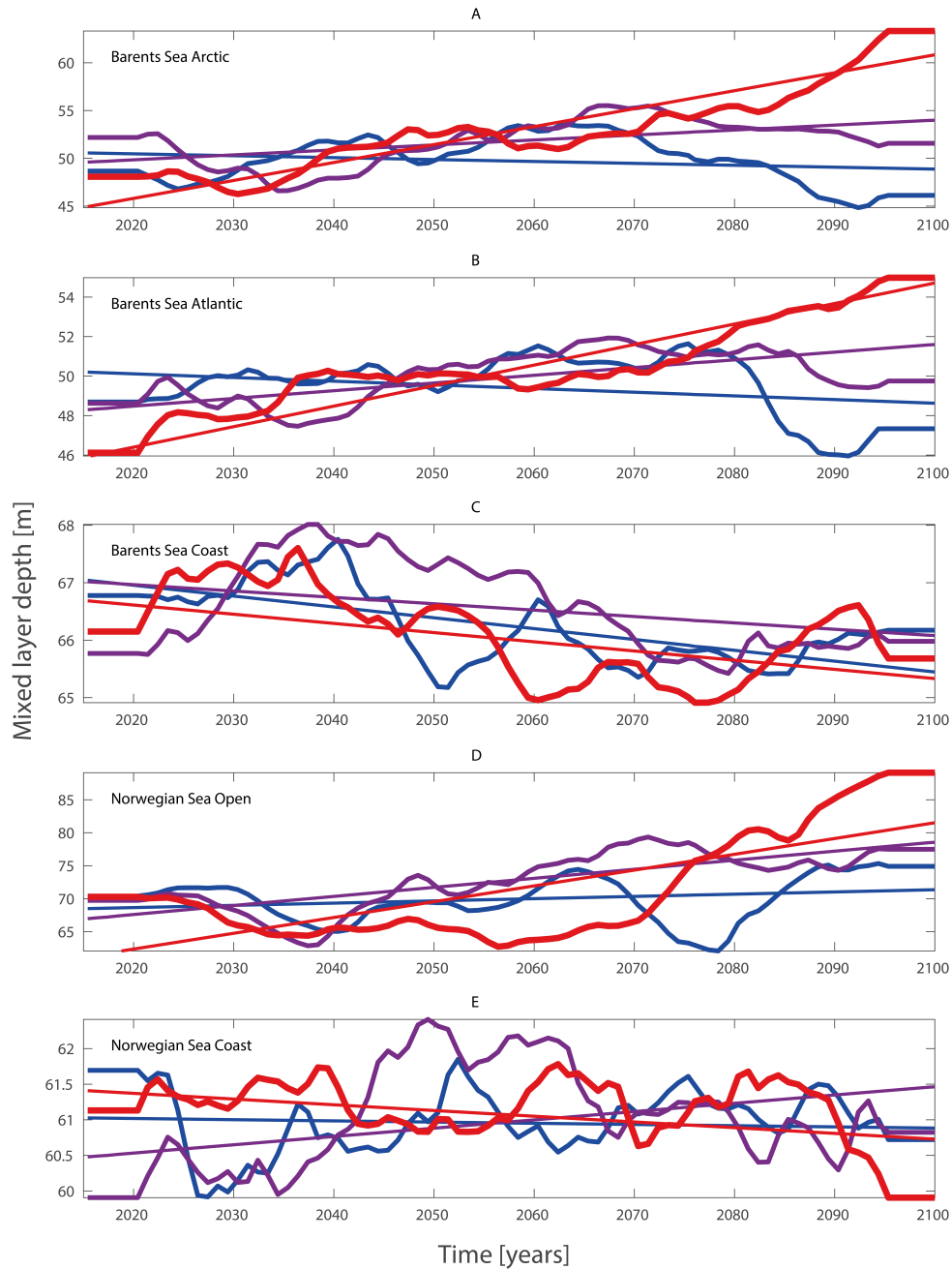


Figure 28. Projected annually averaged mixed layer depth (m) for the period 2015–2100 in various ocean basins and corresponding coastal regions. From upper to lower: Barents Sea Arctic, Barents Sea Atlantic, Barents Sea Coast, Norwegian Sea Open, and Norwegian Sea Coast. Coloured time series indicate the scenarios SSP1-2.6 (blue), SSP2-4.5 (purple), and SSP5-8.5 (red), and corresponding straight lines their trends.

5.2.2 Downscaled projections of primary and secondary production

Projections of net primary production (NPP) and gross secondary production (GSP) with the projected trend-lines are shown in Figs. 29 and 30. In general terms, the NPP in present climate is highest in coastal and ice-free regions with a maximum in the Norwegian Sea Coast box around $150 \text{ gC/m}^2/\text{year}$ and a minimum in the Barents Sea Arctic of approximately $35 \text{ gC/m}^2/\text{year}$. The projected changes are small and similar between the different emission scenarios, except for the Barents Sea Arctic where there is an increase towards the mid of the century in all three scenarios, but thereafter SSP5-8.5 continue to increase so that the NPP at the end of the century is twice that in the beginning, while for the two other scenarios there is a decline so that SSP1-2.6 is at the same level in 2100 as in 2015, while SSP2-4.5 NPP is about 25% higher.

The level in GSP follows that for NPP with highest values in the coastal and ice-free regions. Except for the Norwegian Sea Coast, there is a general increase in GSP in all areas with the largest change for SSP5-8.5 in the Barents Sea Arctic, and the largest increase for SSP5-8.5 followed by SSP2-4.5 and SSP1-2.6 in general. In the Barents Sea Arctic the patterns for GSP and NPP are similar, with an increase towards the mid of the century before the three emission scenarios show different patterns.

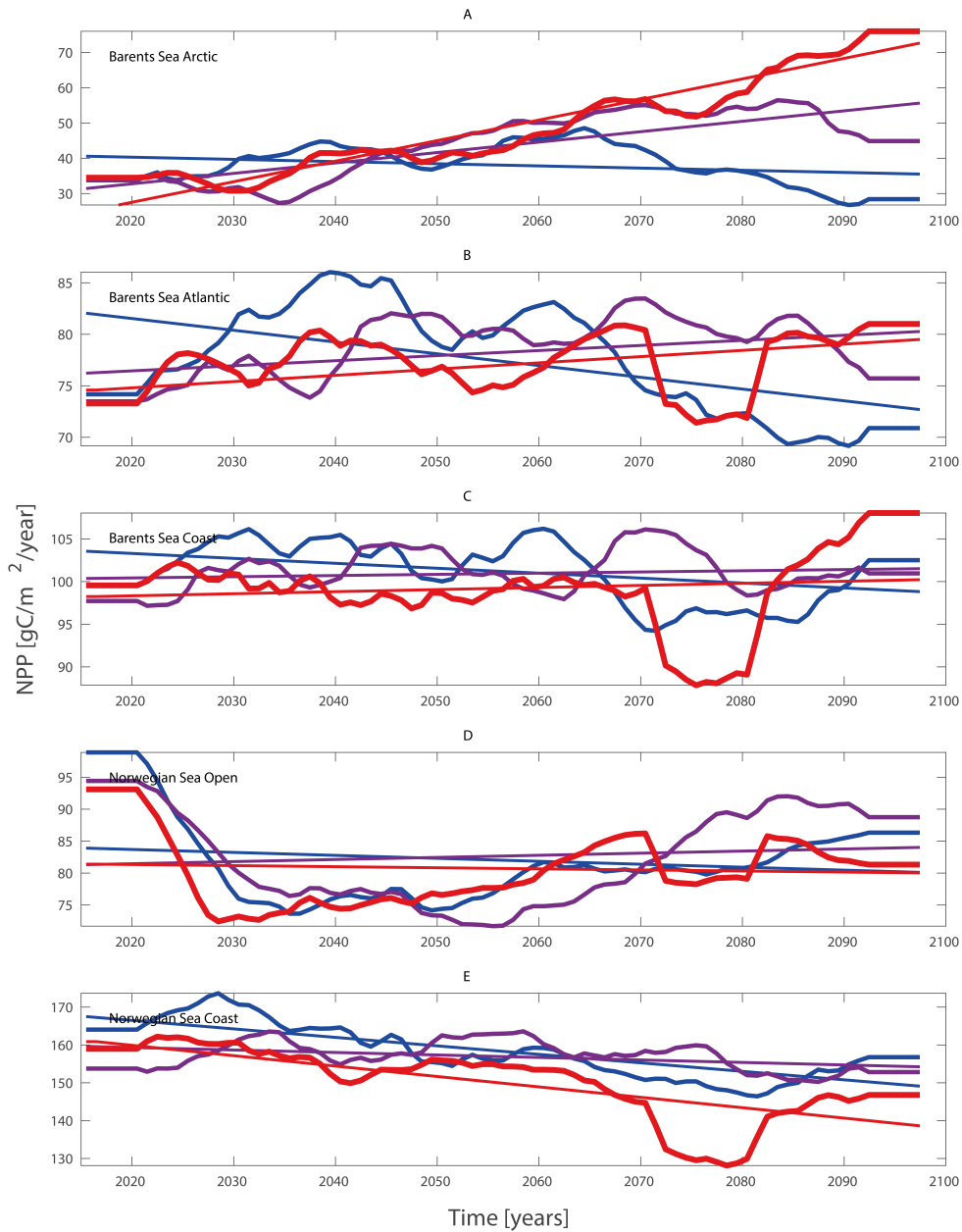


Figure 29. Projected annually averaged NPP for the period 2015–2100 in various ocean basins and corresponding coastal regions. From upper to lower: Barents Sea Arctic, Barents Sea Atlantic, Barents Sea Coast, Norwegian Sea Open, and Norwegian Sea Coast. Coloured time series indicate the scenarios SSP1-2.6 (blue), SSP2-4.5 (purple), and SSP5-8.5 (red), and corresponding straight lines their trends.

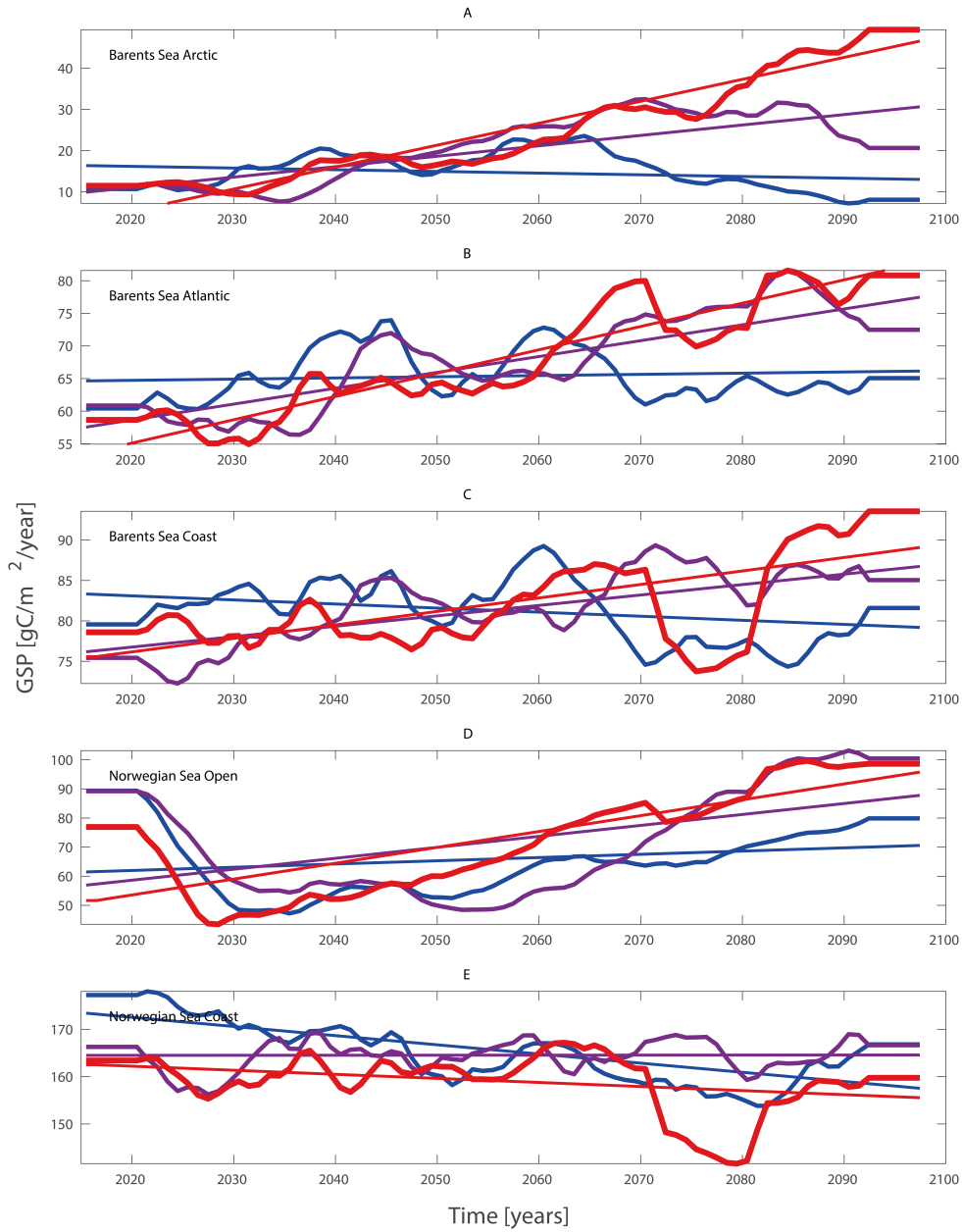


Figure 30. Projected annually averaged GSP for the period 2015–2100 in various ocean basins and corresponding coastal regions. From upper to lower: Barents Sea Arctic, Barents Sea Atlantic, Barents Sea Coast, Norwegian Sea Open, and Norwegian Sea Coast. Coloured time series indicate the scenarios SSP1-2.6 (blue), SSP2-4.5 (purple), and SSP5-8.5 (red), and corresponding straight lines their trends.

5.3 Discussion of results from dynamical modelling

5.3.1 Discussion of main results

Compared to the NEMO-NAA10km-old, NEMO-NAA10km-new is colder in the southern part of the Barents Sea, but less saline in the central part of the Barents Sea, providing shallower mixed layer in the central Barents Sea. How these changes will modify the conclusions in Sandø et al. (2024) must be analysed in detail, but the reduced temperature increase in NEMO-NAA10km-new should not aggravate the negative consequences for the stocks that will be negatively impacted by warming. On the other hand, the positive impacts of less warming on stocks that benefits from increased temperatures might be more limited. In addition to direct temperature effects on plankton production and different fish stocks there are indirect effects of hydrography on the mixed layer depth which in turn impacts plankton production. The plankton production seems to be quite reduced in all areas compared to NEMO-NAA10km-old, but the trends are mostly the same.

The increased temperature will have a negative impact on ice-cover, and together with changes in salinity and wind-stress also an impact on the mixed layer depth. Ice cover and mixed-layer-depth was identified as the main drivers for changes in the Barents Sea primary production in, e.g., Mousing et al. (2023), and consistent patterns in these projections are seen in Figures 26, 27 and 28. The GSP in the Barents Sea partly mirrors the projected changes in NPP, but there are some exceptions. In the Barents Sea Atlantic region the projected increase in GSP is stronger than that in NPP. Mesozooplankton is the main feed for fish larvae, and prey concentration is thereby important for their growth and survival (Folkvord et al. 2009), hence important for recruitment success. The projected increase in GSP in all parts of the Barents Sea is therefore likely to have a potential positive impact for fish recruitment in the area. However, for the total impact on the commercial fish stocks in the area one also needs to take into account that the higher temperatures in a future climate also are expected to impact fish distribution to expand northwards and eastward, potentially also expanding larval distribution (Fossheim et al. 2015). Finally, also the rate of turnover in the phytoplankton community becomes faster with increased temperature. Consequently, the community structure will be more unstable, and, combined with alterations in phytoplankton diversity, this might lead to a loss of ecological resilience in the productivity and functioning of the marine environment (Henson et al. 2021).

The projected NPP and GSP in the Norwegian Sea boxes differs from the Barents Sea projections. In the Norwegian Sea Open there is a strong decrease in both NPP and GSP until 2030. This decrease is probably an artifact that is also seen in the mixed layer depth (Fig. 28) and is probably an initial adjustment due to an

unbalance in the initial field. Even with the positive trend projected after 2030, the NPP does not quite return to the initial level in this area for all emission scenarios, while the GSP at the end of the century is larger for SSP2-4.5 and SSP5-8.5 than for present day. An interesting observation is that the lowest NPP is projected at the end of the century for the most extreme scenario (SSP5-8.5), while the opposite is true for GSP. In the Norwegian Sea Coast box, the results are more consistent with a negative trend towards 2100 with the lowest NPP and GSP for SSP5-8.5. The reduction in zooplankton in the coastal box suggests a negative impact for fish recruitment in that area. This applies to, e.g., Norwegian spring-spawning herring, which historically spawns on the coast from Møre and northwards with transport of eggs and larvae along the Norwegian coast and into the Barents Sea. The herring might face more unfavourable conditions in a future climate. A compensating adaptation might be to spawn further north, with lower distance into the Barents Sea with more favourable conditions for the fish larvae, and the last years this spawning is now concentrated from Lofoten and northwards (Salthaug and Stenevik 2024).

Since the aim of this report is to assess the effects of climate change at the end of this century, we have chosen to focus on downscaling several emission scenarios rather than reducing model errors by downscaling several global models. The selection of scenarios to be downscaled and analyzed for physical and biogeochemical variables in this report was made some time before SSP5-8.5 was widely known to be implausible, and before Burgess et al. (2023) was published. Our choice was made to span the range of possible outcomes from the most optimistic to the most pessimistic scenario. Another choice that was made was which global model should be downscaled, and we chose the Norwegian Earth System Model, NorESM2, because it was evaluated well regarding volume and heat transport to the Nordic region and the Barents Sea among 23 CMIP5 and CMIP6 models (Madonna and Sandø 2022). Despite this evaluation, Chylek et al. (2024), comparing different CMIP6 models for the SSP2-4.5 scenario, found that NorESM2-LM underestimates the future Arctic warming compared to the average of seven other models which were all found to be within 15% of the observed warming in the historical period from 1850–2015. Preliminary results may indicate that temperatures in the SSP5-8.5 scenario from NorESM2 are closer to SSP2-4.5 temperatures in many models when focusing on the Barents Sea, and that this model thus does not necessarily exaggerate the future warming in the SSP5-8.5 scenario with subsequent effects on the marine ecosystem (Sandø et al. 2024).

5.3.2 Challenges with the SSP3-7.0 scenario

The temperature changes projected in our SSP3-7.0 scenario results (not shown) are consistent with the strength of emission scenarios when large basins are considered. This consistency is less pronounced in coastal regions, for which

non-linear effects need to be considered. Specifically, the SSP3-7.0 generates what we believe is too high temperatures along the Norwegian coast. A detailed analysis of the underlying physical processes that can explain this unexpected result are beyond the scope of this report, but several hypotheses can be provided. Recent results of Jahanmard et al. (2024) showed for example that the barotropic transport at Barents Sea Opening, and therefore along the Norwegian coast, is most likely a non-linear process related with wind variability more than wind strength. Wind strength does not change significantly over the Nordic Seas at the end of the 21st century, although the Barents Sea flow does increase, and Jahanmard et al. (2024) could show that a change hidden within the wind signal was indeed responsible. Such a change in wind variability could be for example specific to the SSP3-7.0 scenario.

We can also suppose that a change in stratification at the surface of the ocean, could drive a stronger heat from the surface downward, and explain why sub-surface temperature is more affected in this scenario. This change of stratification could be the consequence of a lower runoff flow along the coast, for example.

6. Marine Heat Waves

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Marine heat waves (MHWs) are episodes of sharp increases in ocean temperature. There are several definitions, the most used one describes a MHW as "a discrete prolonged anomalously warm water event" (Hobday 2016). A MHW can be described by its duration, intensity, rate of evolution, and geographically spatial extent. Individual MHWs have highly different features, but they may (negatively) affect organisms and ecosystems with potentially far-reaching socio-economic consequences.

There has been more focus on MHWs in other (generally warmer) parts of the world, but also in Nordic waters one must be prepared. For example, Mohamed et al. (2022) found that the annual frequency of marine heat waves in the Barents Sea increased by 62% from the period up to 2004 to that from then on. From 1982–2020 half of the days with heat wave status in the Barents Sea were in the most recent decade. At the present global mean temperature of around 1 °C above preindustrial value, the North Sea and Norwegian Sea experience a frequency of MHWs 2–4 times the preindustrial probability. In a world with 3.5 °C warming, the relative probability is estimated to increase to 20–30 times that of preindustrial times (Borgman et al. 2022). The Borgman et al. (2022) report, ordered by the Norwegian Environmental Agency, reviewed and evaluated literature and concluded that scientific papers focused on MHWs in the Nordic Sea areas are few and saw a need for further work.

In Norway IMR and NERSC, collaborating within the Bjerknes Centre for Climate Research, have an ongoing project on characterising historical MHW events in Nordic waters (S. Gonzalez et al., work in prep.). Although not predictions, knowledge of Nordic MHWs is highly relevant for understanding the future climate and its impacts. This work examines both causes of MHWs in high latitude marine systems and their impacts on biological communities and ecosystems. They distinguish between surface MHWs, heavily influenced by local atmospheric conditions, and near-bottom MHWs, determined more by advection/currents in the ocean. The data applied are surface and near-bottom temperatures from TOPAZ reanalysis (1991–2022, 12.5 km resolution). The main findings of S. Gonzalez et al. so far are i) increasing trends in surface and near-bottom MHW frequency and intensities (Fig. 31), ii) highest surface MHW frequency along the Norwegian coast

but low intensity and not persistent. Highest intensities around Svalbard and Barents Sea (Fig. 32), iii) near-bottom MHW characteristics depending on bathymetry. Highest frequencies in the shelf-break area and longest durations at >1000 m depth, and iv) near-bottom MHWs less frequent but more persistent than surface MHWs.

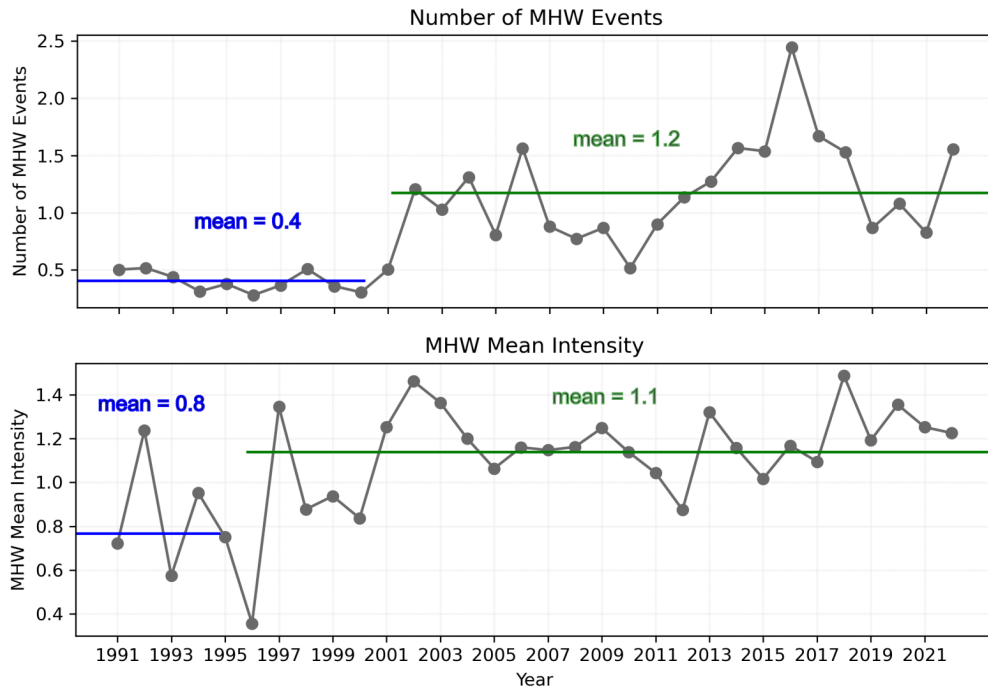


Figure 31. Spatially averaged surface MHW trends. Number of events per year following MHW definition in upper panel and mean intensity (°C) in lower panel. Trends for the whole period shown as stippled line, means for two main periods indicated in respectively blue and green.

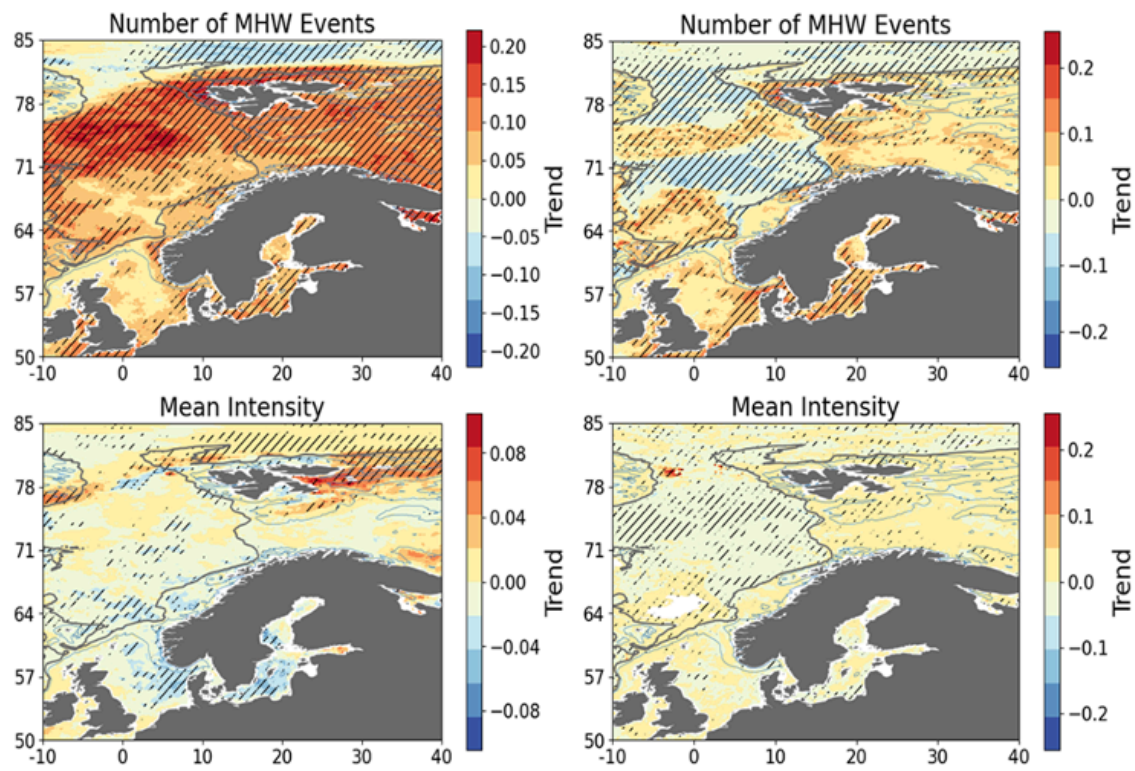


Figure 32. MHW trends, changes 1991–2022. Left surface MHWs, right near-bottom MHWs. Number of events per year following MHW definition applied in upper panels and mean intensity (°C) in lower panels. Horizontal axis is degrees longitude, vertical axis is degrees latitude, colour scales are trends. Note different scales for both frequency and intensity between surface and near-bottom MHWs. S. Gozalez et al., work in progress.

7. Climate projections for the Barents and Norwegian Sea with NoBa Atlantis

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7.1 The NoBa Atlantis end-to-end ecosystem model

The Nordic and Barents Seas Atlantis model (NoBa Atlantis) is an implementation of the general Atlantis framework developed by Elizabeth Fulton at CSIRO, Australia (Fulton et al. 2011). NoBa has 53 species and functional groups, which are defined to represent the functioning ecosystem even if simplified (Fig. 33). Important commercial species, such as Northeast Atlantic cod, snow crab, mackerel and Norwegian spring spawning herring, are all represented by individual components, while small pelagic fish, corals, benthic detritivores and mesopelagic fish are represented as larger functional groups. The model uses a three-dimensional grid to represent the ecosystem, with each grid cell or "box" representing a specific area of the sea. These boxes are defined based on ecological gradients, bathymetry (sea floor topography), and management boundaries. The parameterization of NoBa is provided in detail in Hansen et al. (2016), and a sensitivity study of the most calibrated parameters is performed in Hansen et al. (2019). There are three different species representations available in the Atlantis framework: age structured vertebrates, age structured invertebrates and invertebrate biomass pools. The age structured invertebrates are in NoBa only representing two groups: the shrimp and the cephalopods. Snow crabs are implemented as vertebrates to be able to reconstruct their expansion and potential biomass development in the Barents Sea. Species are seasonally redistributed according to predefined seasonal patterns, except baleen whales, which have a density dependent movement. There are several options for adding temperature sensitivity in Atlantis, requiring information on optimal temperatures for movement, recruitment and spawning, in addition to how temperature impacts their growth rates. In the version of the model used for this project, a knife-shaped cut off has been applied, which in practice means that individuals who experiences temperature outside of its range will 1) either move or die, 2) not be able to spawn and 3) the temperature will impact its growth rates. In this version of the model code, it was not possible to disconnect these, such that temperature effects will always impact all these processes.

ATLANTIS

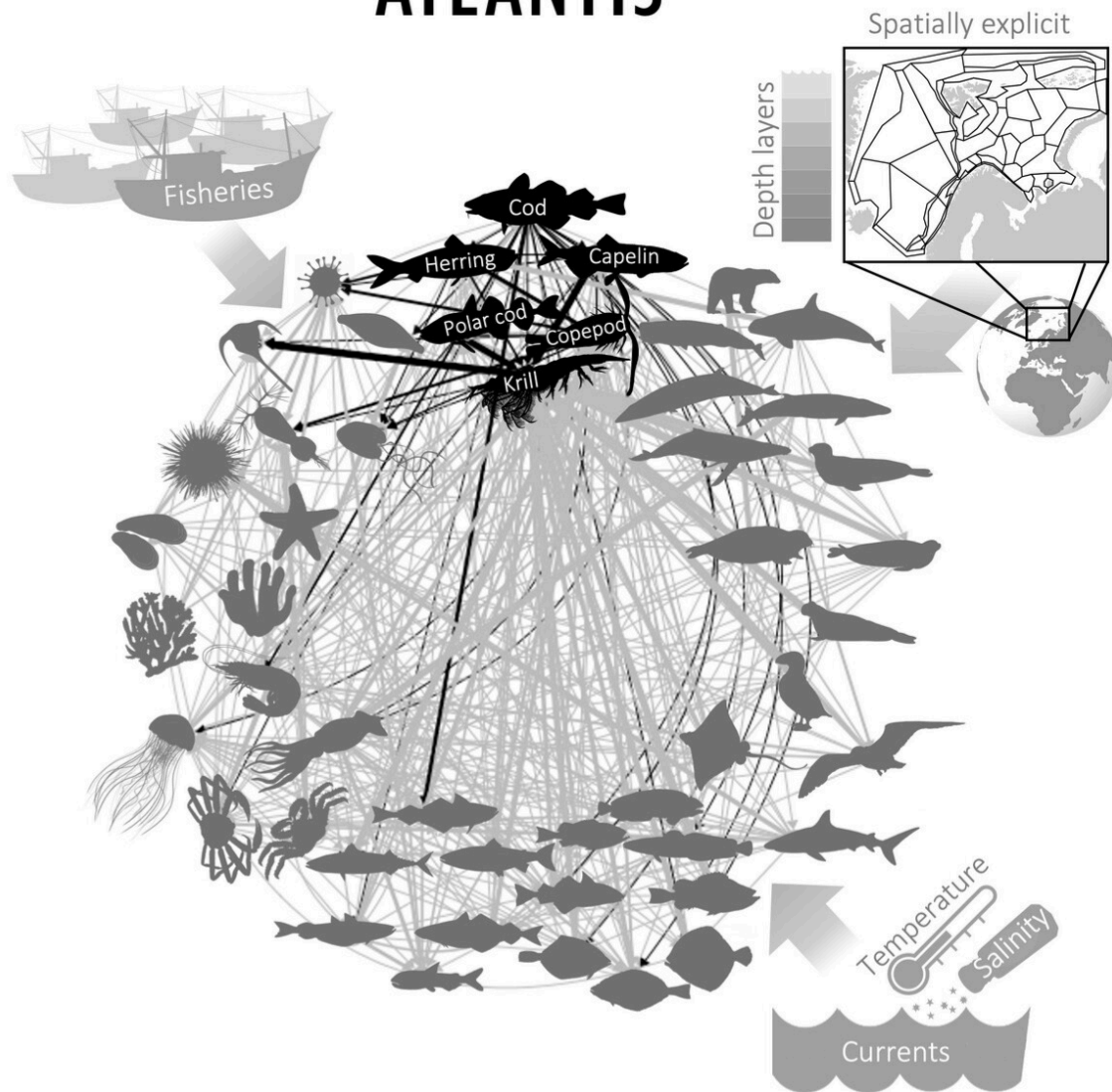


Figure 33. The diet matrix in NoBa Atlantis connects the functional groups, while fisheries, temperature, salinity, ice and currents act as forcing to the model. From Nilsen et al. (2022).

NoBa requires daily input of temperature, salinity, volume flux (between faces and layers in the polygons) and sea ice thickness and concentration. In Nilsen et al. (2023), the impact of resolution of the physical model used for forcing was explored. The study showed that if regional downscaling is not available, a global model can be used as input, as the Atlantis polygons are relatively coarse. However, the downscaled regional model used for forcing in the study was based on the global model, and recent findings have shown that they are both in the colder range of the projections, such that the SSP5-8.5 applied in our simulations are more similar to SSP2-4.5 in other global models. There is ongoing work to downscale from other global models, to evaluate the potential differences between the

projections. Each polygon-layer combination in NoBa gets a daily input of the physical parameters, which is then applied in the biological processes.

7.2 Results and discussion

It has earlier been concluded that the knowledge of the response of phytoplankton and zooplankton to future climate change has only low confidence. In an ecosystem model this would also propagate to higher trophic levels. In the simulations explored here (Nilsen et al. 2024), this uncertainty has been accounted for by adding nine different perturbation simulations (Fig. 34) to each of the three projections (SSP1-2.6, SSP2-4.5, SSP5-8.5). The perturbations have been performed by linearly increasing/decreasing the growth rates of the phytoplankton and zooplankton. The level of the perturbations was based on projected changes in NORWECOM.E2E (Sandø et al. 2024). Note that snow crab was removed from the results due to a bug in their set-up, causing a population crash (not related to temperature change).

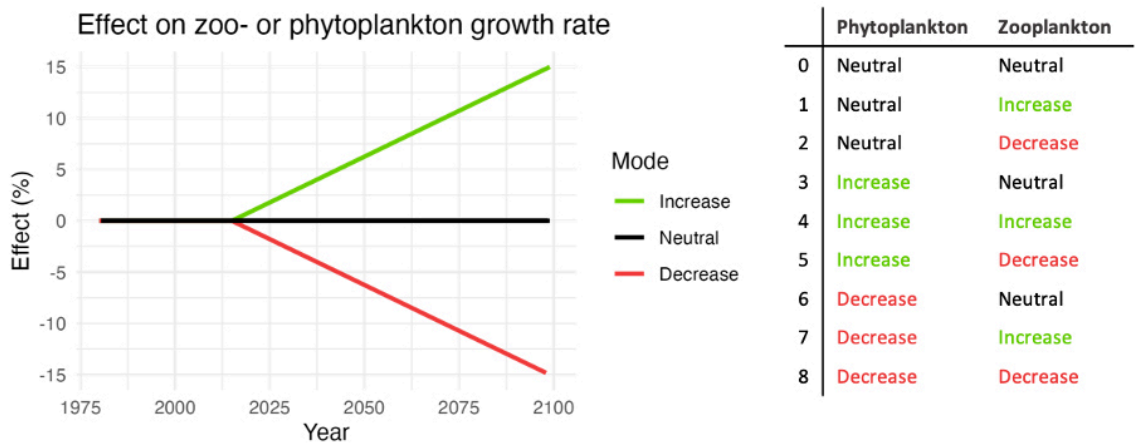


Figure 34. Each future projection includes nine simulations, where a combination of linear increase/decrease of zooplankton and phytoplankton has been applied. From Nilsen et al. (2024).

Due to the level of uncertainties in the study, among others connected to how the individual species' functional temperature response was implemented, the study focuses on the processes behind the responses.

Depending on their temperature ranges, and the accuracy in the knowledge of these, the species have from a strong negative response to a strong positive response. Prawns and mesopelagic fish turned out as climate winners, while, e.g., capelin and Greenland halibut are climate losers (Fig. 35). Polar cod, where a strong negative response was expected, did not show a clear response to temperature.

This can be explained by the lack of connections between the recruitment function of polar cod and sea ice; however, it is not clear whether a strong significant relationship exist for the whole stock, and how dependent their survival is on the sea ice extent in spring and summer.

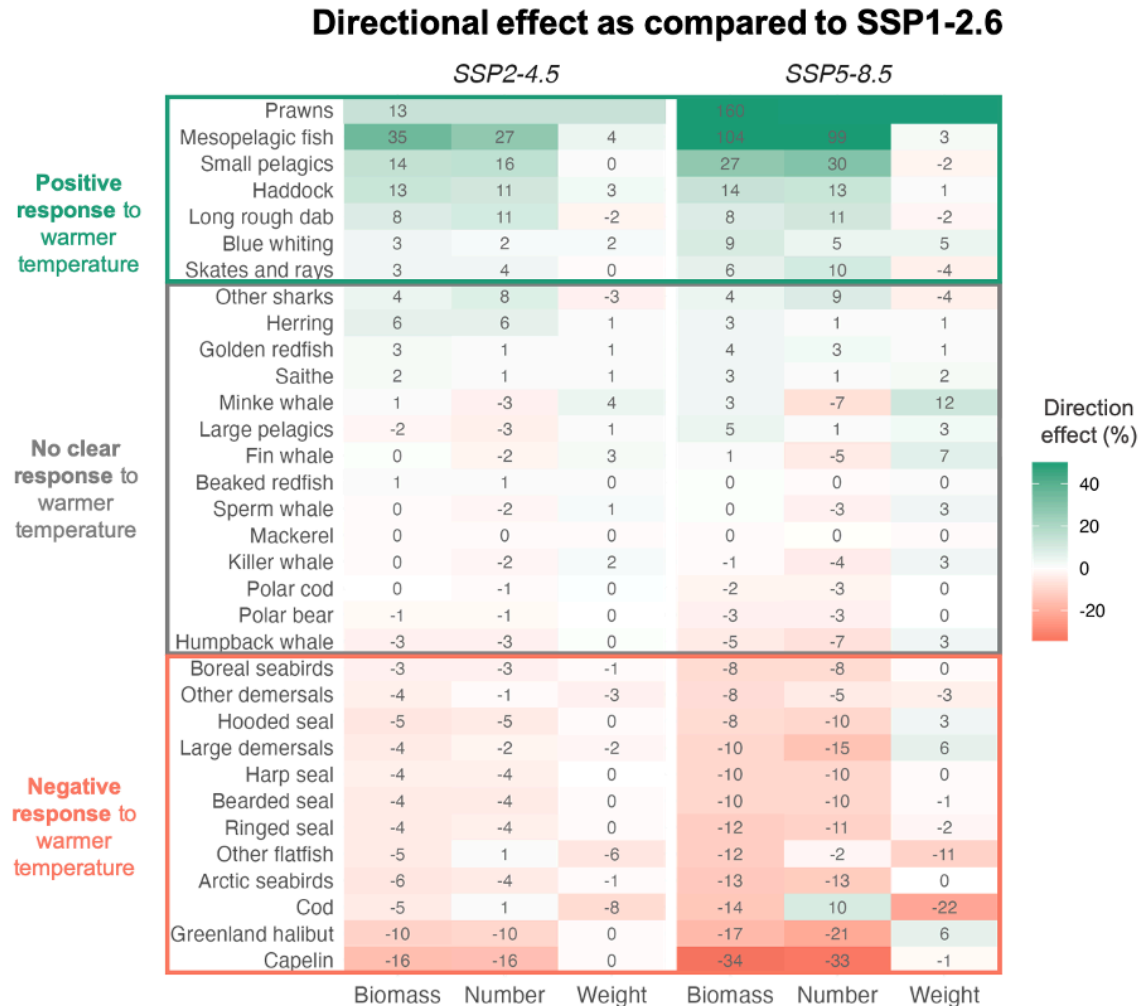


Figure 35. Species response to future projections, when compared to their median levels across 2090–2099 (the last 10 years of the simulation) for the SSP1-2.6 projection. The species are sorted by effect on biomass from positive response (green, increase) to negative response (red, decrease). From Nilsen et al. (2024).

All in all, there were seven species that responded positive to climate change (Fig. 35). When comparing their biomass trajectories, the differences became evident toward the last part of the projections, after 2065. This is the same time slot as when the physical responses diverge in the Nemo-NAA10km model and is thus expected. Haddock was among these species but is known from earlier studies to have strong responses to perturbations in the model system. This is due to its recruitment function, something shown in the large range around its response,

driven by the perturbations in each of the nine simulations representing each of the projections. The prawns experienced a strong growth-related response to higher temperatures, particularly in shallow-depth polygons close to the coast. In some of these polygons, the temperature would increase beyond their tolerance limit toward the end of the projections, but the biomass fraction contained in these polygons is significantly lower than the total biomass, hence a positive response was reported for the population as such (Fig. 36).

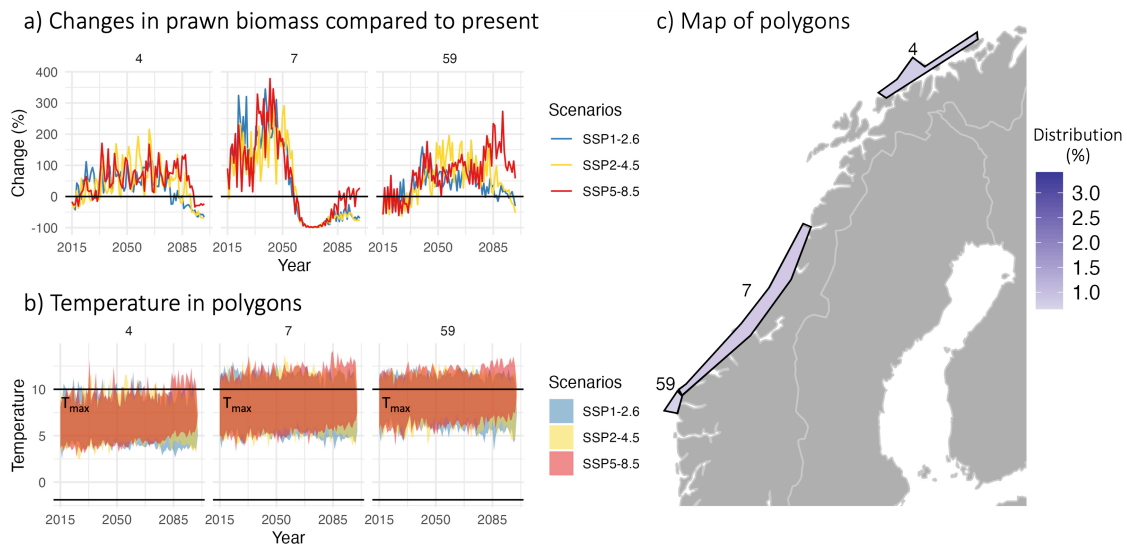


Figure 36. Changes in prawn biomass under three different climate change scenarios a) compared to present, the temperature in the three selected polygons, including tolerance levels (T_{max}) b), and the location of these shallow water polygons c). From Nilsen et al. (2024).

Twelve species responded negatively to the projected climate change (Fig. 35), among these, cod and capelin. The decrease in cod was strongly related to the decrease in capelin, caused by a decline of large zooplankton in their main summer-feeding areas. The consumption of capelin by cod was reduced by 18% in the SSP5-8.5 projection, double the decrease in the SSP1-2.6 projection.

8. Economic consequences for fisheries and aquaculture

Economic consequences of climate change towards 2100 for fisheries and aquaculture in the Nordic region – outcome of a workshop

Geir Ottersen and meeting participants

8.1 Setting the scene

Impacts of climate change are becoming evident also in the Nordic region and people in the seafood industries are becoming increasingly worried. According to the Seafood Barometer for Norway (PwC 2023) the biggest concerns for direct climate risks were increased sea temperatures and more frequent extreme weather, while indirect risks such as consumer preferences, change in regulatory climate and environmental requirements and pricing of climate emissions also were reported by many.

To gain new insight into the future economic and societal impacts of climate change on the marine fisheries and aquaculture sectors in the Nordic region, we held a meeting in Bergen, Norway, in May 2024. The workshop brought together a multidisciplinary expert group of resource economists, fisheries oceanographers, and biologists, and one representative from the fishing industry: all researchers working at the interface between natural sciences and societal impacts. The 14 participants represented Norway, Sweden, Finland, The Faeroe Islands and Germany (participants list in Appendix 2). The majority of the participants have their main expertise on fish in the wild and fisheries, leading to somewhat more focus there than on aquaculture.

Through pre-meeting planning and during the first part of the two-day workshop, we identified a broad range of key topics pertaining to climate change impacts on marine fisheries and aquaculture (Table 4). The perspective was high-level, emphasizing how climate change may force general industry changes and associated societal impacts, and more geared towards brainstorming and discussions than in-depth analysis. The intention was not to provide monetary or point estimates, but rather a well-informed evaluation of likely developments ahead. The meeting was conducted partly as a plenary group, partly in smaller groups of 4-5 people split on Day one by sea area, Day two by aquaculture/fisheries (somewhat similar to the World Café method). While the small group conversations revolved around the identified key issues, they were not strictly limited to them but could freely bring up any relevant emerging topics. However, to

avoid discussions moving far off-target, the small groups were charged with taking notes and reporting their main findings back to the plenary.

Table 4. Main topics and central subtopics discussed.

Main topic	Subtopics (selected)
Physical changes	Rising temperatures, decreasing oxygen levels, extreme weather events
Impacts of these physical changes	Too high temperature inhibits growth and increases health risks especially in farmed fish; higher temperatures negatively affect more southern areas like the North Sea, potential positive effect in northern regions; increasing MHWs negative; decreasing oxygen levels negatively affect the Baltic; increased frequency and intensity of extreme weather events will negatively affect especially offshore farms and product transportation
Technological development	Climate change (CC) mitigation through greener production lines/reduced footprint including electrification. Co-existence like multi-use wind farms and aquaculture. Some countries may shift from food producer more to technology developer and supplier.
Differences in CC impacts between countries, fisheries	Temperature main climate pressure except in Baltic (oxygen, salinity, nutrients). Fisheries more important for national economy of Norway, Faeroe Islands, and Iceland than other countries
Differences in CC impacts between countries, aquaculture	Little developed and low potential in the Baltic; Norway most flexible for adaptation to CC
Fisheries regulations, management, governance	Regulations should take CC into account and be flexible and adaptive; international legal framework; zonal affiliation principle vs historical rights; fuel subsidies
Increasing and new conflicts	Conflicts between wild and farmed fish production; different fishing fleets; nations; within-country regions; fisheries/aquaculture and other industries; competition for land and sea space

Fishing adaptation potential	New species moving in; wider distribution range of commercial species in northerly regions with increased temperatures and reduced ice
Recreational and high-end fisheries	A shift from high volume towards high quality and price professional and recreational fisheries
Aquaculture adaptation potential	New species; moving northwards, offshore, on land
Fish is healthy food	This will likely remain (de facto and in the opinion) independently of CC, but may change because of increased pollution
Fish feed	Marine (Faeroes) vs soy (Norway). Finding sustainable feed is a main bottleneck for expansion, more so with CC
Consumer preferences	Product quality and price; sustainable practices and certification; traceability
Societal and cultural aspects	Fisheries are deeply rooted in the culture of some Nordic countries; we expect a willingness to support even if the economic value decreases

From our first discussions, it was clear that the effects of climate change and potential for future development in fisheries and aquaculture will differ significantly between the different Nordic seas. Climate change impacts will vary significantly across the Nordic region because of the differences in physical and biological properties described earlier. Further, the countries differ also by diverse economies and societal structures, including the historical and present socio-economic placement of fisheries and political priorities between aquaculture, fisheries, and other activities.

The workshop time horizon was to a large degree the same as for the IPCC scenarios, i.e., towards the end of this century. However, as our discussions evolved and it was pointed out that climate change already at present is an important driver, some aspects were focused on the coming two-three decades. Acquiring new fishing vessels typically has a planning horizon of 20 years, while their lifespan is around 30 years, as are the related bank mortgages and ship insurances. Information about climate-driven changes in the fish stocks at such a time scale therefore forms an important basis for investment and risk handling decisions. This is similar for related industries such as land-based fishing and tourist fishing industries. Where relevant we throughout point to which time frame we deal with.

There is inevitably high uncertainty about the future, it be the physical, environmental or socio-economic situation, particularly as far ahead as 2100. It was therefore a priori well understood that tools, knowledge or insight to conduct any meaningful kind of analytical prediction of the situation 75 years ahead do not exist and likely never will. This was not the goal of the workshop. Instead, we build upon climate change scenarios and expected ecosystem impacts at the global (IPCC 2019, 2021) and regional scale (e.g., Meier et al. 2022; Sandø et al. 2024). Further, some socio-economic scenario studies exist for the study region (e.g., Nilsson et al. 2017 for the Barents Sea and Zandersen et al. 2019 for the Baltic). A further challenge with assessing climate change impacts is that it is a globally interlinked problem, making it difficult to isolate the consequences for specific regions. Nevertheless, we expect our report to provide insight and ignite interest in gaining a more robust understanding of the future of the Nordic seas at a regional level.

The ideas and suggestions reported here are not to be taken as consensus opinions of the group as a whole. The participants were invited by virtue of their expertise and expected value to the workshop. They contributed on their own behalf, not as representatives of any country or organization they are employed by or associated to in any other way.

The report is at the highest level structured into a section covering aspects relating to both Fisheries and Aquaculture, followed by sections on each of the two. Within fisheries we further split by geography, considering as separate (although interlinked) regions the Baltic, North Sea, Nordic Seas (Norwegian, Iceland, Greenland seas), and the Barents Sea.

8.2 Expected developments for both fisheries and aquaculture under climate change

Climate change, especially if we are not able to implement successful mitigation measures, will in total have strong negative consequences in the seas around the Nordic countries. Regardless, a report financed by the Nordic Council of Ministers on Nordic business leaders' perspectives on climate change shows that 95% view climate change both as a threat and an opportunity (Haga Initiative 2022). There are indeed opportunities for expanding fisheries on species like hake in the North Sea and king and snow crabs in the Barents Sea. Especially in the northern parts of the Nordic region there is also potential for new aquaculture species and expanding on, e.g., kelp or blue mussels. Despite this, we consider it unlikely that such new activities can replace the diminishing returns from what historically has been important fisheries (like for cod in the North Sea and the Baltic) and aquaculture species (like blue mussels in Danish waters and salmon along the coast of western Norway). Further, climate change will likely bring severe governance and

management challenges. We will need a broad spectre of strategies to meet the issues already arising, and new ones that may arise. While an increasing world population drives towards increased demand for the production from the ocean, there will be restrictions both to natural productivity and willingness to pay related to price/value.

Fishery and aquaculture may have completely different development paths and issues in the future. Fisheries will likely in many areas be challenged by negative impacts of climate change on recruitment, growth reduction, competition from invasive species, acidification (maybe), and other detrimental climate-related impacts. If fisheries are strongly reduced, aquaculture may be subsidised to sustain settlement along the coast, but to thrive the aquaculture industry must be flexible. Technological advancements and economic drivers are crucial for the future. Already now the industries face challenges like high costs (for, e.g., fuel), rising demands for sustainable practices, and competition for land and sea space. While some issues may be solved in the relatively near future (change of fuel), others may intensify. In addition, and especially in Norway, both the fisheries and aquaculture industries must expect debates on the balance between the nation's future role as a food producer or primarily a technology developer and supplier.

8.2.1 Rising complexity physics-biology-societal

In addition to physical and ecosystem changes, societal developments, climate adaptations and policies will also be very important for shaping the future. Effective future governance and policy decisions depend on political will and capability amidst complex, integrated social-ecological systems. A holistic approach is essential, recognizing the interconnectedness of ocean systems.

Skilful predictions of physical changes are difficult, predictions of ecosystem development more difficult, and predictions about how society is heading towards 2100 even more complex. Societal changes are more uncertain and difficult to predict in the long run while as time progresses, more information narrows the option space and reduces uncertainty. Uncertainty will be further reduced if we pass irreversible thresholds and regime shifts, but this is hardly a positive development. Further, we now have big data, artificial intelligence and generally advanced technology. Unfortunately, there are information gaps, which science alone never will be able to bridge. Political developments and arising issues regarding the compliance with current international agreements are extremely hard to predict. A striking case, especially relevant for fisheries, is the situation with Russia. Russia, which covers almost half of the Arctic and until few years ago was (more or less) part of the open information landscape, is now more closed than for many decades.

Also management and regulations, both at the national and international level, will be challenged by the changing climate. The economic and societal consequences of climate change for fisheries and aquaculture are complex and diverse between countries and regions, as well as among large scale and smaller fisheries and aquaculture operations. The changes are likely to require interim measures for adaptation and permanently more flexible regulations. Ecosystem-based management and multispecies quotas may be feasible options. However, one must be aware of the threat of maladaptation – trying to solve one externality to cope with climate change may increase other problems.

8.2.2 More sustainable aquaculture and fisheries

In addition to climate change, the seafood industries are facing increasing demand for eco-friendly products. This implies both focus on fish welfare and the environmental footprint of the activities.

Consumer trends and their stickiness are hard to predict but will play a role in shaping the future of fisheries and aquaculture. Price has been the most important factor in determining consumer choice. In the future, we may face higher food prices in general, caused by a larger population and a globe under tougher climate stress. How this affects seafood prices as compared to other food sources is hard to predict.

Even though there may be opportunities to boost the production of wild fish and other marine organisms in certain areas over both short and long periods, the main driver of overall seafood production growth will have to come through aquaculture. A sustainable increase in seafood production will likely imply both land-based and offshore aquaculture and seafood farming of a wide variety of species. This to meet diverse market demands and reduce the pressure on wild populations and environmental degradation.

There is increasing focus on traceability, documented knowledge of where the seafood item origins and how it was produced. This is emerging as a market trend, driven by consumer preferences and enhanced by branding. Traceability has already emerged in (high-end/restaurant) markets in the US, but also in supermarket chains, which with their large market shares may drive such developments further. Traceability has market value, from consumer preferences, branding purpose, and pressure groups. The Marine Stewardship Council (MSC; <https://www.msc.org/>) is at the forefront of organizations working to ensure that a set of requirements for sustainable fishing are withheld, including a policy for encouraging fisheries to be well managed and better prepared for environmental changes. For farmed seafood, the Aquaculture Stewardship Council (ASC; <https://asc-aqua.org/>) plays a similar role. We expect MSC and ASC, and similar groups, to increase their importance in the future.

8.2.3 Subsidies

We briefly discussed to what degree aquaculture and fisheries in the Nordic countries are dependent on subsidies or other support schemes. Fisheries may be subsidised through tax exemption, reduced fuel prices or other measures. Municipalities are eager to attract the aquaculture industry and prepare the ground for them in various ways, but mainly by dedicating coastal and offshore locations for aquaculture in their area plans. This may not count as subsidies but work in a similar way. Economists are in general sceptical of subsidies because they disturb incentives but can be argued for if there is some kind of market failure involved. Market failure is when observable prices such as prices in commercial markets do not reflect the full impacts of the related activity. This relates to the importance economists put on prices as carriers of information and incentive makers.

The Nordic area is a price taker in the global climate development in the sense that the Nordics have limited influence on the global development, in terms of its share of emissions, influence on global decisions and 'voting power', and based on its share of the global economy. Still, it may be possible to strengthen our influence within the climate change scenario time frame if we become more of a knowledge and technology provider and set an example of how fisheries and aquaculture can be done sustainably in line with climate action. This potential is heightened by especially Norway being a large actor within fisheries and aquaculture. Further, the Nordic countries can influence their own situation through adaptations. This leads to different possible scenarios for the future.

8.3 Fisheries

8.3.1 General issues across sea areas

8.3.1.1 Regulations and management

Our group agreed that the economic and societal consequences of climate change for fisheries in the Nordic region will be diverse and complex, but discussions arose about the degree of impact. Some suggested that fishers will perceive climate impact mainly through alterations in regulation. Fishers may identify climate change impacts as 'just variation'. Natural variation has always been present, and fishers have always adjusted to these. Others argued that this statement underestimates the impact of climate change, which will go well beyond the natural variations that species and populations are adapted to - at least if we look as far ahead as 2100.

In any case the coming changes will challenge the international legal framework on the management of the seas, which we discussed and here briefly outline. Criteria for distribution of catch shares between countries are laid down in the Convention on the Law of the Sea and the UN Agreement on Fishing on the High Seas (1995), where two central principles of distribution are zone affiliation and historical fishing. Other criteria are dependence on fishing and contribution to research and management. However, how the criteria are to be operationalized has not been determined, nor the weighting between them. The criteria thus do not provide clear guidelines for coastal states and relevant distant fishing states, leaving room for interpretation and negotiation (Henriksen and Hoel 2011). Zonal attachment is an important concept within fisheries regulation. This is the principle that quotas or catch shares should correspond to the share of the fish stock biomass present within a country's Exclusive Economic Zone. This means that the fraction of the stock residing within a particular country's economic zone, if necessary weighted by the time it spends in a country's zone over a year, determines the share that this country gets of the total catch quota for that stock.

There is a contradiction between the zonal affiliation principle and historical fishing. The history surrounding the management and conditions for cooperation on the issue of distribution of quota shares of the pelagic stocks in and around the Nordic seas are examples of this (Bjørndal and Ekerhovd 2014). The zonal attachment concept tends to favour the established coastal states interests over distant fishing states historic fishing rights, but our discussions pointed to its disability to cover changes in fish distribution, specifically more permanent redistributions related to climate change. For example, the established Norwegian-Russian agreement for Barents Sea cod may need to adjust if spawning and feeding distributions shift further east because of warmer conditions. This case demonstrates our group's concern about national and international regulations having to be flexible enough to tackle impacts of climate change. Fishers will need to adapt to both climate change itself and related changes to regulations.

One aspect of regulations that we discussed is that Norwegian fishing vessels benefit from subsidized fuel, but with an obligation to land catches at local coastal processing facilities. The latter mechanism aims at securing local employment but has often resulted in employing foreign workers. Norway's fishing subsidies and other aspects of the complex quota system highlight the challenges in balancing local job support and market dynamics. With changing fish distribution patterns and new species entering during the coming decades this will be complicated further. By the end of this century, we expect all petroleum-based fuels to be abolished and new and yet unknown technology to have taken over, the accompanying regulatory system we have no foundation to speculate on.

8.3.1.2 Resilience and adaptation to climate change

Although fishers have learned to live with and adapt to variability enforced through regulations, climate change may have consequences beyond what they can adapt to. Climate-resilient fisheries must either be robust enough to withstand substantial changes or flexible enough to be able to adapt and transform to the new state.

We expect pronounced differences in risks, possible opportunities and the ability to adapt between geographic areas and fleet types. We anticipate that over the coming decades the need for change/diversification in the Nordic and Barents Seas fisheries is less than in the Baltic, which already for some time has been challenged by a mixture of pressures. Also, the larger ocean-going vessels are more flexible to new distribution patterns and even new species than coastal fleets. There is a worry that coastal fleets may disappear from some areas. This points to a (potential) underlying conflict between locally owned and operated (smaller) vessels and larger ones (trawlers, purse-seiners) that may operate more freely in different areas.

8.3.1.3 A shift towards high-end professional and recreational fisheries?

There were worries in our group about the future of commercial fisheries in especially the Baltic where the main commercial fisheries, and fish stocks, of cod and herring are already struggling. The same worry to a certain degree also applies to the North Sea when climate change strikes for full on top of all the other pressures. One scenario is a shift to the situation we have had on land most places in the world for a very long time, with food production totally dominated by agriculture and hunting more of a recreational activity. Tourist fishers may create more value than standard fisheries, at least if one takes the full cascading effects into account, including hotels, renting of boats and fishing gear. While the total worth is hard to estimate even for today, especially in northern Norway many different varieties of tourist fishing – including offshore for cod from the large skrei stock – has increased manifold over recent years. If regulations are followed and fishing is directed towards large healthy populations or cautious catch-release practices, this fishery may remain sustainable also under (moderate) climate change.

We may also see a development where there still is professional fishery but geared more towards high-end and lower volume. This is not totally new, we already have consumer acceptance for a price premium for high quality products, also related to specific gear (cod caught by line rather than trawl, for instance). If these developments are wanted or accepted as inevitable, infrastructure should be more geared towards high quality rather than large quantity. However, such changes and/or reductions will have large broader consequences, especially in smaller

communities built upon fisheries. This opens for more general decisions relating to societal and cultural priorities. In Iceland, the Faeroe Islands, and (parts of) Norway, fisheries are deeply rooted in the culture, and we expect a willingness to support it even if the economic value decreases. Fisheries likely have lower priority in Sweden and Finland where their contribution to total economy is very small. Still, also in Finland and Sweden fish is an essential part of local traditional cuisine and culture (albeit in Finland mainly lake fishing), and the role of domestic fish as a healthy and environmentally friendly choice of protein is already being promoted. Also in Germany where fisheries has low economic value compared to the overall, there is a big public interest in fisheries and also environmental NGOs want to keep it. Thus, Germany maintains fisheries mainly for cultural and touristic reasons. While low volume high quality fisheries a priori should decrease the complexity of management and support sustainable practices, in practice future fisheries management will need to balance economic, socio-cultural, and environmental considerations.

8.3.1.4 Technological developments

This section relates to the coming decades; we have little foundation for saying anything sensible about the technology at the end of the century. Climate change, in interaction with other pressures, will drive development of new technology. The urge for a green transition also puts new demands to the fisheries sector, mainly through requirements related to engines and fuel. New types of fishing boats are developed for use in some Nordic areas, naturally where there is expected returns from such investments. In the Baltic this is not the case, people cannot risk such investments, so the fishing fleet is becoming old. New boat technology must be safe, energy efficient and not too expensive. Electrically powered boats are presently not safe enough nor able to undertake long trips, but hybrid alternatives are being developed. The introduction of CO₂ taxes encourages development of greener fuel. In Norway fishers are subject to such a tax on fuel, although it is partly refunded. For large vessels and/or long trips ammonium should be considered as an alternative fuel. Unfortunately, green fuel adoption is hindered by cost and space requirements for hybrid two engine systems.

8.3.2 Specific climate change related challenges to fisheries per region

8.3.2.1 Baltic Sea

The conditions in the Baltic Sea, with low salinity and oxygen levels, have always been challenging for marine species like cod and herring, although the stocks in long periods have thrived. The recent development with eutrophication, a strong temperature rise, and increased frequency and longevity of marine heatwaves has worsened the situation for established commercially harvested species, and there are low prospects of new species taking their place due to the unique

characteristics of the sea (e.g., brackish water). Sprat are doing quite well but is used nearly only as fish feed and as such has also low value in the market and cannot replace cod or herring. Looking ahead towards the end of the century, even an intermediate IPCC scenario is bad news for the Baltic.

Commercial fisheries, which has been highly important, seems to be losing in competition with other interests. Following the decline of fish resources, the number of fishing vessels is going down. Also, for example in Germany the mean age of fishers has increased a lot, now 57 years with hardly any young people entering. Further, fishing now has relatively low monetary value. For instance, in some harbours fishing vessels have had to move out of the best and most central locations as there is more money in marinas for recreational boats. Still, the social-cultural value of fisheries is significant in some countries bordering the Baltic Sea, especially at the local level there is support.

Fishing is in intense competition for space in the Baltic, not least with the shipping and energy sectors. This is a source of conflict that perhaps could be weakened by good spatial planning, but at least in Germany fishing is not included in the main processes. Fishing also has conflicts with marine conservation, which has high priority. While successful environmental conservation and restoration may be benefactory to fisheries, fisheries are by many considered as one of the main threats to the ecosystem. Based on current evidence, our group considers it highly unlikely that the fish stocks and fisheries will return to the high levels of the past. With increasing effects of climate change, future fishing may be restricted to low volume high-end. This will likely be geared towards tourists who are willing and able to pay a price premium and more for the experience than the food. This form of fishing, especially if catch-release is practiced, may also be marketed as eco-friendly.

8.3.2.2 North Sea

North Sea fish and fisheries are already under strong pressure from climate change, especially rising temperatures. The most prominent case is that of cod, which in the North Sea live towards the southern boundary of the species' preferred temperature. The once large stock (300,000 tonnes in the 1970s), has dwindled, in the southern North Sea there are few cod left. There is little doubt that this is related to intense fisheries. However, there is also considerable evidence for high temperatures being a substantial cause, especially through negatively affecting the main zooplankton prey of the young fish. With continued temperature rise, the future for cod fisheries in the North Sea is bleak.

Sand eel (also called sand lance) is another commercially important fish that is under pressure. Warmer seas, especially during winter, may cause problems, resulting in a decrease in overwinter survival and delayed maturation. However, the most immediate threat is likely through habitat disturbance. The North Sea has

been heavily industrialised for decades. Until recently the main offshore installations were related to petroleum, but now there is also the development of wind farms. This industrial growth poses unknown consequences, potentially displacing traditional fisheries. Danish fishers are particularly concerned about the full development of Dogger Bank, a crucial habitat for sand eels. The combined effects of an increasing number of offshore structures, often in areas of importance for fish and fisheries, and changing climate is highly troublesome.

With increasing temperatures, warm water affiliated species can move in from the south, this is a distinct difference between the North Sea and the Baltic. Hake, a sought-after food fish further south in Europe, have already established themselves in the North Sea and are expected to respond positively to further warming towards 2050. They are presently fished in the North Sea, but the fisheries here are relatively small. Bluefin tuna are also expanding their habitat northwards and are again found in the Skagerrak. There is now a fleet of around 10 vessels fishing Bluefin in Norwegian waters, and in addition a commercial rod and reel fishery targeting recreational fishers. Some flatfish species are also doing well, like plaice, which is especially popular in Denmark and now has an advised quota by ICES of 150 thousand tonnes.

8.3.2.3 Nordic Seas

Norway, Iceland, Faroe Islands, UK, Greenland, and Russia as well as various members of the EU participate in harvest and share the three large pelagic stocks of herring, mackerel, and blue whiting. The fisheries are of considerable commercial importance, and the stocks straddle the Northeast Atlantic, various EEZs and the high seas. These pelagic stocks are currently per definition overfished (in the sense that total TACs are higher than the ICES-based advice) and management in a state of conflict. Still, and although the total biomass is a lot lower than the peak values, none of the three stocks are in serious trouble.

The stocks' distribution patterns are highly variable, to a large degree influenced by stock size and sea temperatures. Higher temperatures in the future may open for new distribution patterns. We consider temperature unlikely to be much of a problem (as direct impact) in the foreseeable future, but if primary production is hit, it will cascade to the pelagic fish. Acidification may become a threat by affecting fish eggs and larvae or through phytoplankton, but too little is yet known to draw any conclusions.

The Norwegian spring-spawning herring stock mainly inhabits Norwegian waters throughout their life cycle but can migrate into Russian waters during the juvenile phase and into Faroese, Icelandic and international waters as adults during the summer feeding period. However, the feeding migration pattern, especially for large herring, has changed several times over the last 60 years (Utne et al. 2012), varying with the size of spawning stock biomass and ocean conditions. The mackerel spend

most of the year in EU and UK waters, but a large part of the stock migrates into the eastern part of the Norwegian Sea and the North Sea from June to October. From around 2007 onwards Icelandic waters have also been inhabited by mackerel, linked to both the stock being large and high-water temperatures.

Changes in stock size and distribution have led to disagreements about the distribution of quota shares and renegotiations of concluded agreements (Baudron et al. 2020). When the negotiations on quota allocation have not progressed, the states have set their own quotas, which has resulted in fishing far more than scientific quota recommendations. Persistent overfishing can lead to overexploitation and greatly reduced stocks. Nevertheless, the states have not been able to agree on joint management and fishing pressure that is not assessed as sustainable continues.

With the sharing of catch quotas based on the zonal affiliation of fish stocks, it is not surprising that changes in distribution and migration patterns lead to a breakdown in existing agreements. It also shows the contradiction between the zonal attachment principle and historical fishing and that a cooperation agreement is not necessarily consistent over longer time horizons (Kvamsdal et al. 2022).

8.3.2.4 The Barents Sea and European Arctic Ocean

We discussed several possible developments in the region. We did not operate with any precise time horizon, but more towards 2050 than further ahead. This brief exercise was partly inspired by an earlier Barents Sea 2050 scenario workshop where several of us also took part. That workshop, reported in Planque et al. (2019), built their analyses upon the four perspectives "fisheries management," "ecosystem," "ocean climate," and "global context and governance". Here we were less systematic, but three scenarios were described: **1. An industrialized Arctic.** With retreating ice cover and higher temperatures in the region there will be a struggle between nations to utilize the more accessible resources. We can imagine an industrialized Arctic with much increased activity in the established shipping, oil industry and tourism industries, and maybe also renewable energy (e.g., wind, wave), and deep-sea mining. Fisheries will then be less important than what they are today, but there could potentially be aquaculture on the coast of Svalbard. In this scenario, the region may become more like the present North Sea in many aspects. In a transition to an industrialized Arctic security and geopolitics will be important. The competition for resources could, as often before, escalate to **2. A conflicted Arctic** with high military presence from different nations and less opportunities for developing industries. The world's two superpowers, USA and China, both have military and commercial interests in the region, and Russia has an extensive Arctic coastline. A more optimistic development could be towards **3. An environmentally protected Arctic.** This would be an expansion of the present cautious fishery management of the international waters of the Central Arctic

Ocean to include limited or no oil and gas exploration, restricted and eco-friendly tourism, no-go marine protected areas, and a focus on preserving healthy fish stocks and nature more generally. This latter scenario would obviously be best for the climate, but it demands high levels of cooperation that seem unlikely today. One can hope that climate awareness at the governmental level increases when the impacts of climate change become severe enough.

From a more strictly fisheries point of view, future management should balance economic, cultural, and environmental considerations, considering public interest and the potential for increased competition from other industries. The Norwegian-Russian cooperation on managing the fish resources of the Barents Sea has for decades been more resilient than most other places, but now faces challenges.

8.4 Aquaculture

The group had broad discussions on the future of aquaculture in the Nordic areas in light of climate change and societal developments. Topics included the pronounced difference between the countries and seas regarding present aquaculture and future potential, a shift from wild fisheries to aquaculture, expansion of aquaculture northwards, offshore, on land and into new species, technology, co-existence with other industries, feed for the fish, and food for humans; all with the backdrop of changes in climate and the consequential impact on the environment. A complicating factor is that climate change will affect aquaculture through a range of different pressures and there are large knowledge gaps when it comes to the combined effect of multiple stressors. It should be noted that another workshop, focusing specifically on climate change and aquaculture, was held shortly prior to ours, more information at <https://nofima.com/press-release/climate-change-adaptation-for-aquaculture-discussed/>

8.4.1 Differences between countries

Among the Nordic countries, Norway and the Faeroes are in the lead in marine fish farming, although also Denmark has had a significant fish sea cage industry for decades and an increasing focus on blue mussels. We consider that Iceland has a potential for increasing production. Finland and Sweden have numerous fish farms in lakes and rivers, but our focus was marine and that was not further discussed. We will see distinct differences in how climate will affect ecosystems and sea farming industries between the Nordic countries. There has been and is little aquaculture in the Baltic proper due mainly to pollution, eutrophication and low oxygen levels. While the group saw the potential becoming further reduced with climate change it should be noted that except in the worst climate scenario combined with very large inputs of nutrients, oxygen levels in the Baltic Sea are

expected to be higher/better by the end of the century than today. Still, rising temperature is a challenge, and the Baltic ecosystems are in need of severe restoration, especially dealing with the large amounts of nutrients that have accumulated in the system during the last century, before substantial aquaculture can be established.

Although both The Faeroes and Norway have their aquaculture dominated by Atlantic salmon and are technologically advanced, there are significant differences. This relates to environmental conditions, with temperatures being more stable in Faeroese water, but with the farms there being closer to the open ocean and more vulnerable to large waves and ocean swells. This will likely cause different impacts from climate change with a general transformation towards both higher temperatures and stronger winds. The combination of this and little remaining place in the fjords will likely hamper further expansion of Faeroese aquaculture.

8.4.2 Fish feed – a main restricting factor

A major difference between the Faeroese and Norwegian salmon farming is the fish feed. The Faroe farms mainly use marine-based feed, typically blue whiting, while Norway relies heavily on plant-based feed, mostly soya from Brazil. Unfortunately, neither of these practices are sustainable, especially if the industries are to scale up. Faeroese salmon are considered to have the highest quality (also because they are slaughtered at a larger size) and get a price premium, the highest price in the world market. However, the practice of using small pelagic fish as salmon feed puts pressure on the world's fish stocks and their ecosystems. Still, using blue whiting as feed is less unsustainable than sardines or anchovies, which to much larger degree are directly eaten by humans. Plant-based feed ingredients may to certain degree replace fishmeal and fish oil, but demand land and water resources. Relying on soya from Brazil is especially troublesome, as the soybean production has led to clearing of large areas in the Amazon rainforest. Both this and the long-distance transportation to the salmon farms cause substantial greenhouse gas emissions accelerating climate change – the opposite of climate change mitigation.

As for fish caught in the wild, there is a rising demand for sustainable practices in the aquaculture industry. The debate on the demand side, including the carbon footprint of farmed salmon and ecological farming certifications, reflects changing consumer preferences. Traceability, documented greener production lines including knowledge of where the seafood item origins and how it was produced, may secure a price premium. Finding ways to feed the fish in a sustainable way is perhaps the factor most strongly restricting substantial expansion of the aquaculture industry. A number of innovative and more sustainable feed solutions have been suggested and studied, including algae, insect meal, by-products from production of other

food (such as using dairy waste for shrimp farming), and laboratory produced single-cell proteins. So far, price and the need for scale-up possibilities has been too challenging to make any of these into real-world solutions.

8.4.3 Challenges and potential means of adaptation

Although climate change will affect fisheries very differently across the Nordic sea areas, we expect an overall decline. An expansion in fisheries is unlikely, that must come in aquaculture. Such a shift is influenced not only by decreasing limits to productivity (carrying capacity) in the wild fish stocks, but also by consumer trends and technological advancements within aquaculture, suggesting a future where farmed fish plays a dominant role. We expect geographical shifts (northwards) to lower temperatures, new species, new technology, and/or offshore and/or on land. Geographical moves and expansion of cod and kelp farming present opportunities, but also challenges. Temperatures will likely become too high at some existing salmon farms in south-western Norway within ten years, already the expansion is into more northerly and cooler areas. Moving the core of Norwegian salmon aquaculture northwards may reduce conflicts along the wild versus farmed salmon axis, but introduce new lines of conflict between aquaculture, fisheries for e.g. cod, and other industries. Management should be flexible enough to respond adequately to changes driven by climate and/or market demand. For example, in Norway, new regulations are opening opportunities for diverse species like lobster and halibut.

The vast majority of fish farms in the Nordic region are of the sea cage type, also known as net pen or semi-closed farming systems. According to the industry, this conventional technology will be the main production method for many years to come (PWC 2023). However, looking “some decades” ahead, the industry believes that an increased focus on new technologies, such as offshore and land-based production and closed marine cages, will create a shift away from the conventional technology that is totally dominating today (PWC 2023). Although still in its infancy, offshore aquaculture farms are operative in Norwegian waters and others are planned. There are several reasons for this development. There is limited space close to the coast, the best locations are taken. Offshore there is room for larger installations. Offshore locations reduce the threat from and spread of diseases and parasites, like sea lice, that challenge coastal fish farms. Advances in automation and smart technology now make it more feasible to operate fish farms further from the coast.

However, there are also factors that challenge offshore fish farming. Firstly, it is very expensive, establishing a new offshore farm costs a lot more than a coastal one, despite new technology also routine operation and maintenance at sea is costly. Related to this is technological and logistic challenges. Offshore farms must endure tough environmental conditions, including strong and variable currents,

strong and high waves, and exposure to storms. This requires robust and often expensive infrastructure. Increased windiness and waviness is expected, further stressing the infrastructure. Wind and waves may also stress the salmon, fish welfare must be taken into consideration. The Norwegian Ministry of Trade, Industry, and Fisheries recent strategy document "Business plan for the Norwegian sea areas" (NFD 2024) states that the government is working on developing a separate licensing regime for offshore aquaculture with strict requirements for sustainability and coexistence between different marine industries.

Although uncommon in the Nordic area, Recirculating Aquaculture Systems (RAS), have also been introduced. Such systems are enclosed, sealed off from the environment and replace the natural flow of water in the sea with a water filtration and recirculation system. As a result, they can be and most often are placed on land. Recent technological advances and growing regulatory support (e.g., Norway is incorporating land-based farms into their aquaculture strategies) are making it feasible to farm fish and other aquatic species in controlled, land-based environments. There are environmental-based arguments both in favour and against a switch towards more land-based aquaculture. Closed land-based systems will diminish the impact on marine ecosystems by reducing pollution, issues with wild (e.g., salmon) populations, and the salmon lice infestation. On the other hand, RAS consumes large amounts of fresh water, requires much more energy than the natural flow of water utilised by cage systems, and will have to compete with other activities for space on land. RAS plants can in principle be placed close to the cities where the markets are, but scarcity of land in such areas drives the costs up. Also, countries like Norway, have, with a long coastline and proximity to open sea areas, a natural advantage for coastal and offshore aquaculture. This may not be the case for land-based operations, thus there may be little motivation at the national level for shifts in that direction.

8.4.4 Potential co-location and cooperation with other industries

Climate change may encourage and enforce different industries to work together. Our discussions touched upon co-existence of wind plants and kelp aquaculture and even potential multi-use wind farms and aquaculture infrastructure. Several possibilities are being explored in the EU funded project "Offshore Low-Trophic Aquaculture in Multi-use Scenario Realisation in North and Baltic Seas" (OLAMUR; olamur.eu; coordinated from IMR). This includes demonstration cases where kelp and blue mussels are grown within windfarms and near a trout farm. This includes work lead from Aarhus University that demonstrates the potential of multi-use in offshore areas, highlighting both sustainable energy, nutritious seafood, and restorative ecosystem services through nutrients and carbon capture and utilization (Maar et al. 2023b). They more particularly examined co-locating wind farm with blue mussels and sugar kelp aquaculture in the North Sea - Baltic Sea transition zone.

8.4.5 Adaptation measures including technological development

There is a broad range of solutions available and also ideas in the pipeline. These span from genetically adjusted fish to new nets that can be pulled down to adjust temperature and avoid surface marine heat waves. However, there are also downsides, genetic modification is debated and complicated. Fish that are modified to cope with higher temperatures may as a side effect become more vulnerable to low oxygen content.

In addition to being a large fish producer, Norway is a leader in providing technology and knowledge, for instance in rearing new species (like cod) and applying genetic tools to enhance specific targeted fish properties. With Norway's high costs and a location far from large markets, our discussions suggested that the country could move more towards becoming a supplier of technology more than actual fish. However, awareness of impacts of climate change is still often low and adaptation measures not prioritized. This is problematic, as climate change, especially through rising sea temperatures, is expected to have increased negative impacts on the aquaculture industries, already in the near future. Challenges include intensified marine heat waves and algal blooms, more jellyfish invasions, parasites and diseases. Sea lice is a severe problem both economically and for fish welfare. Also, the treatments to get rid of sea lice are problematic from a fish health and – welfare perspective. In addition to gill problems, skin health is currently the main factor leading to loss, and this is mostly related to injuries caused by treatment. Further, increased temperature has shown to worsen the effect from production related stress.

Higher temperatures also tend to spread and increase the lice problem. Unfortunately, this is already happening - unusually warm water during the summer of 2024 caused severe lice issues much further north than earlier. The knowledge level of impacts of MHWs like this is low, but we expect them to be quite different in, e.g., northern Norway than in the Danish straits.

Technology should also be applied towards climate change mitigation, that is reducing the GHG emissions from the industry. Pressure towards sustainability on the demand side, including reducing the carbon footprint of farmed fish and ecological farming certifications, reflects changing consumer preferences. This may help drive development of more green technology. Ideally, as pointed to in the aforementioned strategy document (NFD 2024), the cultivation and farming of seaweed and kelp can also be a means for nature-based carbon sequestration.

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Appendix 1. Description of changes and evaluation of new NEMO-NAA10km model

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Correction algorithms for improving river runoff fields

NorESM2 Climate Downscaling, a first attempt with constant runoff

A first batch of simulation was started in 2020, based on outputs of the NorESM2 climate model. The design of the atmospheric forcing, adapted from the NorESM2 climate model was straightforward, but required a re-design of the oceanic boundary conditions, as using them directly produces ocean modelling simulations with an unrealistic Atlantic Meridional Overturning Circulation (AMOC) of 60 to 80 Sverdrup. The runoff that can be extracted from the NorESM2 climate model turned out to be un-realistic, as its historical simulation exhibits a freshwater flow towards the ocean that is higher by 20% than that observed by Dai and Trenberth (2002) during the period 1950–2014. Its geographical distribution is also biased. Therefore, the downscaling simulations used a climatological runoff, which gives realistic results in terms of salinity in the simulation but does not take into account the expected increase of runoff and hydrological cycle towards the Arctic Ocean, during the 21st century.

NorESM2 & EC-Earth Climate Downscaling within NorScen

A correction algorithm for river runoff output of climate models

Within NorScen, we aimed at providing river runoff fields that are realistic, and that follow the inter-annual variability of the climate model runoff, to the climate downscaling simulations. Development time was therefore invested into this task. River runoff outputs of climate models are two-dimensional fields, which for every coastal point of the ocean component of a climate model, provide a runoff value to the ocean. Each point corresponds to a drainage area outlet, but the representation of drainage areas varies between grid and models. Meanwhile, it is impossible to represent river runoff as two-dimensional fields, as they are on one hand discrete distributions, and on the other hand runoff conservation is essential which does not permit any spatial interpolation to enable comparison. A method is needed to perform this comparison.

To perform this task, the runoff of the climate model is re-routed to the Nemo-NAA10km, this means that for a given runoff point of the climate model, the runoff is re-routed towards the closest coastal point of the Nemo-NAA10km grid. River outflow locations can differ from one model to another, but integrating the river runoff along a coastline, should lead to the same accumulated value. Therefore, our strategy is to integrate along a coastline that spawns the entire coast of the Nemo-NAA10km grid. To create this coastline, one starts at the edge of the domain, on a coastal point located on the US East coast, and an algorithm searches for the closest coastal point, and so on, until the entire coast of the Nemo-NAA10km is covered. Some unphysical connecting jumps to islands or disconnected coastal areas may occur, but prove to be unimportant, as they create a coastal index that is identical and will be applied exactly in the same manner to all runoff inputs. This algorithm provides a pointer that covers the entire coast of the Nemo-NAA10km domain. The mean climatological runoff provided to Nemo-NAA10km in hindcast mode, and extracted from Dai and Trenberth (2002), is projected on this coastal index axis, as well as the mean climate model runoff for the historical period 1950–2014. This projection is made from a cumulated point of view, so that runoff projection on the coastal axis index is a strictly increasing function. This choice also allows getting a continuous function, although its derivative is not, since not all coastal points are related with a runoff input, nor this runoff input can be considered as constant. Finally, using a cumulative approach, allows replacing similar runoff inputs (i.e. corresponding with the same river or drainage area) but rerouted to different grid cells, to be close to one another on the coastal axis index. Once the reference hindcast runoff, and the climate model, are placed as cumulated runoff along the coastal axis index, a transfer function between the two is computed, with the shape of a second-degree polynomial, which coefficients can be computed based on simple matrix inversion. This allows for the computation of a corrected cumulated runoff function. The correction algorithm, and more specifically the polynomial transformation (after minor adjustment), is then assumed to work for any runoff field, during all the simulation. This method provides a valid correction of climate model runoff, for a given climate model, for the historical period 1950–2014 as well as for climate projections.

This algorithm, once applied to the runoff fields of the NorESM2 and EC-Earth climate models, allowed for the creation of monthly runoff fields, for each year of the period 1950–2100. These fields follow the inter-annual variability of each climate model original runoff fields, while being bias corrected and consistent with the original runoff inputs of the Nemo-NAA10km hindcast simulations.

A correction algorithm for precipitation fields of climate models

First attempts at downscaling the EC-Earth climate model led to unrealistic results, in which the North Atlantic and the Arctic Oceans were transformed into a brackish structure, with very low SSS values. However, such SSS values, are not

simulated in the original EC-Earth simulations used as input for these climate downscaling. Sensitivity experiments revealed that the precipitation fields of the EC-Earth model were overestimated, and responsible for this freshening. The mechanisms through which these overestimated precipitation fields do not produce a strong negative SSS anomaly in the EC-Earth climate model are unclear. One could speculate that the evaporation rate over the ocean is higher in EC-Earth, or that the export of freshwater through the AMOC is higher than in Nemo-NAA10km, perhaps due to a deeper mixed layer. But the point is that we cannot use the EC-Earth precipitation fields as they are for downscaling experiments. A strategy is therefore needed to bias-correct the EC-Earth precipitation fields, for the purpose of downscaling EC-Earth climate simulations using Nemo-NAA10km.

We first identify that at the beginning of the historical period, the EC-Earth precipitation fields are actually lower on average for the Nemo-NAA10km domain, than the ERA5 precipitation fields. The strong freshening is related with a very strong trend of increase of the EC-Earth precipitation fields towards the end of the 20th century and through the 21st century. A trend which is not observed in the ERA5 precipitation fields. However, the difference of trend for precipitation trends, between ERA5 and EC-Earth, is very different depending on location, with a strong dependence on latitude.

For each (discretized) latitude along the latitude axis of the precipitation field, one can therefore define a trend correction to make the trend of ERA5 and EC-Earth precipitation fields fit during the 1979–2014 period. This correction, in the form of a constant coefficient for each discretized latitude component, is applied throughout the entire simulation 1950–2100. First, what should be the linear trend of precipitation in EC-Earth is computed, for a given year, and a given latitude, based on the corrected linear trend. Second, this value is subtracted from the EC-Earth precipitation field, for the same given year, and the same given latitude.

A comparison between the original EC-Earth precipitation fields, and the corrected ones, shows that most of the correction is applied at latitudes above 40 °N.

Comparison between results from new and previous version of NEMO-NAA10km

The comparison is done for the intermediate greenhouse gas concentration scenario SSP2-4.5. The new model version, with improved runoff distributions, has increased surface salinities in parts of the Barents, Kara and Norwegian seas and decreased salinities north of Greenland and in the East Greenland Current (Fig. A1, middle panel). However, the difference between the surface salinity in the two versions for the SSP2-4.5 scenario at the end of this century (Fig. A1, right panel, indicates that NEMO-NAA10km-new has less increased salinities in the Barents,

Kara, and Norwegian seas compared to NEMO-NAA10km-old and less decreased salinities north of Greenland and in the East Greenland Current than NEMO-NAA10km-old. We are yet unable to explain the very pronounced difference between models in the region north of Greenland (intense red in Fig. A1, right panel). However, note that the changes in surface salinities generally were more extreme in the old version. This is also true for SST in the Norwegian and Barents Seas (Fig. A2, right). The combined effects on mixed layer depth is biggest in the subpolar region and in the Norwegian and Barents seas (Fig. A3, right), with less deep mixed layer depth most places in the new version.

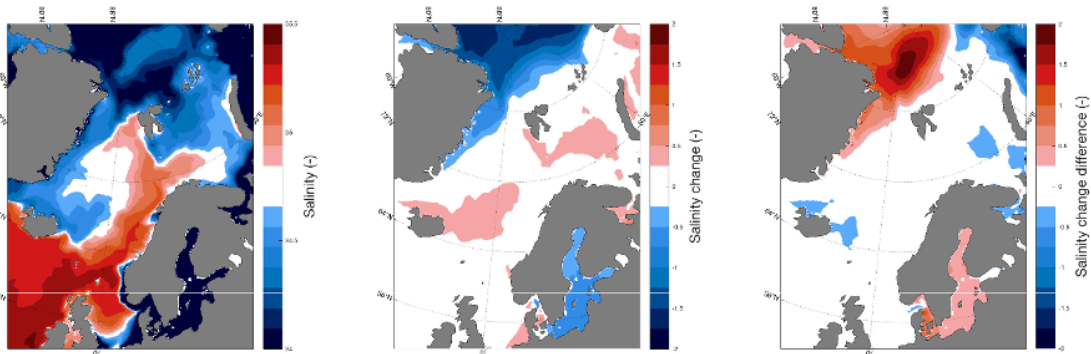


Figure A1. Average March sea surface salinity (SST) in NEMO-NAA10km-new (2015–2034, left panel), average SSS change in NEMO-NAA10km-new from period 2015–2034 to period 2080–2099, mid) and average difference in this SSS change between NEMO-NAA10km-new and NEMO-NAA10km-old, right).

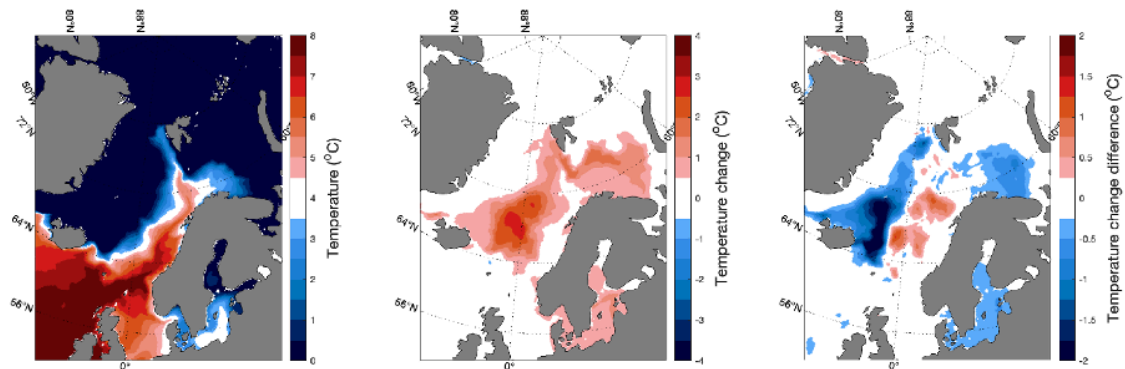


Figure A2. Average March sea surface temperature in NEMO-NAA10km-new (2015–2034, left panel), average SST change in NEMO-NAA10km-new from period 2015–2034 to period 2080–2099, mid) and average difference in this SST change between NEMO-NAA10km-new and NEMO-NAA10km-old, right).

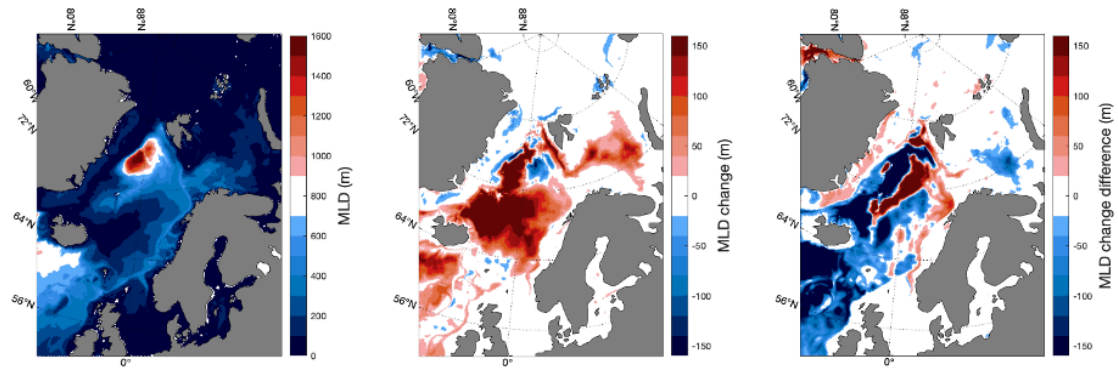


Figure A3. Average March mixed layer depth (MLD) in NEMO-NAA10km-new (2015–2034, left panel), average MLD change in NEMO-NAA10km-new from period 2015–2034 to period 2080–2099, (mid) and average difference in this MLD change between NEMO-NAA10km-new and NEMO-NAA10km-old, (right).

Appendix 2. Participants list for workshop

Participants at the workshop on Economic consequences of climate change towards 2100 for fisheries and aquaculture in the Nordic region.

Name (alphabetical order)	Employed by	Country
Anne Britt Sandø	Institute of Marine Research (IMR)	Norway
Elisabeth Ytteborg	Norwegian Food Research Institute (NOFIMA)	Norway
Geir Ottersen	IMR	Norway
Gjert Dingsør	Ocean going fishing fleet organization	Norway
Hans Ellefsen	University of the Faroe Islands	Faroe Islands
Jan Erik Stiansen	IMR	Norway
Johanna Yletyinen	University of Jyväskylä	Finland
Leif Sandal	Norwegian School of Economics (NHH)	Norway
Margrete Aanesen	Centre for Applied Research (SNF at NHH)	Norway
Nils-Arne Ekerhovd	SNF	Norway
Rüdiger Voss	University of Kiel	Germany
Sturla Kvamsdal	SNF	Norway
Susa Niiranen	Stockholm Resilience Centre	Sweden
Yuanming Ni	SNF	Norway

About this publication

Effects of climate change on future environment and marine life in the Nordic sea areas

Geir Ottersen, Lars Arneborg, Marie Maar, Elin Almroth-Rosell, Sam Fredriksson, Silvana Gonzalez, Cecilie Hansen, Magnus Hieronymus, Robinson Hordoir, Janus Larsen, Ye Liu, Ina Nilsen, Anne Britt Sandø, Sofia Saraiva, Vibe Schourup-Kristensen, and Morten D. Skogen

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