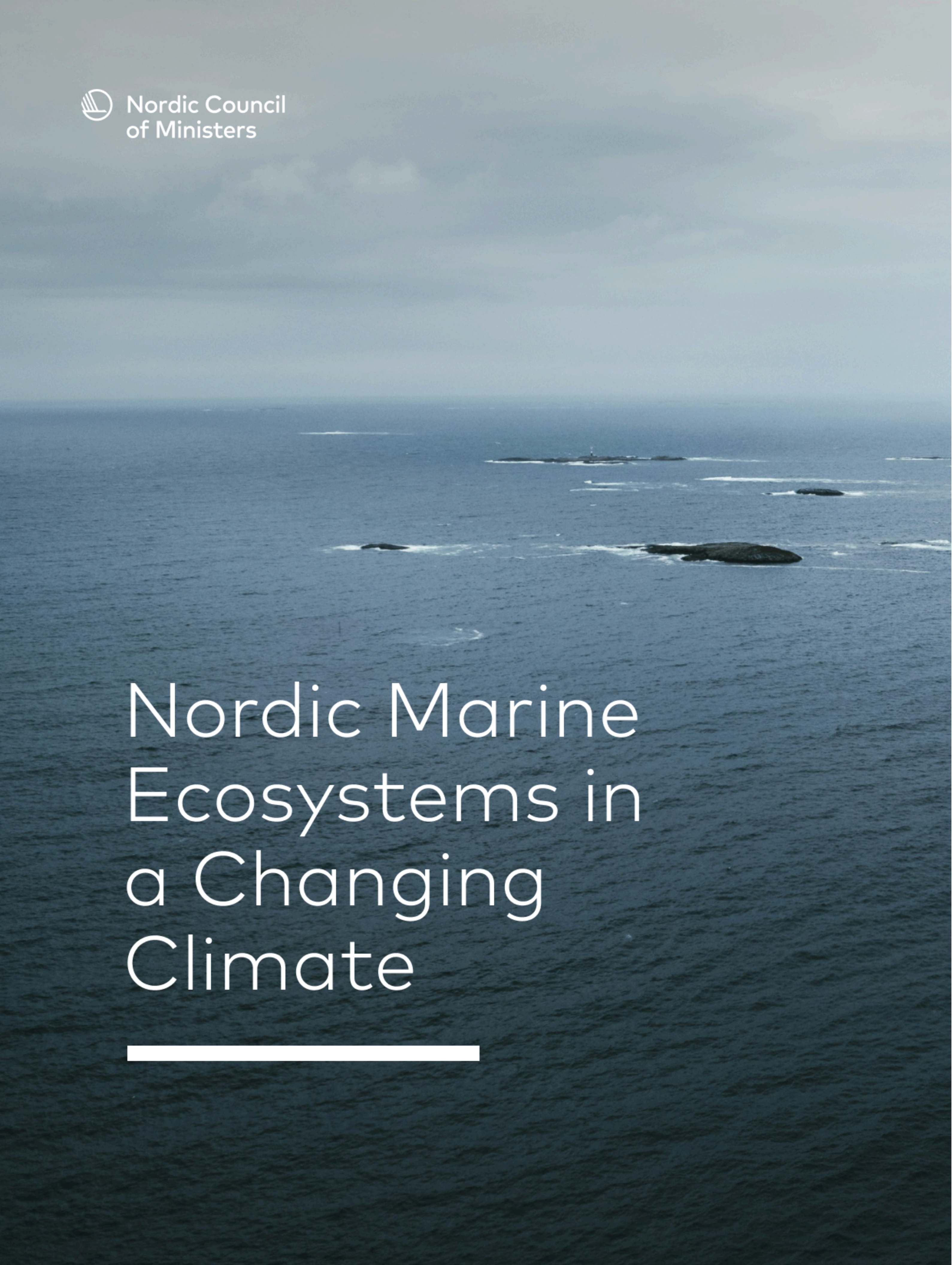

Nordic Council
of Ministers

Nordic Marine Ecosystems in a Changing Climate

Contents

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Foreword

This report is the main contribution to the project *Nordic Marine Ecosystems in a Changing Climate* – NorMECC, funded by the Nordic Council of Ministers (NCM) through the Nordic Working Group for Oceans and Coastal areas (NHK). The project and report is based on the NCM programme *Marine Management and Climate* and NHK's goal of achieving increased knowledge of the expected effects of climate change on all the Nordic seas up to the year 2100. The main target groups for the report are our commissioners at the NCM, national ministries and directorates in the Nordic countries, other researchers regionally and internationally, and the Nordic population at large.

The United Nations' Intergovernmental Panel on Climate Change (IPCC) has over the recent years published several comprehensive reports within its 6th assessment cycle (AR6), including a Special Report on the Ocean and Cryosphere in a Changing Climate. However, although AR6 contains an enormous amount of high-quality information, also on climate change impacts on marine ecosystems, the IPCC work is global, and this does not allow for in depth assessments of effects on marine life in the Nordic sea areas. Still, there is indeed substantial knowledge on expected impacts of climate change on the populations, species, and ecosystems in the seas around the Nordic countries, but the information has only partly been made available outside scientific publications and expert groups.

The aim of NorMECC and this report is to rectify this by obtaining and making available a good overview of the already observed and expected future responses to climate change of a wide range of marine species in the Nordic waters of the Baltic Sea, the North Sea, the Norwegian and Icelandic Seas, the seas around Greenland, and the Barents Sea. The report reviews and assesses scientific articles and other knowledge sources, including papers published up until February 2025. In addition to this literature review, we also provide a short synopsis of the input from a small, targeted group of Nordic managers and decision makers who were challenged to describe which climate change related pressures they consider to be the largest treats to our marine ecosystems.

In the main review section of the report, we have chosen to be quite thorough, including comprehensive referencing. While we thus strive to provide knowledge extensively, 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, Denmark, the Faroe Islands, Finland, and Sweden wish to thank colleagues from within and outside the project for ideas and contributions.

Oslo/Bergen March 10th, 2025

Geir Ottersen, Institute of Marine Research, Norway
Project leader NorMECC and lead author

Summary

The Baltic Sea

Climate change is expected to significantly impact the Baltic Sea by increasing surface temperatures, shortening ice cover periods, intensifying eutrophication, and lowering salinity and oxygen levels. These changes are likely to partially counteract and undermine the positive effects of ongoing and planed nutrient reduction measures. The physical and biogeochemical conditions in the Baltic Sea are diverse, so are the ecosystem response to climate change expected to be.

Phytoplankton are already experiencing earlier spring blooms and prolonged growing seasons. Future projections indicate a decrease in spring blooms and an increase in summer cyanobacteria blooms. However, if the primary production stays high or decreases compared to today´s conditions depend largely on the interplay of climate change impacts on the sea and the level of nutrient load from land. It is likely that zooplankton will be affected by temperature and salinity changes, leading to shifts in species composition.

In the Baltic Sea the benthic animals and plants (such as bladderwrack and eelgrass) are generally expected to be more affected by eutrophication due to nutrient overload than direct effects of a warming climate. The BS' deep bottom areas, particularly in the Southern and Central regions, suffer from chronic lack of oxygen, which affects benthic biodiversity. The area which such problems may expand significantly with increased water stratification and decreased ventilation of deeper waters. Especially if also nutrient loads continue to be high, even larger areas of the Baltic Sea may become void of benthic macrofauna. Simulation studies suggest that benthic responses to environmental change are hard to estimate, being nonlinear and decoupled from pelagic responses, with varying outcomes depending on nutrient loads and climate scenarios.

Climate change is expected to alter the fish species composition by the end of the century. In general, climate change-driven changes in temperature, ice-cover, salinity, and river-discharge will affect coastal and migratory fish (fish from freshwater origin) in particular, whereas the pelagic and demersal fish (fish of marine origin) mainly respond to changes in water temperature, salinity, and oxygen conditions. The effects on commercially valuable species like cod, sprat, and herring remain uncertain. Still, potential benefits for sprat reproduction are anticipated, while cod and herring will be challenged by yet lower salinity and oxygen levels. Invasive species like goby may benefit from climate change.

Baltic seabirds are experiencing altered wintering patterns and breeding times, with mixed responses among species. Bottom feeders benefit from reduced ice cover, while fish-feeders are less favoured. There are four marine mammal species resident in the Baltic Sea: Baltic grey seal, ringed seal, harbour seal and harbour porpoise. They are generally expected to be negatively affected by climate change, both directly through habitat loss due to reduced ice-cover, rising sea levels, and decreasing salinities, and indirectly via changes in prey.

Overall, future climate projections suggest significant changes in the Baltic Sea's biogeochemical conditions, likely affecting many plant and animal species through distribution, growth, behaviour, and interactions. Future conditions will depend on which climate and nutrient management scenario that will be realized.

The North Sea

Future projections indicate a decline in North Sea primary production by up to 30% by the end of the century. This reduction could negatively impact the marine ecosystem's food resources, but may also mitigate eutrophication, improving water quality and reducing harmful algal blooms. The development of primary production depends on biogeochemical processes and future climate scenarios, with varying impacts under different nutrient load conditions. Overall, water quality in the NS is expected to improve within the scenarios explored. Because of rising temperatures and reduced nutrient availability, the size of the typical NS zooplankton will decrease. This both because of a shift towards smaller species and within-species size reductions. A significant regime shift in the 1980s altered zooplankton dynamics, with warmer waters favouring the temperately adapted *Calanus helgolandicus* over *Calanus finmarchicus*. Projections indicate future northward shifts for both these species and further decrease in *C finmarchicus* abundance, especially under strong warming scenarios.

Climate change is also significantly affecting bottom-dwelling species in the NS, altering their distribution and composition due to factors like changing sediment composition and rising temperatures. Many invertebrates have expanded their northern range boundaries, including the Pacific oyster, which has invaded Nordic waters from the south, with a recent population explosion along the Norwegian Skagerrak coast. Projections through 2099 under a medium climate scenario suggest continued northward movement of benthic species, while more than 60% of the 75 studied species are expected to experience habitat loss.

NS fish populations face mounting pressures from climate change, with rising sea temperatures affecting both physiology and ecosystem dynamics. Many species have shifted distributions northward or into deeper waters over the past 20 years as an adaptation to warming conditions. Populations of cold-temperate species like cod, saithe, and haddock, already occasionally close to their upper thermal tolerance limits, are expected to decline, while warm-temperate species like European hake may benefit.

Climate change is also significantly impacting NS seabirds. Most species are projected to experience further declining breeding success. Key impacts also include changes in prey availability, particularly the decline of important species like *C. finmarchicus* and sandeels. Increasing temperatures and storminess are directly affecting breeding conditions and chick survival, especially for shoreline nesting species. Some species may adapt by shifting distribution, but species' ability to adapt to rapid climate changes will determine their long-term survival.

Marine mammals in the NS will experience both direct impacts, including physiological stress from temperature changes affecting metabolism and reproduction, and indirect effects involving changes in prey availability and habitat loss. Most NS mammal species have broad temperature tolerance and varied diets, making them generally quite resilient. Already observed impacts include range shifts, with warm-water animals becoming more common and cold-water species less frequent. Future climate challenges include sea level rise affecting seal breeding grounds in the southern NS, while also the harbour porpoise, the most abundant marine mammal in the NS, is identified as potentially vulnerable.

Climate change is expected to have pronounced holistic ecosystem effects on the North Sea. A key impact is the projected decrease in primary production, which forms the foundation of the marine food web. This reduction affects zooplankton, fish, seabird and mammal populations, and overall marine biodiversity.

The Norwegian and Iceland seas

The Norwegian and Iceland seas are nutrient-rich and support diverse marine life such as zooplankton, fish, whales, and seabirds. Despite their high latitude, these seas remain ice-free year-round due to the continuation of the Gulf Stream. The region plays a crucial role in global ocean circulation, with the Atlantic Meridional Overturning Circulation transporting warm, saline water northwards and cold, dense water southwards. For this area we give a more integrated ecosystem description, focusing on bottom-up, food driven mechanisms and energy flowing throughout the environment and ecosystem. Climate is a main driver, influencing physical, biogeochemical and biological processes.

Bottom-up processes, such as changes in zooplankton and forage fish populations, are critical to understanding the declines in fish stocks and seabird populations in the subpolar North Atlantic over the past few decades. The strong atmospheric jet stream and subpolar gyre is an important driver, influencing temperature, salinity, and nutrient content, impacting the food web from zooplankton to commercial fish and seabirds.

Pulses of intensified atmospheric activity, often proxied by a high North Atlantic Oscillation (NAO) index, increase nutrient upwelling and primary production on the south Iceland and Faroes shelves, benefiting zooplankton and fish populations. This was the situation during the late 1980s and early 1990s, but a sudden weakening in 1995–1996 changed the size and circulation of the Subpolar Gyre, negatively affecting sandeel abundance, while benefiting species like blue whiting that thrive in warmer, stratified waters.

Major shifts in gyre circulation and ocean currents, such as those in the mid-1990s, have led to changes in water properties and marine species distributions. Long-term trends, including declining silicate levels, suggest that climate change will fundamentally alter the functioning of marine ecosystems in the coming decades. Understanding these processes is essential for predicting future ecological changes in the Nordic Seas.

Seas around Greenland

Greenland has during the recent decades experienced rapid warming, affecting ice cap melt rates, ocean temperatures, and ecosystem structures. These changes are projected to become more pronounced over the coming century. CMIP6 models project air temperature increases over 5 °C and significant precipitation increases by the end of the century under the high emission SSP5-8.5 scenario. Within this scenario glacier volume loss could reach 67%, leading to increased freshwater runoff. This will have significant marine implications as glaciers retreat inland. Changes in mixed layer depth and nutrient distribution will impact marine life and ecosystem dynamics around Greenland.

Currently, marine primary productivity around Greenland is higher in the warmer, ice-free southern regions. Projections suggest a decline in productivity in these southern areas due to stronger stratification and nutrient limitations. Conversely, in northern areas like Baffin Bay and the eastern Greenland Sea increased productivity is expected due to reduced ice cover and increased light availability. Also, CO_2 uptake will lower pH levels, likely negatively affecting organisms with calcium carbonate shells, with more severe effects in the south.

Projections give a decrease in zooplankton biomass in the ice-free southerly Greenland waters. Further, the important copepod *Calanus glacialis* is being replaced by the smaller, less fatty *C. finmarchicus* due to changes in sea ice cover and temperature. *C. glacialis* has been retreating northward in Baffin Bay, and this trend is expected to continue. The commercially vital northern shrimp is similarly shifting its habitat northward in response to temperature changes. However, the overall impact on the Greenlandic shrimp stock and industry remains uncertain.

In the Arctic, pelagic and benthic productivity are closely linked, leading to a decrease in benthic biomass and species variety with increasing latitude, ice cover, and depth along the west Greenland shelf. Projected decreases in ice cover and increases in primary productivity in poleward areas around Greenland are expected to enhance organic matter flux to the seafloor, benefiting northern benthic communities. Bottom temperatures have risen by over one degree since 1990, prompting poleward expansion of communities, especially west of Greenland. Factors like acidification, bottom trawling, and increased walrus feeding due to reduced ice cover may negatively impact Greenlandic benthic communities.

The fish around Greenland are already affected by increasing temperatures and decreasing ice cover, leading to changes in habitats and food availability. Boreal species, like mackerel, are moving northward, while abundance of Arctic bottom dwelling benthivores and demersal fish is declining. By 2100, biomass is projected to increase by up to 50% (under SSP5-8.5) in areas currently ice-covered during winter, like Baffin Bay and the east Greenland Sea. Overall, continued warming and reduced sea ice are expected to drive further changes in fish distributions, with consequences for fisheries.

Greenlandic seabirds are facing significant changes due to climate change. Specialized Arctic species, like the ivory gull, are particularly vulnerable to shifts in sea ice and prey availability, potentially leading to population declines. In contrast, generalist species may adapt or even thrive under new conditions. The little auk, the most abundant seabird in the Atlantic Arctic, dependent on Arctic copepods, is also at risk due to habitat shifts. However, some seabirds, such as the Common Eider and Great Black-Backed Gull, benefit from warmer conditions and have increasing populations and habitats expanding northward.

Climate change is affecting the habitats also of Greenlandic marine mammals, especially ice-dependent species like narwhals, walruses, and seals. Studies show a major loss of summer habitats for the Arctic ice-dependent whale species bowhead whale, beluga, and narwhal. Walruses rely on ice, and their numbers have dropped in some areas due to sea ice decline. On the other hand, walruses have a good heat tolerance, and longer ice-free periods may also have a positive effect, giving prolonged access to foraging and access to terrestrial haul-outs. In southeast Greenland, boreal cetaceans like pilot whales and dolphins are increasing in number as summer ice cover decreases, leading to major habitat changes.

In general, the Arctic marine ecosystem around Greenland is changing rapidly due to climate change, with rising temperatures and decreasing sea ice altering habitats and species distributions. For Greenlandic waters several positive impacts are expected from moderate climate change. Projections indicate increased primary and secondary production in northern Greenland, leading to an increase in fish biomass. Diverse species, including *Calanus glacialis* and narwhals will move northward. Also economically important species, such as shrimp and halibut, are moving further north, benefiting local fisheries. In southern Greenland, warmer waters are attracting boreal species like mackerel and tuna, which could enhance future fisheries also there.

The Barents Sea

In the northern, seasonally ice-covered, part of the Barents Sea, limited light has hindered primary production. This has resulted in short and geographically limited phytoplankton blooms. Recently, the BS has seen a dramatic increase in net primary production due to reduced sea ice coverage. Spring phytoplankton blooms are occurring up to a month earlier and expanding northward at approximately 1° per decade. Model projections through 2100 under various climate scenarios suggest continued increases in primary production, with the most pronounced changes expected under higher emission scenarios. The effects vary by region, with northern parts of the Barents Sea benefiting from increased light exposure due to ice reduction, while southern areas are more influenced by wind-induced mixing and nutrient availability. Further, as ice coverage diminishes, a shift from ice-algal to open-water phytoplankton production is expected.

Ice-restricted primary production has until recently led to low food availability for zooplankton. Ongoing and future decreases in ice coverage will significantly expand and prolong secondary production, especially under the SSP8.5 scenario. Also, the fundamental transition from ice-algae to open-water plankton blooms will affect zooplankton community composition and size distribution. These changes in zooplankton communities are expected to continue and intensify with ongoing climate warming.

Benthic animals in the BS adapted to warmer temperatures may expand their range northward, while cold-adapted species may struggle as they cannot easily relocate. Many benthic animals are sessile and cannot move away from warmer waters, relying on gradual larval dispersal. Active movers like the red king crab and snow crab are expanding their range. While the expansion is not directly linked to climate change, rising temperatures may facilitate further spread northward and offshore. Northern prawns demonstrate a notably positive response to warming scenarios in model projections, especially the SSP5-8.5 high-emission scenario. Increasing sea temperatures and retreating ice will likely expand fisheries northward, putting additional pressure on previously unaffected benthic species.

Fish in the Barents Sea have historically been significantly affected by temperature variability. Higher temperatures and retreating sea ice, recently in 2004–2014, have expanded feeding areas for boreal species like Atlantic cod, while negatively impacting small Arctic fish species. The cod population has since decreased to “normal” levels, but this period may serve as an indicator of potential permanent changes under continued climate warming. Distinguishing between natural variability, climate change, and direct human pressures on harvested fish stocks is challenging. Future climate change will likely play a dominant role but impacts on fish stocks will vary. Recent modelling studies present contrasting projections for species like Atlantic cod and capelin, with some showing benefits from increased production and expanded distribution, while others suggest negative responses through the food chain.

Seabirds, which like mammals generally are at the top of the marine food web, are affected by climate change directly via extreme weather, but indirect effects through changes in food supply are likely more important. Changes in the timing of food availability, like the mismatch between ice melt and plankton blooms, can negatively impact Arctic seabird breeding. The islands around the Barents Sea host approximately 20 million seabirds during spring and summer, with 90% belonging to just five species. Recent population trends vary notably, with an important species like black-legged kittiwakes showing stability in Svalbard but declining in mainland Norway. Model projections suggest a general pattern of continued negative climate change impact on Arctic seabird populations throughout the Nordic- and Barents Seas.

Marine mammals in the Arctic including the northern BS are quite robust to direct climate change effects. However, reductions in sea ice are likely to negatively impact especially seals and walruses by directly reducing or removing their established breeding habitats and more indirectly by shifting the general location and timing of lower trophic level productivity. Also, several seal species already exhibit heightened vulnerability to rising temperatures. Model projections indicate increased negative responses to warming temperatures for various seal species, especially under higher emission scenarios. The effects of warming on whale species are more uncertain, but some, like bowheads, are expected to lose significant habitat under high emission scenarios.

The Barents Sea ecosystem is undergoing substantial transformations, leading to shifts in species distribution and community structure. While the differences in impact between emission scenarios are quite moderate towards 2050, they are pronounced toward the end of the century. Rising temperatures are, and will continue to, reduce ice cover, modify the mixed layer depth and alter nutrient mixing, impacting primary production and propagating through the food web. Marine heat waves are expected to become more frequent and intense, posing challenges for Arctic ecosystems. Further northward expansions of Atlantic communities, both pelagic and benthic, displacing Arctic species, are expected. Model projections and expert evaluations point towards mixed responses to future climate change, with some populations likely being negatively affected and others positively. However, changes will undoubtedly occur at the ecosystem level. A complicating factor is that for some central species (e.g., Atlantic cod) different models project contrasting developments also within the same climate scenario. Thus, there admittedly remains considerable uncertainty in projections for higher trophic levels.

The largest climate change related threats to marine ecosystems in the Nordic region – views from policy makers and managers

Policy makers and managers where asked to point out what they consider to be the largest climate change related threats to marine ecosystems in the Nordic region. These pressures could be physical or more related to biogeochemical alterations. The following were highlighted, although not all are relevant for all the Nordic sea areas: Rising sea temperatures, more frequent and intense marine heat waves (MHWs), retreating sea ice, sea level rise, changes in freshwater runoff, coastal browning, eutrophication, and oxygen depletion. Secondary consequences included increasing number of harmful algal blooms, and general loss of biodiversity.

Rising sea temperatures is a relevant issue for all our areas, brought up by "everyone". However, both mechanisms and consequences differ. It was also said that a gradual, slow, temperature rise may be less troublesome for marine life than more intense episodes, like MHWs. Negative ecosystem effects are generally considered most likely in areas that already are warm, but the most fundamental change will be in regions that today are (seasonally or more permanently) covered by ice. This naturally covers the very northern parts of the Nordic sea areas, but as pointed out, also large parts of the Baltic. The average length of what is called ice winter is projected to shorten 6 days per decade in the Bothnian Bay during this century (based on moderate RCP4.5 scenarios). Sea level rise was mentioned, but by a physicist, not the biologically oriented managers. Still, some areas will suffer 30–40 cm rise until 2100 (also within RCP4.5) and this will affect near-coast life. Eutrophication and biogeochemical changes are of major concern, especially in the Baltic. Here land-based eutrophication and atmospheric climate change are sources, which in turn intensify changes in marine biogeochemistry including reducing oxygen levels.

The respondents were also charged to suggest means to further develop Nordic cooperation across national borders aiming to sustainably solve common environmental challenges. This as a follow-up to questions to a panel debate at the final conference of the Nordic Council of Ministers Vision Project *Marine Management and Climate* in Gothenburg, November 2024.

The importance of marine protected areas (MPAs) was highlighted by respondents. It was said that by including MPAs more actively into marine management, one would better provide for safeguarding of important ecological functions and resilient ecosystems. Main suggestions for expanding from today’s MPAs is i) to better take expected climate change impacts into consideration when designating MPAs, ii) to undertake more coordinated work towards establishing cross-border MPAs in shared Nordic waters, including iii) to develop common management plans for larger cross-border MPAs.

It is also important for successful Nordic cooperation to establish a platform where all necessary data is accessible to relevant countries, so well-balanced decisions between harvesting and conservation can be made. This will also be enhanced by closer collaboration between managers and scientists. With regards to restoration of damaged ecosystems some see it as a last resort, due to its cost compared to not deteriorating, others view it as a needed and positive means that should improve marine nature's resilience against climate change.

Abbreviations and explanations

AMAP	Arctic Monitoring and Assessment Programme, a Working Groups of the Arctic Council
AMO	Atlantic Multidecadal Oscillation
AR6	IPCC's Sixth Assessment Report
AW	Atlantic Water masses
BACC	Assessment of Climate Change for the Baltic Sea Basin
Benthic	Refers to anything associated with or occurring on the bottom or in the sediments there
Benthos	Benthic animals, plants, and microorganisms
Browning (coastal)	Darkening water, typically because of increase in dissolved organic matter
Cetacean	Whales, dolphins, and porpoises (subset of marine mammal)
Chlorophyll-*a*	The primary photosynthetic pigment found in plants, algae, and cyanobacteria
CMIP	Coupled Model Intercomparison Project https://wcrp-cmip.org/ Massive multi-model runs at the foundation of IPCC assessments. There are several generations, we refer to CMIP5 and the most recent finalised CMIP6. CMIP7 runs are ongoing but not produced.
Demersal	Refers to fish and other animals that live near the bottom (opposed to pelagic)
EIC	East Icelandic Current
Eutrophication	(Problematically) high nutrient levels
GSP	Gross secondary production. Measure for growth and reproduction of marine animals that feed on primary producers and other organic matter (typically zooplankton).
HAB	Harmful algal bloom

HELCOM	The Baltic Marine Environment Protection Commission
Hypoxia	Oxygen depletion. Low oxygen concentration. Anoxia is an extreme version.
IPCC	The United Nations' Intergovernmental Panel on Climate Change
Marine mammals	In this report restricted to cetaceans (whales, dolphins, and porpoises) and seals
MHW	Marine heat wave
MLD	Mixed Layer Depth
MPA	Marine protected area
NoBa Atlantis	The Nordic and Barents Seas Atlantis model (NoBa Atlantis)
Nordic Seas	Greenland, Iceland, and Norwegian Sea
Nordic Sea areas	All major seas in the Nordic region, the overall area covered in NorMECC and this report
NorESM	Norwegian Earth System Model, a coupled global earth system model
NorScen	Nordic climate Scenarios, related NCM funded project
NOSCCA	North Sea Region Climate Change Assessment
NORWECOM.E2E	NORWegian ECOlogical Model system end-to-end. A marine ecosystem model.
NPP	Net primary production. Biomass produced by plants and algae (primarily phytoplankton) through photosynthesis, minus the organic material consumed for their own respiration.
NPZD	Nutrient-Phytoplankton-Zooplankton-Detritus model. NORWECOM.E2E for instance.
Ocean acidification OA	Changes in chemical properties of the ocean due to increased levels of CO2 entering from the atmosphere. Decrease in pH.
Pelagic	Residing in free water masses (as opposed to demersal, benthic…)

ROMS	Regional Ocean Model System
SPG	Subpolar gyre
SPNA	Subpolar North Atlantic
SSP1-2.6	SSPs, Shared Socioeconomic Pathways, are scenarios of projected global changes up to 2100 adopted by IPCC. E. g., SSP1-2.6 is a low emission scenario labelled “Sustainability (Taking the Green Road)”. 2.6 refers to additional radiative input of 2.6 w/m^2 by 2100. Corresponds to average global temperature increase of 1.5–2.0 °C
SSP2-4.5	Intermediate IPCC scenario “Middle of the Road”. Temperature increase ca 2.7 °C
SSP3-7.0	High emission scenario "A Rocky Road" Temperature increase ca 3.0 °C
SSP5-8.5	Extremely high emission scenario “Fossil-fuelled Development” Temperature increase 4.3 °C or more

Introduction

In its Sixth Assessment Report (AR6), the United Nations' Intergovernmental Panel on Climate Change (IPCC) leave no doubt that marine ecosystems will be strongly affected by climate change. IPCC AR6 stresses that climate change is even greater and clearer than previously demonstrated, "recent changes in the climate are widespread, rapid, and intensifying, and unprecedented in thousands of years" (IPCC 2021), and that the effects on humans and nature will be very 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.

Globally, average sea temperature is 0.88 °C higher in 2011–2020 compared to 1850–1900 (IPCC 2021). In the North Atlantic the increase has been about the same. In addition to a relatively slow gradual trend, there are natural fluctuations on different time scales. Due to the uptake of excess heat caused by warming of the atmosphere, the world's oceans have steadily warmed since the 1970s. For 2023, the average sea surface temperature for the European oceans was the warmest on record and associated with extreme heatwaves in the northeastern Atlantic Ocean (ESOTC 2023). Besides warming, the increase in carbon dioxide emissions has led to ocean acidification. Increasing the concentration of CO_2 in the atmosphere affects the acidity of seawater, which generally reduces the pH and saturation state of carbonate minerals (aragonite and calcite). This development is clear and will continue over the 21st century (IPCC 2019). Also reduced oxygen levels are anticipated in many regions. In addition, climate-change induced alterations in weather patterns, including more intense rainfall, may enhance runoff increasing coastal eutrophication and browning.

So far, the world's oceans have absorbed about a third of the human CO_2 emissions to the atmosphere. From now on they will be increasingly affected by both heat and CO_2 uptake. Climate scenarios are a tool used by IPCC to study and quantify how future developments are highly dependent on the extent to which we in the coming decades are able to reduce greenhouse gas emissions. These scenarios are a foundation for the future climate simulations run by global climate models (in IPCC context especially the Coupled Model Intercomparison Project, present generation is Phase 6, CMIP6). The degree of projected warming depends on future emission scenarios (Representative Concentration Pathways) and their narratives that describe different pathways of societal development, including factors like economic growth, population change, education, technology, and governance (Shared Socioeconomic Pathways). This integration considers both socioeconomic pathways and their associated emissions trajectories. For example, a sustainable socioeconomic pathway (SSP1) with a low-emission scenario (RCP2.6) reflects a world making strong efforts to reduce emissions. In contrast, a worst-case scenario (SSP5-8.5) merges a fossil-fuelled development pathway (SSP5) with a high-emission scenario (RCP8.5).

Warmer water alters organisms' metabolisms by increasing oxygen demand and causing mobile species to shift their distribution ranges. This leads to changes in food webs and ecosystem dynamics, as already observed in the Nordic Seas. Extreme temperature events, named marine heatwaves (MHWs), can severely affect species, especially during summer. Higher temperatures will in many regions cause environmental conditions that are new to species living in that specific area (Blenckner et al. 2021), pushing many marine species and ecosystems beyond their adaptive capacities, with potentially widespread consequences. Increasing sea temperature leads to ecological changes, through affecting, e.g., physiology, competition between species, access to food for early life stages and distribution and migration patterns.

Ocean acidification causes conditions that may be corrosive for calcium carbonate shell-producing organisms. Such changes in ocean chemistry are potentially a major challenge for several forms of marine life, making it hard to build and maintain their shells and skeletons. This especially affects corals, molluscs and calcifying algae, but also sea snails with "hard parts". In the North Atlantic Ocean, the potential impacts on cold-water corals are expected to be severe (Fransner et al., 2022). Generally, other parts of the ecosystems will likely be affected, although the degree is uncertain as scientists disagree about the sensitivity of species to acidification and their scope of adaptation to the new conditions (Meredith et al. 2019, Ottersen et al. 2023).

In this report, we present an up-to-date overview of knowledge on the expected future of a wide range of species and ecosystems in the seas around the Nordic countries under climate change. The weight is on impacts of warming and, mainly in the Baltic, also lack of oxygen. Acidification is introduced, but not covered thoroughly as the degree of biological effects generally still is unclear and disputed. Phytoplankton may, e.g., have the capacity to compensate for ocean acidification under a range of temperatures and pH values (Hoppe et al., 2018, Meredith et al. 2019).

The report is based upon examination and assessment of research studies from reputable journals and organizations, which provide scientific backing for our evaluation of observed and projected climate change effects on marine ecosystems in the Nordic marine regions. The time horizon is to a large degree the same as for the IPCC scenarios, i.e., towards the end of this century. However, climate change is already at present an important driver, and some aspects were focused on the development over the coming two-three decades.

The seas of the Nordic region (map in Fig. 1) are characterized by expected rapid climate development and unique marine environments and ecosystems, which may be especially vulnerable to climate change. While the impacts of climate change on marine life most likely will be severe for all the Nordic sea areas, they are not at all expected to be the same. Consequently, we at the highest level structure the report by geographical area: the Baltic Sea, North Sea, Norwegian and Iceland seas, Seas around Greenland, and Barents Sea. Biodiversity and productivity in the Baltic Sea already face challenges from problematically high nutrient levels (eutrophication), occasional oxygen deprivation and salinity levels that are very low for marine species (such as cod and herring). The North Sea also has an extensive total burden from many other human impacts in addition to climate change. In the north, the Barents Sea and northern parts of the Greenland-Iceland-Norwegian Sea (also named the Nordic Seas), some of the largest changes on the planet are expected, associated with increased sea temperatures and reduced ice cover.

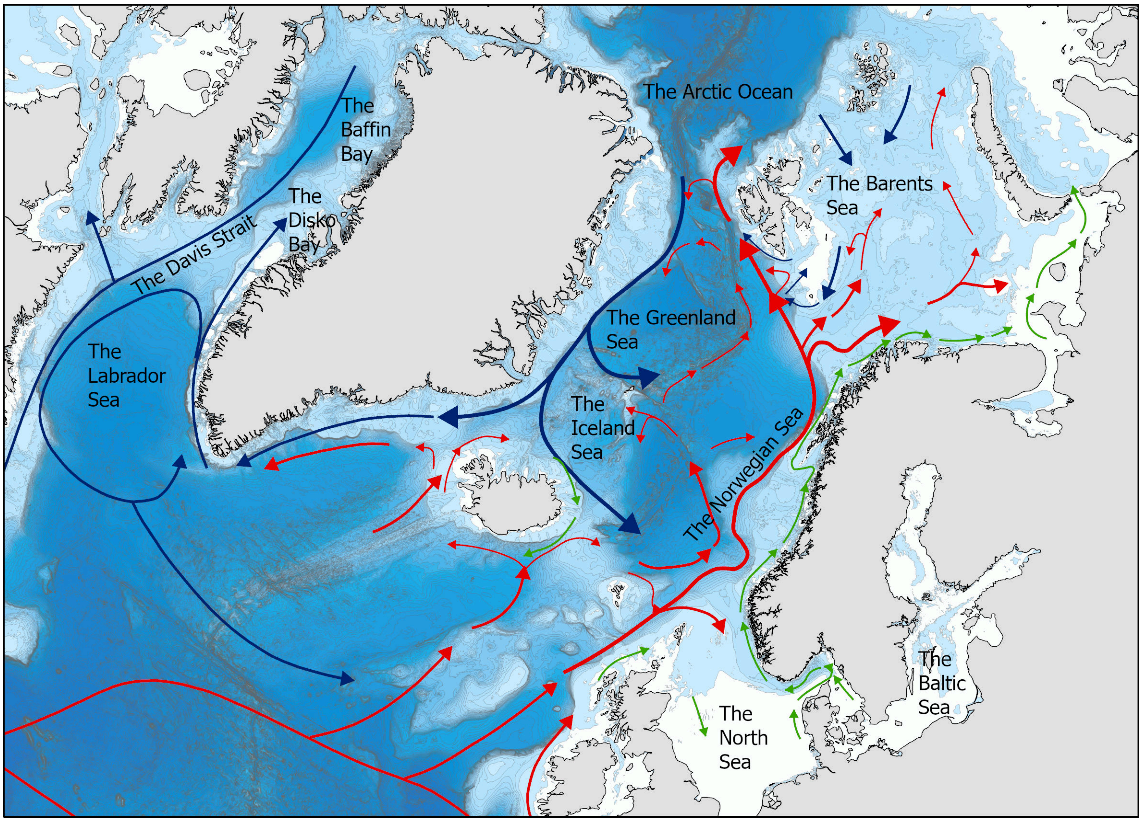

Figure 1. The main seas treated in this report with currents imposed: Atlantic currents with relatively warm and saline water (red arrows), Arctic currents with colder and less saline water (blue arrows), and fresher coastal currents (green arrows). Nuances of blue denotes bottom depth, the darker the deeper. Map by Per Arne Horneland, IMR.

Measurement series since the 1990s show an increasing degree of acidification, significant decrease in pH, almost everywhere in the North Sea and Norwegian Sea where we have sufficient data to investigate trends (Ottersen et al. 2023). It should be noted that since the solubility of CO_2 is higher in colder water, polar regions are more vulnerable to OA. The addition of fresh water from sea-ice melt and river runoff reduces the ocean's buffering capacity further accelerating OA in northern areas including parts of the Barents and Nordic Seas, especially on the freshwater-influenced shelf areas (e.g. Drinkwater et al. 2021). In the worst-case scenarios, the pH in the Nordic Seas will be markedly lower in the year 2100 than today.

Other climate-related effects that are important for organisms and marine ecosystems in (parts of) the Nordic region are sea level rises (coastal erosion and habitat loss), reductions in sea ice cover (affect ice-dependent species, such as polar bears and seals), changes in ocean circulation (changes in the distribution of small non-active swimming organisms and nutrients), and decreases in oxygen (affects species life and reproduction). Key characteristics and expected consequences of climate change of the different seas covered in our assessment are summarised in Table 1.

Table 1. Key characteristics and expected consequences of climate change of the different 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, intensify eutrophication, and lower the salinity and oxygen levels. Human use includes 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 its busy shipping lanes and historically rich fishing grounds. Consequently, marine life in the North Sea faces an extensive total burden from many other human impacts, including eutrophication, habitat damage and overfishing, in addition to climate change.

Norwegian and Iceland seas	The Nordic Seas are deep and open ocean. Despite of the northerly location, most of the area are ice-free year-round due to the warm Atlantic current. Large quantities of phyto- and zooplankton are produced here. This allows the free water masses of the Norwegian and Iceland seas to be the habitat of large fish stocks, in particular herring, mackerel and blue whiting. Their distribution is highly temperature dependent. Ocean acidification has advanced faster here than the global average.
Seas around Greenland	The seas around Greenland, including coastal waters, support diverse marine life, including seals, whales, and (primarily arctic) fish. During the past decades, the region has experienced rapid warming, with consequences for e.g. the ice cap melt rate, ocean temperature and ecosystem structure. Fish stocks are already affected by changes in the physics, primary and secondary production, affecting habitats, food availability, and predation pressure, and species are migrating north. Such changes are projected to continue over the coming century.
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 here, temperature increase resulting in a fundamental change from a seasonally ice-covered to a permanently open ocean system. Maritime transport and tourism is increasing, potentially causing further pressure on the ecosystem.

In addition to this review, we also provide a short overview based on input from a small, targeted group of Nordic managers and decision makers. They were asked to describe which climate change related pressures they consider to be the largest treats to our marine ecosystems, and also to suggest means to further develop Nordic cross-border cooperation to sustainably solve common environmental challenges. Marine Protected Areas (MPAs) independent of national boundaries were particularly highlighted by respondents. This latter section is a follow-up to questions to a panel debate at the final conference of the Nordic Council of Ministers Vision Project Marine Management and Climate in Gothenburg, November 2024.

Expected main climate change impacts on marine ecosystems in the Nordic sea regions

The Baltic Sea

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Unlike the other Nordic seas, the Baltic Sea is semi-enclosed and has only a narrow connection to the North Atlantic via the Danish Belts and Kattegat. This unique feature, and the large catchment area with many rivers entering the Baltic Sea, makes the water masses there less saline (i.e., brackish) than common for seawater, and results in strong environmental gradients both in temperature and salinity. Moreover, climate change effects on the Baltic Sea will vary between different parts of the sea. Sea level rise, for instance, has less effect on the northern parts of the Baltic Sea than the southern regions due to differential post-glacial uplift. The Baltic Sea ecosystem is impacted by multiple drivers, eutrophication and lack of oxygen being key environmental stressors (Fig. 2). In this chapter, when discussing the ecosystem effects of climate change, we adopt the common view (supported by ecosystem modelling), that climate change partially will counteract and undermine the positive effects of nutrient reduction measures. For more comprehensive information on climate change impacts on the Baltic Sea ecosystem we recommend in particular the in-depth reviews conducted within the Second Assessment of Climate Change for the Baltic Sea Basin (BACC; BACC II Author team 2015) and Baltic Earth Assessment Reports (BEAR; especially Viitasalu and Bonsdorff 2022).

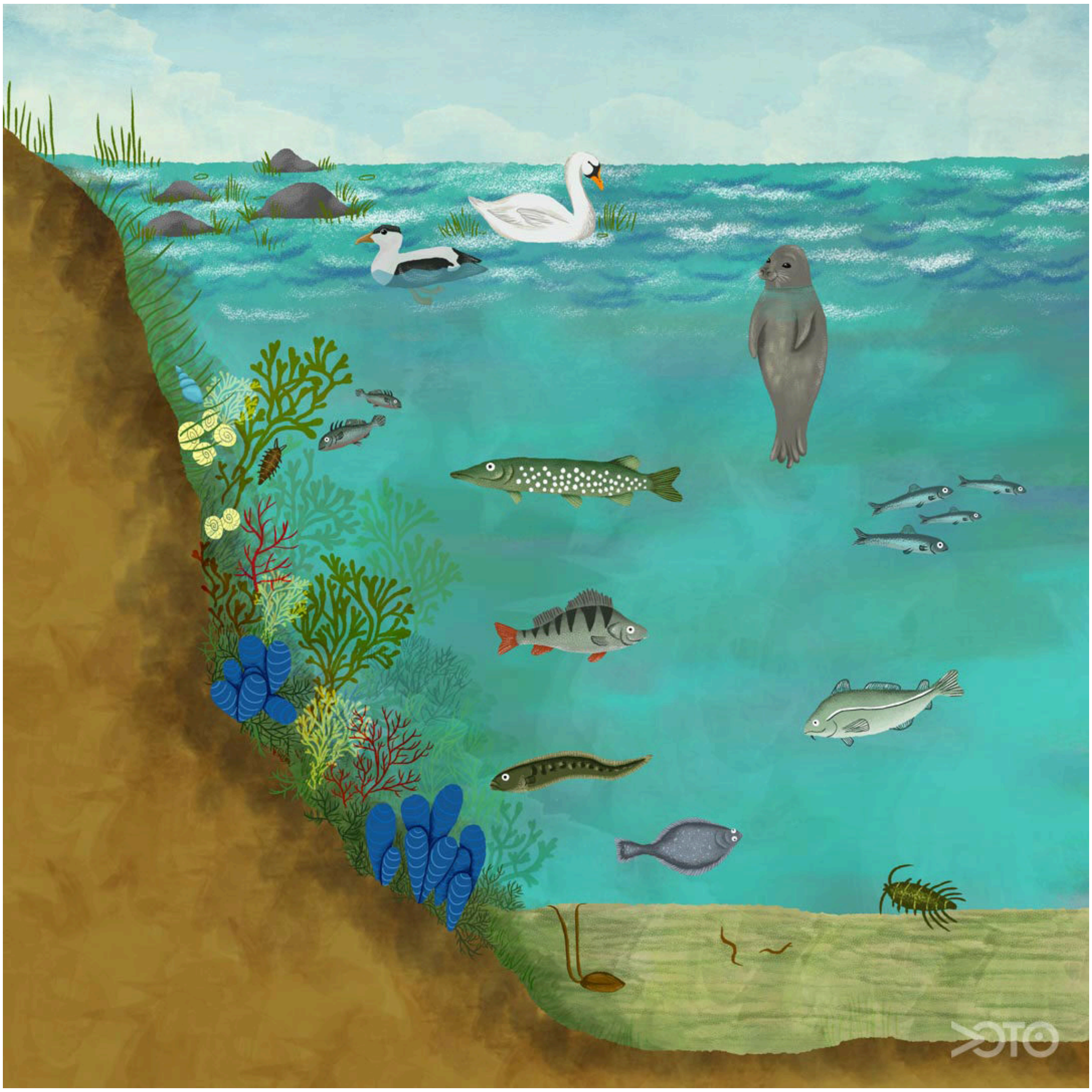

Figure 2. An artist's view of important parts of the Baltic Sea ecosystem(s). Although relatively species-poor compared to many other seas, the Baltic Sea is home to many species including a variety of algae, seagrass, crustaceans, molluscs, fish, seabirds, and mammals. Due to its brackish water environment and decreasing salinity levels towards the north both freshwater and marine species inhabit the Baltic Sea. Graphic from Voice of the Ocean foundation (https://voiceoftheocean.org/baltic-sea-biodiversity/)

Primary Production

For phytoplankton, clear symptoms of climate change, such as early spring blooms (Hjerne et al 2019, Jan et al 2024) and prolongation of the growing season, are evident over recent decades and can be explained by rising temperatures (Viitasalu and Bonsdorff 2022). However, climate effects vary from species to species and across the spatial gradient in the Baltic Sea. Future projections indicate a decrease of phytoplankton bloom in spring and an increase in cyanobacteria blooms in summer (Viitasalu and Bonsdorff 2022). These projections also depend largely on the interplay of climate change and the level of nutrient load from land. These climate and nutrient load scenarios also determine if the primary production stays high or decreases compared to today´s conditions. In the case of cyanobacteria, uncertainties remain because some field studies claim that cyanobacteria have not increased, and some experimental studies show that cyanobacteria's responses to temperature, salinity, and pH vary from species to species. An increase in riverine organic matter (browner water) may also decrease primary production in the Northern Baltic Sea, but the relative importance of this process in different areas is not well known. Bacteria growth is favoured by increasing temperature and organic matter, but complex effects in the microbial food web are probable.

Secondary Production

For zooplankton, the direct effects of changing climate include temperature and salinity impacts on metabolism and growth, as well as dietary effects of changes in primary production. The response of zooplankton is often species, and species group, specific. In the past, for example, larger zooplankton species (such as *Calanus*), that form an important food source for planktivorous fish and larvae of piscivorous fish, have been negatively impacted by decreases in salinity and increases in water temperature. Meanwhile, some smaller zooplankton species, present also in fresh waters, have benefitted from such environmental change. Hence, it is likely that the changing climate will result in changes in the zooplankton composition in the Baltic Sea. Serandour et al (2024) project that most of the species are likely to experience an increase in the area with suitable conditions in the northern part of the Baltic Sea under future scenarios, driven by increasing water temperature. Yet, this improvement may be countered by the projected decrease in salinity levels which would prevent the northern expansion of marine-originated zooplankton species. It has also for long been suggested that changes in the timing of phytoplankton blooms, due to earlier ice break-up, may result in changes in the temporal overlap between zooplankton and its food resources, and potentially even mismatches may occur. However, only little evidence is currently available on these dynamics.

Frequent jellyfish blooms with substantial biomass have been observed in the Baltic Sea, but no overall increase in jellyfish density across the region has yet been established. In the recent decade the species *Blackfordia virginica* has been established in the south-west area of the Baltic Sea (Jaspers et al., 2018). This species is regarded as an invasive species due to its successful establishment in various brackish regions of the Atlantic, Pacific, and Indian oceans and has therefore likely a high potential for a strong colonization in the Baltic Sea in the future.

Benthic plants and animals

The deep bottoms of the Southern and Central Baltic Sea, as well as the Gulf of Finland, suffer from a chronic lack of oxygen, which is a key driver in defining the presence and composition of benthic fauna (Fig. 3). When water temperatures increase, also the water-column's capacity to withhold oxygen decreases. Further, future climate projections for the Baltic Sea indicate increased water stratification, and hence potentially decreased ventilation of deeper waters, which can result in increased benthic and deep-water hypoxia (low oxygen concentration). This is particularly a risk in case no significant reductions in nutrient inflow to the sea are accomplished. As a result, even larger areas of the Baltic Sea may become void of benthic macrofauna in the future and species particularly sensitive to low oxygen concentrations (e.g. amphipods) may decrease in abundance, while more tolerant species take up more space.

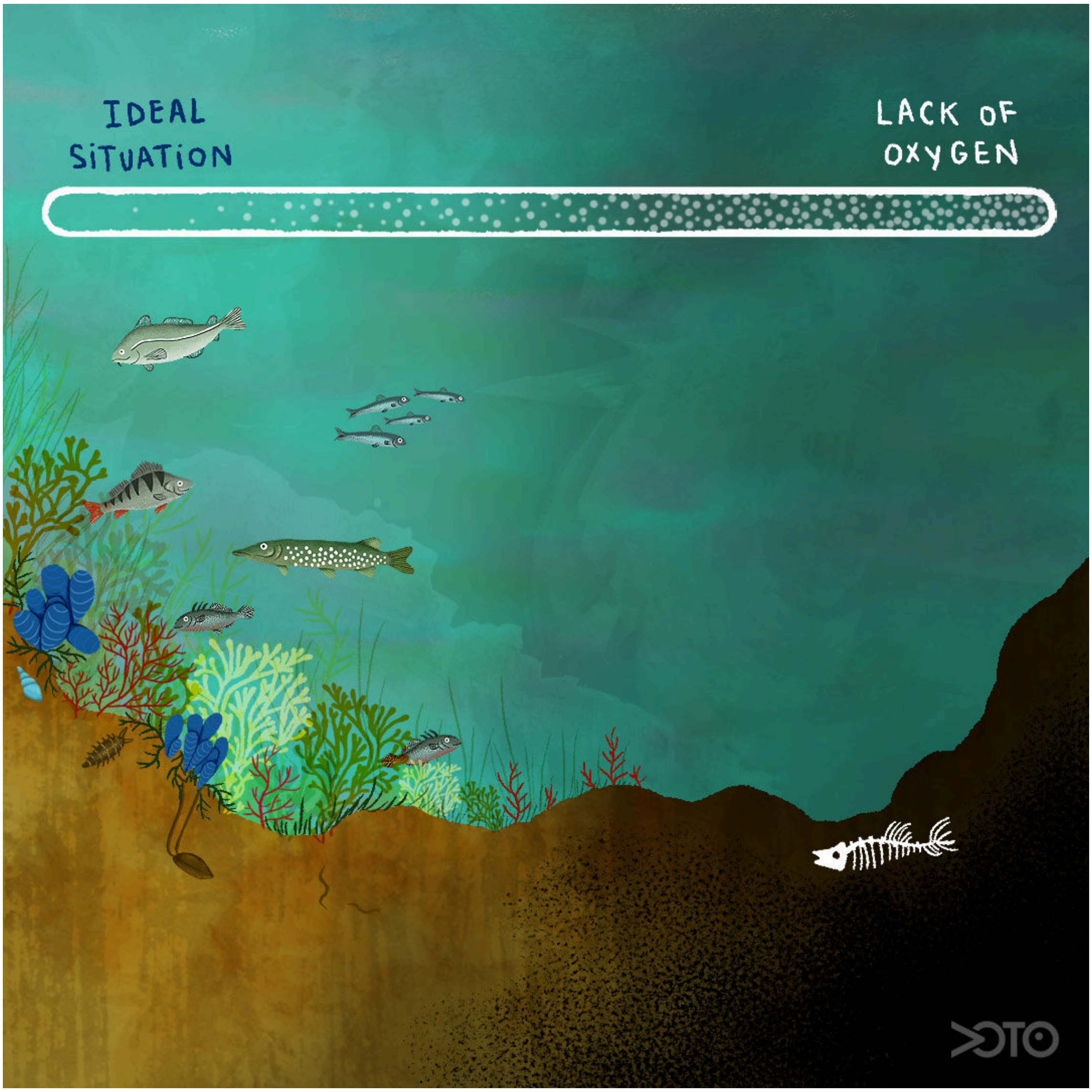

Figure 3. Eutrophication may lead to a lack of oxygen, hypoxia, especially at or near the seabed. The Baltic Sea is unfortunately naturally disposed to hypoxia mainly due to being an enclosed, shallow sea with only limited and sporadic water exchange with the North Sea. Hypoxic areas lose their function as a habitat, damaging the food web and ultimately Baltic Sea biodiversity. Illustration from Voice of the Ocean foundation (https://voiceoftheocean.org/baltic-sea-biodiversity/)

In a simulation study, Ehrnsten et al. (2020) extended an existing model of benthic macrofauna coupled with a physical–biogeochemical model of the Baltic Sea. This expanded model allowed them to examine how changes in nutrient levels and climate in combination affects the biomass and metabolism of seafloor animals, looking at both past patterns and future scenarios. In scenarios with decreasing nutrient loads according to the Baltic Sea Action Plan overall macrofaunal biomass was projected to decrease significantly by the end of the century despite improved oxygen conditions at the seafloor. In a very different scenario with nutrient loads similar to the highest historically recorded, climate change counteracted the effects of increased productivity. Biomass increased up to mid-21st century but then decreased, giving very little net change by the end of the 21st century compared to present. These results indicate that benthic responses to environmental change are nonlinear and partly decoupled from pelagic responses (Ehrnsten et al. 2020).

In more coastal and shallow parts of the Baltic Sea, the future trajectory of benthic fauna may differ from that of the deep-sea basins. Also here, hypoxia is a defining factor if present but also changes in primary production (food source), predation, ice-conditions and introduction of non-indigenous species affect benthic fauna. Hence, the response of shallow water benthos to changes in climate is likely very heterogeneous depending on local environmental conditions, as well as species composition. In the northern Baltic Sea, for example, salinity seems to be one of the key drivers defining benthic fauna composition, including the likelihood of non-native species invasions (Holopainen et al. 2016).

The same is largely true for the benthic plants, of which for example bladderwrack and eelgrass have key functional roles in the ecosystem providing both habitats for coastal organisms, as well as climate regulation via carbon capture. However, as the photic zone is shallow in most parts of the Baltic Sea, benthic plants are likely affected by changes in ice-conditions, temperature increase, as well as run-off from land affecting water transparency and thus light capture of these photosynthetic plants.

Still, in the Baltic Sea benthic plants and animals are generally expected to be more affected by eutrophication due to nutrient overload than direct effects of a warming climate.

Fish

Scientific evidence suggests that climate change (in combination with other anthropogenic drivers) will change the fish species composition in the Baltic Sea by the end of the century. The direct impacts of climate change on the Baltic Sea fish occur mostly through changes in water temperature, salinity, oxygen and pH levels. Fish species will respond to climate change impacts in diverse ways, based on a complex interplay between their physiology and habitat preferences. In general, climate change-driven changes in temperature, ice-cover, salinity, and river-discharge will affect especially coastal and migratory fish (fish from freshwater origin), whereas the pelagic and demersal fish (fish of marine origin) mainly respond to changes in water temperature, salinity, and oxygen conditions

(HELCOM/Baltic Earth, 2021). Moreover, species with complex life cycles, particularly those that move/migrate between freshwater and seawater, may be very sensitive to climate change effects (Moll et al. 2024).

The effects of climate change on the marine fish species of high commercial value (cod, sprat, herring) remain uncertain (Viitasalo and Bonsdorff, 2022, Andersson et al. 2023). Higher spring and summer temperatures could increase the success of sprat reproduction (Viitasalo and Bonsdorff 2022), but there is limited knowledge on the (combined) effects of increasing temperature and lower salinity on sprat (Andersson et al. 2023). Climate change will add pressure on herring and cod, in the Baltic already living on the borderline of their preferred conditions. Especially cod are heavily exploited, and research indicates that climate change can contribute to retaining the low cod abundance (Viitasalo and Bonsdorff, 2022, Andersson et al. 2023). If climate change leads to lower salinity and decrease in oxygen in the Baltic Sea, cod may suffer from lower reproductive success and decrease in food availability. Herring may be physiologically able to adapt to the new conditions, but the fishing pressure and ecosystem change could hinder the adaptation, especially if there are changes to the zooplankton that herring preys on (Andersson et al. 2023). Higher temperatures appear to provide a longer reproductive season for stickleback, yet the increase in temperature may reduce their reproductive success (Olin et al. 2022). Thus, the net direct effect of climate change is unclear also for stickleback.

Baltic Sea's invasive fish species (e.g. goby) have proven capable of adapting to different environmental conditions and are thus projected to benefit from the climate change (Moll et al. 2024). Rising seawater temperature may increase the abundance of some Atlantic fish species in the Baltic Sea, such as anchovy and tuna. However, this is highly uncertain as the Baltic Sea environmental conditions, especially salinity and oxygen levels, differ pronouncedly from what these fish are used to.

Seabirds

Climate change is altering the wintering patterns of sea birds in the Baltic Sea, with bottom feeders benefiting from reduced ice cover, while fish-feeders are less favoured (Marchowski et al 2017). Species-specific responses vary, with some species thriving and others declining. Breeding failures of common guillemots and their nest attendance can be partly linked to heat stress in the current extremely warm summers (Olin et al 2024). The observed northward distributional shifts might continue in the future (Pavon-Jordan et al 2019). Overall, future projections of how seabirds are affected by climate change are complex and can include reduction of habitats due to sea level rise, timing of migration, changes in prey availability and heat stress.

Additionally, the ongoing issue of contaminant exposure continues to impact the health and population abundance of Baltic sea birds, potentially interacting with climate change effects (Sonne et al 2020). Climate change is also causing earlier spring arrivals and breeding times for many bird species in the Baltic region. This earlier timing enhances breeding performance, leading to population growth for some species.

Marine mammals

There are four marine mammal species resident in the Baltic Sea: Baltic grey seal, ringed seal, harbour seal and harbour porpoise. Climate change is expected to affect these animals, both via direct physical changes that affect their habitats (e.g., changes in ice-cover and decrease in low lying haul-out areas due to increase in sea levels), and via ecosystem effects (i.e., changes in prey). Recent studies show that increasing sea-levels and decreasing salinities can result in loss of habitat for the grey seal and harbour seal, particularly in the Southern Baltic Sea (van Beest et al. 2022). The habitat suitability of the currently rarely observed harbour porpoise, on the other hand, is expected to increase. There is also some indication that increased sea water temperatures may increase the amount of parasites amongst marine mammals.

Holistic ecosystem considerations and summary of main effects of climate change

Overall, future climate projections indicate significant changes in the Baltic Sea's biogeochemical conditions, which will likely affect species distribution, growth, behaviour, and interactions. It is important to note the real risk of major changes, including both novel (never yet observed) and currently existing, but disappearing, conditions across different climate and nutrient management scenarios. Such environments will impact many plants and animals, including iconic species like cod, eelgrass, and starfish (Table 2). This underscores the importance of pre-emptive adaptive management to account for these emerging conditions resulting as compound effects of climate change and other human pressures (Blenckner et al 2021).

Table 2. Some anticipated major consequences of climate change on the Baltic Sea ecosystem(s).

Phytoplankton	Earlier spring phytoplankton bloom
	Longer summer phytoplankton growing season and longer summer blooms
	Potential increase in cyanobacteria blooms
Zooplankton	Change in species composition due to climate-induced temperature and salinity changes
	With further northern Baltic salinity decrease a change towards even more freshwater related species such as Cladocerans and Bosmina
	Various species-specific responses
Benthic plants and animals	Negative impact on benthos of increasing area with oxygen deficiency, oxygen-sensitive species most affected
	Besides climate multiple drivers affect especially coastal benthos
	Salinity-sensitive species especially affected in the northern Baltic due to changes in salinity (freshening related to ice-melt expected)
	Invasive species may put local species at risk
Fish	Species compositional change. Especially related to increasing temperatures and decreasing salinity and oxygen levels
	Some species likely favoured by temperature increase (e.g., stickleback, sprat and (the to the Baltic invasive) round gobi
	Cod likely negatively affected, less clear climate-induced effects on herring
Marine mammals	Ringed seal reduction due to decrease of sea ice cover
	Habour and grey seal populations may decline if salinity decreases strongly
	Harbour porpoise may be positively affected by increasing temperature

Seabirds	Species-specific changes in composition and migration patterns
	Some species may breed earlier, but depends on available resources during
Socioeconomic consequences	If extreme storm events increase, this will complicate maritime traffic, aquaculture, fisheries, and coastal protection against erosion.
	Fisheries will be affected by changes in fish abundance and distribution
	In aquaculture, increase in water temperature and potential decrease in salinity may decrease fish wellbeing and yield, and limit species selection for fish farming.
	Industries and coastal communities may have to prepare for greater variability in environmental conditions (MHWs, sea ice)

It is important to note the uncertainties in future projections of climate change impacts on the physical and biogeochemical environment of the Baltic Sea, particularly regarding salinity, storminess, and sea level rise (Meier et al 2022). These uncertainties arise from various factors. First, salinity changes are uncertain due to the complex interplay between wind patterns, freshwater inflows from rivers, and sea level rise across the entire Baltic Sea gradient. Although some models predict a slight decrease in salinity, the results are not statistically robust across different scenarios. Similarly, projections for sea level rise vary, especially because they depend on global climate models and assumptions about ice melt rates, with considerable variation in potential outcomes. These combined uncertainties create challenges in projecting future environmental conditions for the Baltic Sea's ecosystem.

Climate change is expected to have significant socioeconomic impacts on the Baltic Sea region, affecting both industries and communities that rely on its resources. Fisheries, a key economic sector, will face challenges due to changes in fish species composition and the continued low abundance of cod if the salinity decreases and temperature increases (Viitasalo and Bonsdorff 2022). Culturally important winter fishing activities in the northern Baltic Sea will likely suffer from sea ice loss. In aquaculture, changes in water temperature and salinity could necessitate a shift toward more heat-tolerant species. Warmer waters can lead to more frequent algal blooms, reducing water quality and harming fish health. Such conditions could increase the risk of disease outbreaks and lower aquaculture yields (Krämer et al. 2013).

Since high concentrations of human settlements and transport infrastructure are located along the Baltic Sea's coast, climate change may raise the direct costs of coastal protection and have indirect effects on sectors like tourism. Sea level rise and its consequences (for example, flooding, erosion, ecosystem changes, and the intrusion of saline water into coastal groundwater aquifers) will vary across the region and will be most noticeable in the southern and southeastern parts of the Baltic Sea. Already now, many eroding coastlines in the region are artificially stabilized. If storms become more frequent and/or intense, coastal protection efforts must account for accelerated coastal erosion (Krämer et al. 2013). Strong impacts on offshore wind farms are not expected (HELCOM/Baltic Earth 2021).

The North Sea

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The North Sea (NS) is a shallow semi-enclosed northeastern marginal sea of the Atlantic Ocean. The sea experiences strong tidal movements and storms, particularly during winter months, and its waters support diverse marine ecosystems, including various species of fish, sea birds, whales and seals (Fig. 4). The North Sea has significant oil and gas reserves, busy shipping lanes and historically rich fishing grounds. Consequently, marine life in the NS faces an extensive total burden from many other human impacts, including eutrophication, habitat damage and overfishing, in addition to climate change.

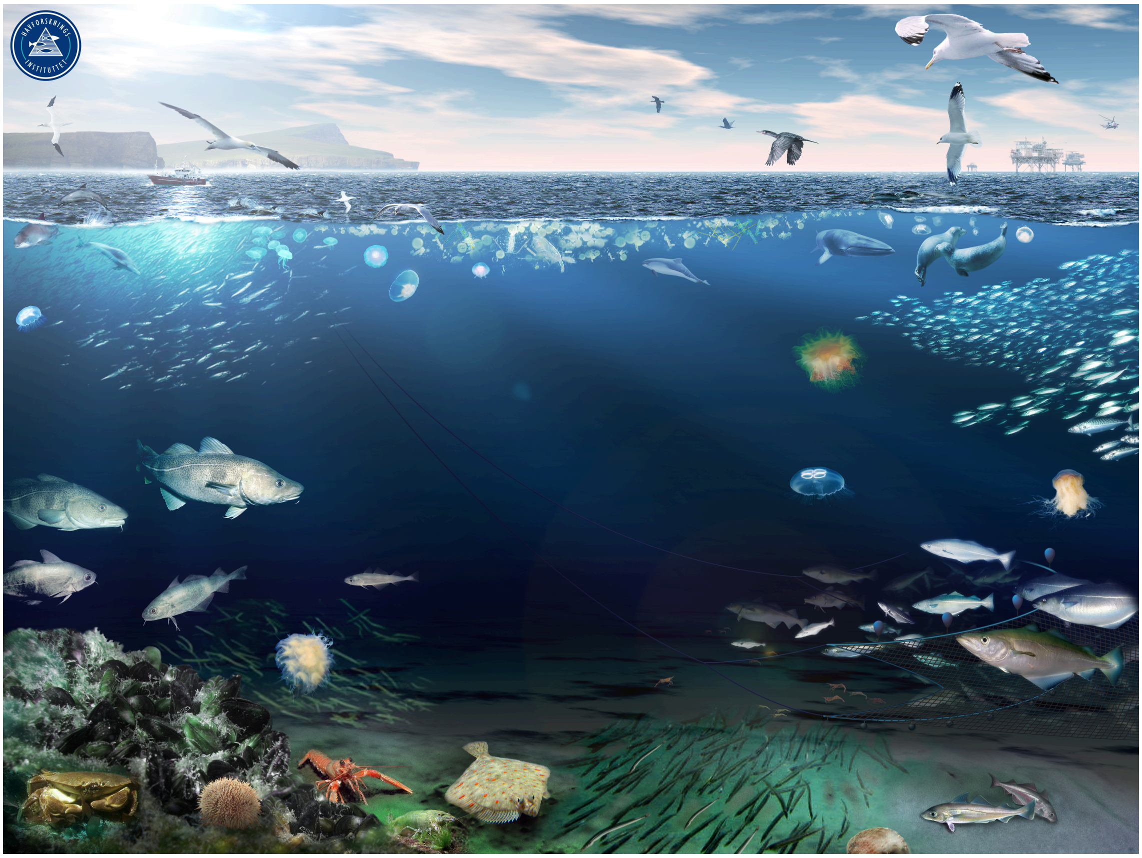

Figure 4. An artist's view of the North Sea ecosystem. Credit: Institute of Marine Research.

Primary production

Projections of future climate show that North Sea primary production will decline (Laufkötter et al. 2015, Sandø et al. 2022, Ottersen et al. 2025). By end of century, overall community production is projected to decrease by up to 30% (Carozza et al. 2019, Kwiatkowski et al. 2019). If this is a good or bad thing is not obvious, there will be both benefits and downsides for the marine ecosystem. The main negative consequence is that this may significantly reduce the NS' capacity to generate the fundamental food resources that sustain marine life. This aspect is somewhat elaborated on under Holistic, below.

On the other hand, reduced primary production could help mitigate the problems with eutrophication (excessive enrichment with particularly nitrogen and phosphorus) that currently prevail in parts of the NS (as in the Baltic). This could enhance water quality, including increasing oxygen levels and improve conditions for animals and plants, especially benthic organisms. Lower primary production would also likely decrease the occurrence and severity of harmful algal blooms.

In any case, the development of primary production and phytoplankton concentration depends on the changes in underlying biogeochemical processes and even uncertain knowledge of future development under climate change is of high importance. A thorough study on projected future hydrography and biogeochemistry in the NS (and the Baltic Sea) was recently conducted by SMHI within the NorScen project (Ottersen et al. 2025). They downscaled global earth system model climate projections to the North Sea and Baltic Sea with the ocean model NEMO-SCOBI (Ruvalcaba-Baroni et al. 2024). Downscaling was done for the historical period 1951–2014 and for 2015–2100 under the two scenarios SSP1-2.6 and SSP3-7.0. An important aspect is that in this study future nutrient loads from rivers were estimated and included (Ottersen et al. 2025). Projected values of temperature, salinity, and Dissolved Inorganic Nitrogen (DIN) and Phosphorus (DIP) concentration are presented there. Chlorophyll-*a* is (together with nutrients and temperature) a useful (although not perfect) indicator of primary production. The projected differences in surface chlorophyll-*a* concentration between the average historical conditions and for the period 2070–2099 within the two scenarios are shown in Fig. 5, while Fig. 6 shows the temporal development. Note the geographical differences. While the chlorophyll-*a* concentration tends to increase in the western parts of the NS, it declines in the eastern part, the Skagerrak and especially the Kattegat (Figs. 5 and 6). The results in Ottersen et al. (2025) confirm the importance of riverine nutrient loads for the NS (and Baltic Sea) biogeochemical variables dynamics and plankton production.

Two climate scenarios project different impacts. Under SSP1-2.6, conditions generally improve (from a reducing eutrophication point of view): diminished river nutrient loads lead to decreased primary production and better bottom oxygen conditions across most areas. Within SSP3-7.0 projected river runoff and primary production is higher. Still, also this scenario indicates some improvement to current conditions for primary production and eutrophication challenges. Thus, at least within the scenarios applied, the effects of a changing climate are smaller than effects of considered nutrient load changes, and water quality conditions in the North Sea are expected to improve (Ottersen et al. 2025).

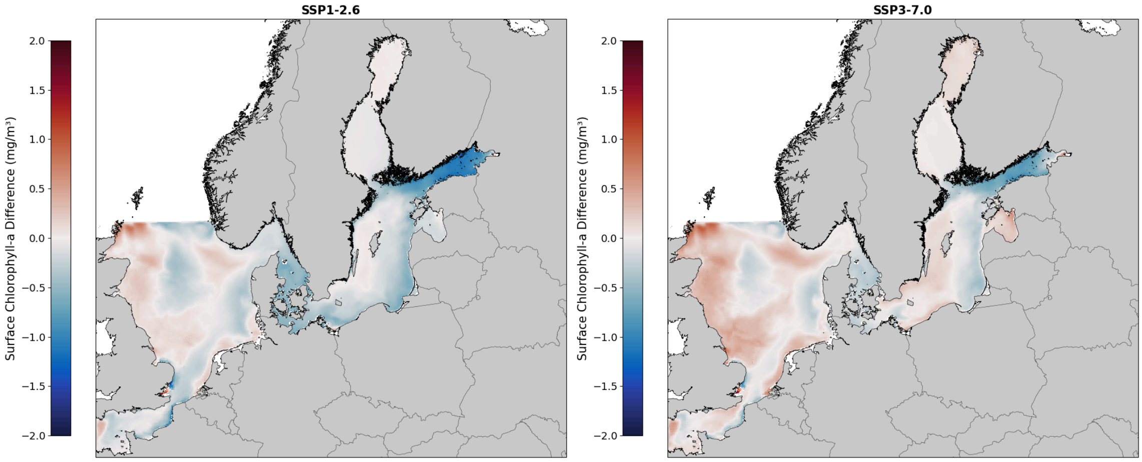

Figure 5. Surface chlorophyll-a concentration: differences between average current conditions (1985–2014) and future scenarios (2070–2099) SSP1-2.6 (left) and SSP3-7.0 (right). From Ottersen et al. 2025.

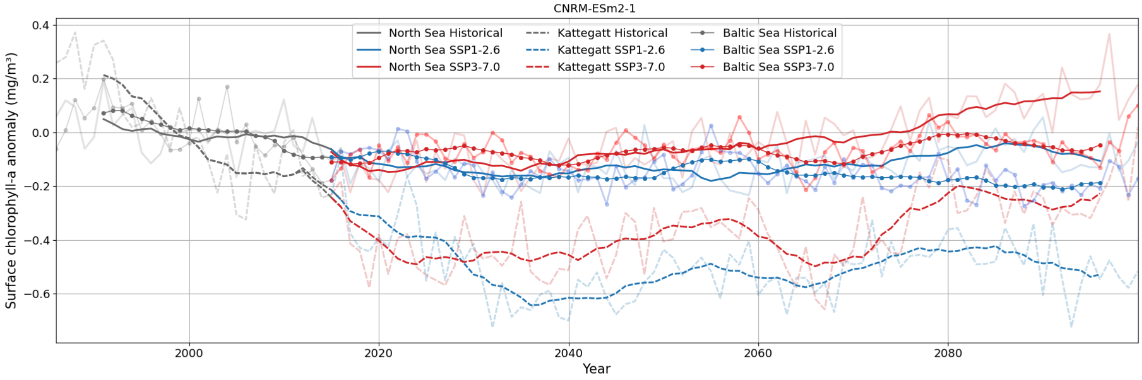

Figure 6. Surface chlorophyll-a concentration changes: Regionally averaged time series of the differences relative to the historical period 1985–2014 for the scenarios SSP1-2.6 (blue) and SSP3-7.0 (red) in the three regions North Sea (solid), Kattegat (dashed) and Baltic Sea (dotted). Transparent lines represent the annual mean, whereas the bold lines show a 10-year running mean. From Ottersen et al. (2025).

Secondary production

Climate change affects both biomass and species composition of zooplankton communities in the North seas. The size of zooplankton in the NS has generally decreased over time. A general decrease in the mean size of zooplankton has been observed, so has a shift towards smaller species. These changes are linked to environmental change, including temperature increases and decreases in nutrient and phytoplankton availability (Marques et al. 2024).

Climate-driven changes that took place in the 1980s have been described as a regime shift, affecting both temporal and spatial synchrony of plankton dynamics (Defriez et al. 2016). With the projected substantial climate change, the plankton community will likely be further affected. A thorough review was done by Brander et al. (2016), but that is now some years ago and no explicit projections were made in that assessment. The best described development so far is that with warmer waters the copepod species *C finmarchicus* is being outcompeted by the similar, but more heat-loving relative *C helgolandicus*, which has expanded its distribution from the south (Beaugrand et al. 2002).

Looking ahead, projections by Villarino et al. (2015) for the North Atlantic, including the western North Sea, found a northward shift in the gravity centre of *C. helgolandicus* of 17.8 km per decade from the present period (2001–2020) to the future (2080–2099), and correspondingly for *C. finmarchicus* 3.7 km per decade. They also projected changes in phenology for *C. finmarchicus,* an advance in the annual peaks of 12–13 d between present time and the end of the 21st century.

The thorough projection study by Sandø et al. (2024) also investigated the accumulated directional effect on *C. finmarchicus* in the North Sea. They took into consideration a range of different pressures and assessed the cumulative impact under the climate projections SSP1-2.6, SSP2-4.5 and SSP5-8.5. They found that, mainly due to negative effects of decreasing net primary production and rising temperatures, *C. finmarchicus* will decrease further in the NS. This is projected to be the case for all scenarios, but especially with strong warming (SSP5-8.5). *C. finmarchicus* (in addition to cod) is the species most negatively affected by such conditions *(*Sandø et al. 2024).

Benthic plants and animals

Climate change is significantly impacting bottom-dwelling species in the NS. The distribution and composition of these organisms is primarily governed by key environmental factors including sediment composition, depth, food availability, and water temperature. Additionally, currents play an important role since most benthic species have larvae that are transported by water masses.

As temperatures have increased in recent decades, many benthic invertebrate species have expanded their northern range boundaries in the NS, while deteriorating in the south. The effects of climate change on these organisms in the NS appear to stem from three main factors: changes in temperature, nutrients, and hydrodynamics, which significantly impact their food supply and reproduction patterns. Projections through 2099 under a medium climate scenario suggest continued northward movement of benthic species, but more than 60% of 75 studied species are expected to experience habitat loss. The benthic species of the southern NS, where the strongest temperature increase is projected, are particularly at risk. Here the distributional changes are expected to affect the functioning of the ecosystem, since key species showed northward shifts and there are high rates of habitat loss (Weinert et al. 2016). This highlights the significant challenges these organisms and communities face in adapting to changing environmental conditions.

In a related study Weinert et al. (2022) simulated spatial changes in southern North Sea species intensity of bioturbation (alterations of soils and sediments by organisms through burrowing, shifting particles and more) for the years 2050 and 2099 based on one species distribution model per species driven by bottom temperature and salinity changes. They found that while the total bioturbation remained relatively constant in the southern NS, the bioturbation potential for four out of seven species was projected to increase, mainly due to their concurrent northward range expansion (Weinert et al. 2022). This shows that climate change may alter the environment by acting through animals, not just the other way round.

A drift simulation model study found that warmer climate has enhanced opportunities for Pacific oyster larvae to successfully develop and drift from Danish and Swedish spawning areas and survive at landing sites along the Norwegian Skagerrak coast (Rinde et al. 2016). The observed 1.6 °C increase in sea surface temperature from 1990–2014 created suitable conditions for larval development and survival along the Norwegian Skagerrak coast since 2000. Since the study was conducted the number of Pacific oysters along the southern coast of Norway has exploded and future warming will likely increase this development further, although successful local population establishment may also be challenged by competition, predation and diseases (Rinde et al. 2016).

Fish

Several climate change related pressures are already affecting fish populations in the NS or are projected or at least expected to cause alterations in the future. As most other places, the North Sea is experiencing increasing sea temperatures. This affects fish both directly through physiology and indirectly, through distribution of prey, predators, and competitors. We summarise key challenges and responses in Table 3.

Table 3. Climate change related pressures on North Sea fish and expected responses.

Climate change related challenges	Response pattern
Reproduction	Warmer waters can impact the reproductive success. Higher temperatures will affect the development of eggs and larvae. This will potentially affect early life stage survival rates and recruitment of young into the population. For species preferring relatively cold water, like cod or herring, the impacts are expected to be negative.
Prey availability	Abundance and availability of prey species will be affected and affect fish. Changes will occur in fish prey organisms such as zooplankton, crustaceans, molluscs, and smaller fish. This is expected to impact the fish food supply, affecting their growth and survival. Increased temperature will be the main pressure, but potentially also oxygen reduction and acidification.
Migration Patterns	Many fish have developed specific migration patterns, typically related to season and spawning. Changing environmental conditions could affect fishes' seasonal movements and spawning locations, potentially leading to mismatches between the timing of spawning and optimal environmental conditions for larval survival
Increased Competition and Predation	As species distributions shift, established North Sea fish populations are expected to face increased competition for resources and predation from (more southerly) species entering the North Sea.
Sea level rise	Rising sea levels can lead to coastal erosion and habitat loss for species that depend on coastal and intertidal zones
Increased storm frequency and intensity	More frequent and intense storms can affect fish negatively both through direct damage and indirectly. Species with near-surface eggs and larvae may meet increased early life stage mortality by offspring being killed by waves. Also, increased storminess will damage habitats such as seagrass beds, which are important nursery grounds for many young fish.

NS fish are well studied, and their response in distribution to climate has been documented for at least 20 years. A much-cited article in the journal *Science* (Perry et al. 2005) was among the first to provide a solid analysis documenting that NS fish distributions had shifted in response to climate change. They found that nearly two-thirds of the species had changed mean latitude or depth, primarily northwards and/or into deeper water. Later studies confirmed a long-term distribution shift for NS sole and place (Engelhard et al 2011) and for cod to the northern and northeastern parts of the NS. While the former was attributed mainly to climate change, also differences in fishing pressure was important for the cod (Engelhard et al. 2014). It should be noted generally that detected distribution shifts may suggest that individual fish have moved, but just as often that recruitment or mortality rates have changed and differ between areas. There may also be genetically distinct population units with different life histories, for instance temperature preference, within the same management unit (stock). For instance, Heath et al (2014) found that two subpopulations of Atlantic cod cohabit the NS. These factors add to the complexity met when projecting population development under climate change.

Cold-temperate fish species in the NS, including cod, saithe, haddock, and Norway pout, are already living at their thermal tolerance limits. These gadoid populations face a troublesome future, with projections by Kjesbu et al. (2022) pointing to continued declines through 2050 under the moderate climate change scenario RCP5.5. The situation is strengthened by the NS' current system, which with warming effectively creates an ecological trap. This circulation pattern (Sundby et al. 2017) carries young fish from northern spawning grounds into increasingly warm southern waters during summer and autumn, resulting in high mortality rates and poor recruitment (Kjesbu et al. 2023).

Sandø et al. (2024) confirmed the negative outlook for NS cod. They also examined accumulated directional effects on a range of species as a function of climate exposure and sensitivity attributes but expanded to include the three scenarios SSP1-2.6, SSP2-4.5. and SSP5-8.5. Based mainly upon trends in mean bottom temperature and abundance of the *C. finmarchicus*, important food for early life stages of NS cod, they expect a strong further decline under SSP2-4.5 and SSP5-8.5 (Sandø et al. 2024).

While cod and other species suffer from a warming NS, some will benefit. The European hake is a warm-temperate codfish species that already have established themselves in the NS and are expected to respond positively to further warming. This, and similar, changes will likely have significant impacts on the ecosystems. Hake is a voracious predator with a much larger trophic impact than cod. It is therefore likely that expanding hake populations will have a larger top-down trophic effect on the food web and potentially the biodiversity of the North Sea ecosystem (Cormon et al. 2016, European Marine Board 2024).

Seabirds

Climate change is expected to significantly impact seabirds in the NS, primarily through alterations in breeding success, food availability, and habitat conditions. For example, Searle et al (2022) show that climate-driven changes negatively affect the breeding success of five seabird species (Atlantic puffin, common guillemot, black-legged kittiwake, great black-backed gull, and razorbill) with four of these species projected to experience large declines in the future. Changes in climate variables can lead to reduced availability of key prey species, heat stress in chicks, and other negative effects on breeding success. For example, the Atlantic puffin is negatively affected by rising sea surface temperatures, while the black-legged kittiwake shows strong negative effects of temperature on land on breeding success. These climate-driven changes are expected to have detrimental effects on the breeding success of these species in the future. Only one species (northern gannet) is expected to see an increase in breeding success under future climate conditions due to a broader diet (feeding for example on sandeels, mackerel, herring, and other small fish species; Searle et al 2022). Additionally, breeding success is strongly correlated with the availability of key prey species, such as *C. finmarchicus*, which is declining especially in southern areas of the NS due to climate change (Frederiksen et al 2013).

Seabirds are experiencing indirect impacts from climate change through distribution shifts and abundance in prey availability, for example for *C. finmarchicus* and fish (sandeels) species. These changes are reducing the breeding success and growth rates of several seabird species. These changes in lower trophic levels disrupt the energy pathways to seabirds, affecting the seabirds' survival and reproduction (see for example Church et al 2018).

Climate change is also likely to directly affect the habitat for seabird populations, for example through sea level rise and increased storminess. Rising sea levels may reduce the amount of breeding habitat available for shoreline nesting species such as terns. Strong storms can cause large-scale mortality of seabirds both in winter and summer, in particular for cliff breeding birds (Mitchell et al 2020). Due to altering conditions seabird species might also change their distribution, but their capacity to maintain population sizes depends on their ability to adapt to fast changing climate conditions (Burthe et al 2014).

Marine mammals

With "marine mammals" we here cover cetaceans and coastal seals, the former includes dolphins, porpoises, baleen- and toothed whales. The thorough NOSCCA assessment (Quante and Colijn 2016) classifies the main threats from climate change on marine mammals as direct and indirect. All organisms have tolerance limits, and exceeding these can negatively directly impact metabolism, growth, reproduction, or cause death. "Warm-blooded" animals like marine mammals must maintain a (more or less) constant body temperature, requiring extra energy when ambient temperatures change. Extreme weather or temperature changes can harm these species, leading to population decreases due to thermal stress. In addition to the direct physiological temperature effect, climate change is also expected to affect marine mammals indirectly by, e.g., altering prey availability or critical habitats like nesting beaches for seals (Howard et al. 2013; NOSCCA). Compared to some other animals, most seal and cetacean species are believed to have varied diets and are capable of switching from one prey to another in response to their availability. Further, at much lower latitudes than the NS there have been mass mortality events of both dolphins and baleen whales related to harmful algal blooms, which again may be linked to climate change (Evans and Waggitt 2020).

Fortunately, the marine mammal community in the NS is dominated by cetaceans and seals with a broad temperature tolerance. This should make them generally less vulnerable to climate change than marine mammals in, for instance, the Baltic Sea. This is supported by few observed effects of climate change on seals and cetaceans in the NS region. There has, however, been apparent range shifts, with some increase in observations of more southerly warm-water cetacean species and cold-water species becoming less common. Still, both seal and cetacean species may be prone to negative indirect effects potentially related to climate change driven temperature increase (Evans and Waggitt 2020). Also, in the future, seals that breed or haul-out in low lying coastal areas will likely be vulnerable to sea level rise and increased storm surges. For the NS region, this is an issue especially for seals in the south (Evans and Bjørge 2013, Evans and Waggit 2020). In their thorough evaluation of climate change effects on marine mammals, Evans and Bjørge (2013), admitting that their projections were on the border of speculation, point to some species that are expected to suffer from climate change and others that may benefit (Fig. 7). A species that may be negatively affected is the harbour porpoise, the clearly most abundant marine mammal in the NS, with an estimated population of somewhat below 100,000 individuals (Evans and Bjørge 2013).

Figure 7. Potential winners (left) and losers (right). Top left: short-beaked common dolphin [Credit: P. Anderwald]; top right: white-beaked dolphin [Credit: K. Hepworth]; bottom left: Atlantic grey seal [Credit: P. Anderwald]; and bottom right: harbour seal [Credit: P.G.H. Evans]. From Evans and Bjørke (2013).

MCCIP, the UK Marine Climate Change Impacts Partnership, identified the following list of key challenges and emerging issues related to marine mammals. Although these are for UK waters, they should be highly relevant for the NS more generally:

- Establish long term monitoring of distribution and abundance change for cetacean species to assess impacts of climate change
- Distinguish climate effects from other drivers in recent observed changes in seal populations
- Quantify the synergistic effects of climate change and other human stressors on cetacean range shifts
- Understand how direct impacts on lower trophic levels affect top predators through improved links to upper trophic levels in ecosystem models

Holistic ecosystem effects

As described under Primary Production above, production at this lowest trophic level is projected to decrease in the NS with climate change. This is worrying, as primary production forms the foundation of the marine food web. Less primary production consequently means less food availability for zooplankton, which in turn affects fish populations and other marine organisms that depend on them. This could potentially impact both overall production and marine biodiversity. The reduction in primary production may particularly affect species that have evolved to thrive in the current productivity levels of the NS.

A recent thorough synthesis of climate change impacts on the Wadden Sea shows how complex ecosystem effects may be in this south-eastern part of the NS and more generally (Buschbaum et al. 2024). Climate change will act through different pressures and influence different parts of the food web. The more direct effects acting on one part of the ecosystem can propagate, causing overall consequences that are very hard to predict (Fig. 8).

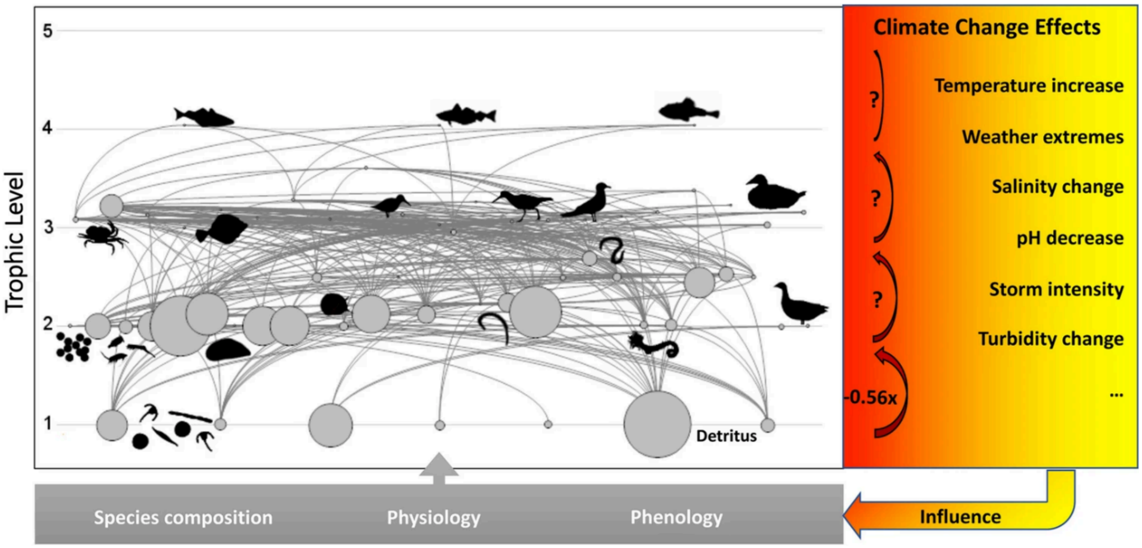

Figure 8. Schematic representation of climate change impact on the different trophic levels. Different climate change effects alter the species composition, physiology and phenology of organisms with unknown implication for the entire food web. Effects can potentially cascade from one trophic level to the preceding one. The illustration, from Buschbaum et al. (2024) is for the Wadden Sea food web, but the principle is general.

The most important physical changes considered in that assessment are increasing sea temperatures and sea level rise. Rising sea levels threaten to transform coastal ecosystems, potentially converting tidal zones into lagoon-like environments as critical thresholds are exceeded. This transformation endangers vital habitats including mudflats, salt marshes, and seagrass meadows through coastal erosion and altered sediment patterns. Meanwhile, ocean warming is restructuring marine communities at multiple levels: disrupting plankton cycles, shifting benthic species composition from cold- to warm-adapted organisms, and unravelling established predator-prey relationships. These changes are further complicated by the emerging threat of parasites and pathogens, whose potential for causing mass mortalities remains poorly understood despite their ecological significance (Buschbaum et al. 2024).

Another example of effects of climate variability and change cascading through the NS food web is the well-described case of zooplankton and gadoid fish. *C. finmarchicus* is an important link between the production of phytoplankton and several fish stocks (Aksnes and Blindheim, 1996). As we reported under Secondary production, rising temperatures have caused this copepod to be gradually replaced by its southern relative, *Calanus helgolandicus* (Beaugrand et al. 2002). While these species appear similar, this shift has significant ecological consequences. *C. helgolandicus* produces less nutritious larvae and spawns at different times than its northern counterpart, creating a temporal mismatch with the feeding needs of young cod larvae. This disruption of the established predator-prey relationship, known as the match-mismatch hypothesis (Cushing 1990, Durant et al. 2007), has contributed significantly to the decline of NS cod populations, alongside pressure from commercial fishing. The case illustrates how climate warming can impact marine ecosystems by disrupting the synchronization between species' life cycles. Also the more general trend mentioned towards smaller zooplankton individuals and species is problematic, as smaller zooplankton typically contain less energy, making them less nutritious for the fish, seabirds, and other animals that depend on them.

Seabirds are typically high in the food chain and depend upon production at lower trophic levels. Brander et al. (2016) summarised several studies demonstrating statistical connections between seabirds and plankton and fish prey. However, most often the actual pathways climate signals follow through the food web to impact seabird life-history traits remain elusive (Brander et al. 2016).

Norwegian and Iceland seas

Hjálmar Hátún, Faroe Marine Research Institute, Faroe Islands

These seas, together with the Greenland Sea covered below, comprise the Nordic Seas. These seas have cold, nutrient-rich waters, which support a diversity of marine life, including enormous amounts of zooplankton, large fish stocks, whales, and seabirds (Fig. 9). The region – remote to major cities – is to less degree than most under direct pressure from land-based human activities. Despite their high latitude, most of the Norwegian and Iceland seas remain ice-free year-round thanks to as a continuation of the Gulf Stream. The region plays an important role in global ocean circulation as the Atlantic Meridional Overturning Circulation (AMOC) here constitutes a conveyor belt where relatively warm and saline Atlantic water masses flow into the Norwegian Sea from the south, are transported north and westwards to the Greenland Sea where a fraction of the then cold, dense waters sinks and flows southwards, driving the thermohaline (water density determined) circulation (Fig. 9).

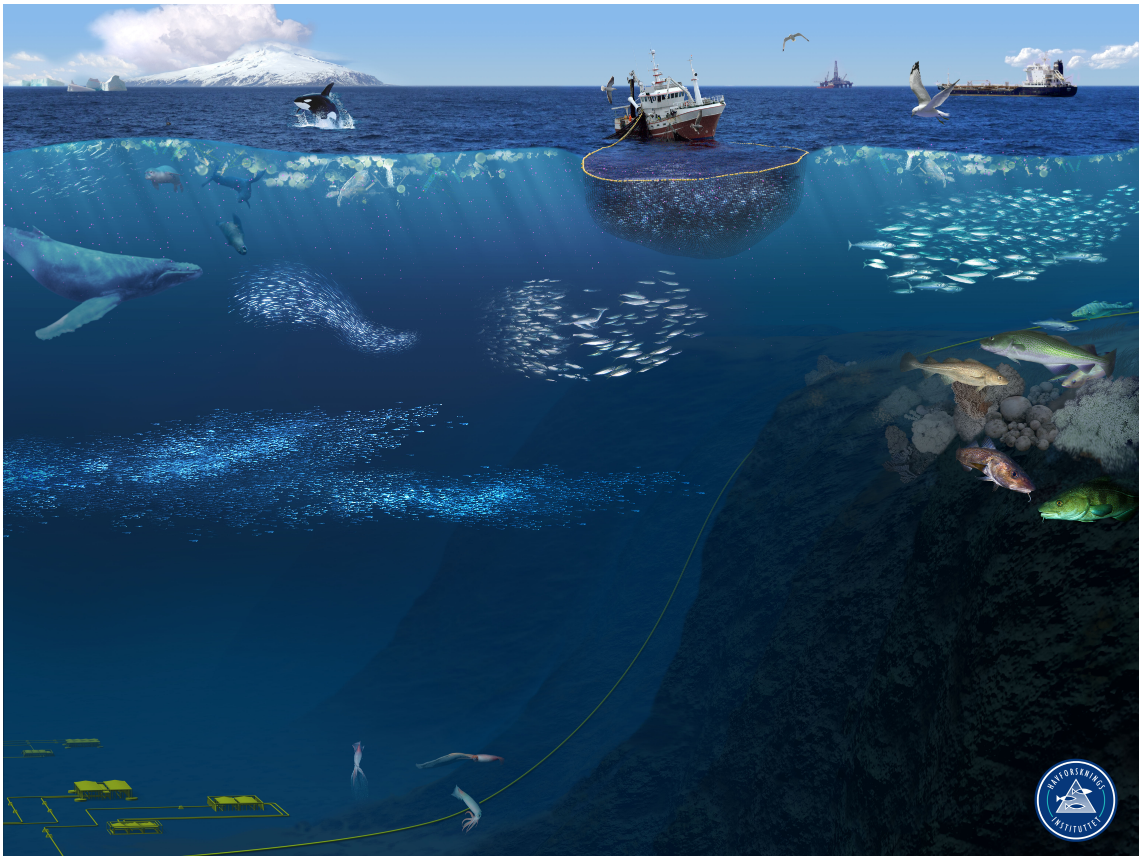

Figure 9. An artist's view of the Norwegian-Iceland Sea region. Credit: Institute of Marine Research, Norway.

For this area we have chosen a different approach to our presentation. Instead of by species group we here give a more integrated ecosystem description, focusing on bottom-up, food driven mechanisms and energy flowing throughout the environment and ecosystem. Climate is a main driver, influencing physical, biogeochemical and biological processes. To better understand the effects of climate change, we need to understand as much as possible about the mechanisms through which climate impacts the Nordic Seas ecosystem today.

Introduction to the bottom-up drivers of the region

The population sizes of several demersal fish stocks (e.g. Atlantic cod) and seabird species (e.g. kittiwakes) in the subpolar North Atlantic (SPNA) have been declining during the last 2–3 decades. A critical question is whether this is due to anthropogenic influence, natural environmental cycles or maybe (and more likely) a combination of these. The fisheries do, naturally, directly impact commercial fish stocks, but direct exploitation cannot explain, e.g., the decline of kittiwakes, which are not being harvested by humans. A decline in common food resources for both fish and birds is a plausible candidate, where the ecologically important copepod *C. finmarchicus* and forage fish like sandeel and Norway pout are primary candidates. While acknowledging the importance of top-down impacts, the following summary is limiting to bottom-up (food driven) processes. This bottom-up perspective focuses on the most plausible physical drivers underlying ecosystem changes on the south Iceland, Faroe and Norwegian shelves – especially through the trophic pathway from large zooplankton (copepods) via forage fish (e.g., sandeel and Norway pout) to commercial fish stocks and seabirds. Historical temporal changes in the SPNA are here categorized into *i*) recurrent pulses every 5–8 years, *ii*) major longer-lasting shifts and *iii*) long-term trends.

The strong and highly variable atmospheric jet stream impacts all three shelf environments both through direct air-sea interaction, and indirectly through changes in large-scale ocean circulation, which subsequently impacts the shelves laterally by ocean-shelf interaction. In our simplified perspective, we discuss how the size and circulation strength of the subpolar gyre (SPG) regulates the temperature and salinity (Hátún et al., 2005) and the biogeochemical and biological content (Hátún et al., 2016; Hátún et al., 2017a) in the relatively warm and saline Atlantic Water (AW). This *Atlantic inflow* flows westwards south of Iceland, crosses the Iceland-Faroe ridge and flows poleward through the Faroe-Shetland Channel. The AW properties thus impact the south Iceland (Hátún et al. 2016) and Faroes (Hátún et al. 2021a, Jacobsen et al. 2019) shelves directly and are likely to influence the Norwegian shelf as well. Immediately north of the Iceland-Faroe ridge, the AW meets south-eastward flow of cold and low-saline waters from the East Icelandic Current (EIC), which carries large amounts of nutrients and zooplankton into the southern Norwegian Sea (Kristiansen et al. 2019). Interplay between the AW and the (modified) East Icelandic Water from the EIC determines the physical oceanography and planktonic food abundance in the southern Norwegian Sea, which has potential to influence the Faroe (Kristiansen et al., 2021) and Norwegian shelves (Skagseth et al. 2021). Like the SPG regulates the distribution of, and mixing between, source water masses west of the British Isles, the Norwegian Sea gyre regulates water mass distribution and mixing in the southern Norwegian Sea (Hátún et al., 2021).

Pulses

Periods with an intensified atmospheric jet stream, often proxied by a high North Atlantic Oscillation (NAO) index (Hurrell, 1995), increases heat losses from the SPNA oceans and this induces deep winter convection, which is especially strong in the Labrador and Irminger Seas (Yashayaev 2007). Strong convection increases the volume/size of the SPG and invigorates nutrient upwelling and thus primary production. Increased SPG volume, as well as the action of winds (through the so-called wind stress curl) brings the nutrient and zooplankton rich SPG water closer to the south Iceland and Faroes shelves, and can in this way "blow life" to these shelf ecosystems (Hátún et al. 2016). Such pulses have been documented to *a*) increase the nutrient contents all the way from the Labrador Sea, across the Irminger Sea and the Iceland Basin and into the southern Norwegian Sea (Hátún, et al. 2017a), *b)* increase the abundance of the subarctic zooplankton species *C. finmarchicus* in the central Irminger Sea, the south Iceland shelf (Hátún et al., 2016) and in the subarctic water masses in the Norwegian Sea (Kristiansen et al. 2021), *c*) increase the breeding success of the seabird black-legged kittiwake (Hátún, et al. 2017b) and the total abundance of juvenile fish on the Faroe shelf (Jacobsen et al. 2019). During the last half century, such pulses occurred in the years: 1976, 1984–1985, 1987, 1993–1995, 2000–2001, 2009, and 2017.

Major shifts

Associated with the same atmospheric drivers, but with additional profound shifts in gyre circulation and major ocean currents, we have also witnessed longer lasting shifts in the northeastern Atlantic. After a period with generally high NAO index values during the late 1980s and early 1990s, an abrupt weakening in the atmospheric forcing during winter 1995–1996 led to much weakened winter convection, which again initialized a major decline of the SPG size and circulation (Häkkinen and Rhines 2004, Hátún et al. 2005). Less subarctic water reached the mixing region west of the British Isles, and the AW therefore became both warmer and more saline, but poorer in nutrients and *C. finmarchicus* (Hátún, et al. 2009a). This, and the simultaneous strong decline in sandeel abundance, likely caused seabird populations like the world's largest puffin colony, located in the Icelandic Westman Islands (Vestmannaeyjar), to decline, although the puffin abundance has since ca 2015 strongly increased again (Mehto 2021). The strong subarctic pulse in 2000–2001 gave Calanus-dependent species on the south Iceland and the Faroe shelf a much-needed injection, but after this pulse had passed these shelf ecosystems went into a serious recession. This event also had detrimental impacts along the European margin, were e.g. the sandeel abundance and the prosperity of several seabird species strongly declined (Coulson 2011). The mid-1990s change had, however, positive impact on the large pelagic blue whiting stock (Hátún et al. 2009b), which is less sensitive to food availability early in the season (before May), and which benefits from a warmer and more stratified ocean. Many new marine species with warmer water affinity entered Faroese and Icelandic waters during this event (Valdimarsson et al. 2012), and it is therefore justifiable to refer to this as the mid-1990s regime shift (Hátún et al. 2009a).

Since the above discussed pulses and longer-lasting shifts are related to similar physical processes, it is not trivial to determine whether a present or recently observed change represents a pulse, or if it marks a shift to a new state. Although the pulses around 2000–2001 and 2008–2009 were evident in hydrographic records around the northeastern Atlantic (clearest in salinity) and in biological production on the Faroe shelf (Jacobsen et al. 2019), they were not strong enough to flip the SPNA back into a subarctic state – like in the early 1990s. A major pulse initiated by increased convection during the winters 2014–2016 (Yashayaev and Loder 2016) managed, however, to re-invigorate the SPG, evidenced by a drop in sea surface heights south of Iceland (Hátún and Chafik 2018) and in the most rapid salinity drop in historical records in the same region (Holliday et al. 2020). Observations during the following years have demonstrated that the system shifted back to a state resembling the early 1990s. It is therefore timely to review possible ecological changes in the northeastern Atlantic for the years after 2015. And for those species exhibiting a change, to distinguish if this was a post-2015 pulse or maybe a more lasting shift back to a subarctic/more productive state.

Discussions on the Norwegian Sea must include the additional influence by the EIC. The properties and transport in the EIC are, as mentioned, related to the SPG story due to similar atmospheric forcing, and since the AW properties in the clockwise circulation constitutes one of the sources for the EIC (Valdimarsson et al. 2012). The SPG and EIC signals are, however, not the same. The EIC influx was strong during the 1990s, and this brought large amounts of large and lipid rich copepods (*C. hyperboreus* and large stages of *C. finmarchicus*) into the Norwegian Sea. This influx declined sharply in 2003–2005, and with it decline the abundance of the nutritious zooplankton (Kristiansen et al. 2019). This relatively warm and saline Atlantic period prevailed until around 2016, when the EIC influx increased yet again, which immediately brought more of the subarctic copepods to the waters north of the Faroes, and even east to the Norwegian slope (Kristiansen et al. 2021, Skagseth et al. 2021). These shifts in the Norwegian Sea likely have implications for zooplankton and the fish species herring, mackerel, and salmon. Updates on the further development of these processes and their potential impacts on adjacent shelves and seabirds is warranted.

Long-term trends

Evidence for longer-term physical and ecological trends must also be discussed, especially now anthropogenic climate change is projected to fundamentally alter the functioning of marine ecosystems during the next 50–100 years (IPCC 2019, 2022). Only few hydrographical and biological records are longer than 50 years, and since the North Atlantic Ocean is characterized by a natural cycle of 50–60 years (the Atlantic Multidecadal Oscillation, AMO, Goldenberg et al. 2001), it is not trivial to distinguish between uni-directional trends and natural variability. Although we regularly read about warming trends and biota migrating polewards, fact is that increasing temperature trends are difficult to establish from hydrographic records in the northeastern Atlantic. The first order signal in these hydrographic records is a mid-1990s warming, followed by about twenty years with anomalously high temperatures and a subsequent temperature decrease down to the early 1990s level, i.e. the above-mentioned shift. The pre-bloom (winter) silicate levels throughout the entire SPNA have, on the other hand, been declining since the 1980s in a more linear fashion than what can be ascribed to SPG-related natural variability alone (Hátún et al. 2017a). Silicate is the limited nutrient in the SPNA, so if this trend persists through the coming decades, the working of North Atlantic subarctic marine ecosystems is bound to change - fundamentally. It is conceivable that the mentioned bio-physical linkages, established during a period with higher nutrient concentrations already are altered. Based on a review of recent ecosystem changes on the Iceland, Faroe and Norwegian shelves, we should be able to test and maybe adjust/improve previously proposed hypotheses on bio-physical linkages.

Seas around Greenland

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The seas around Greenland consist of both regions with cold polar and warmer Atlantic waters, providing very different conditions for marine life and potential for harvesting. Cold polar water that flows south on both sides of the country meets with warm Atlantic water and creates particularly favourable production conditions in areas on the continental shelf (Fig. 10). Due to Greenland's northern location, most waters experience seasonal ice coverage in winter, the main exception being Southwest Greenland.

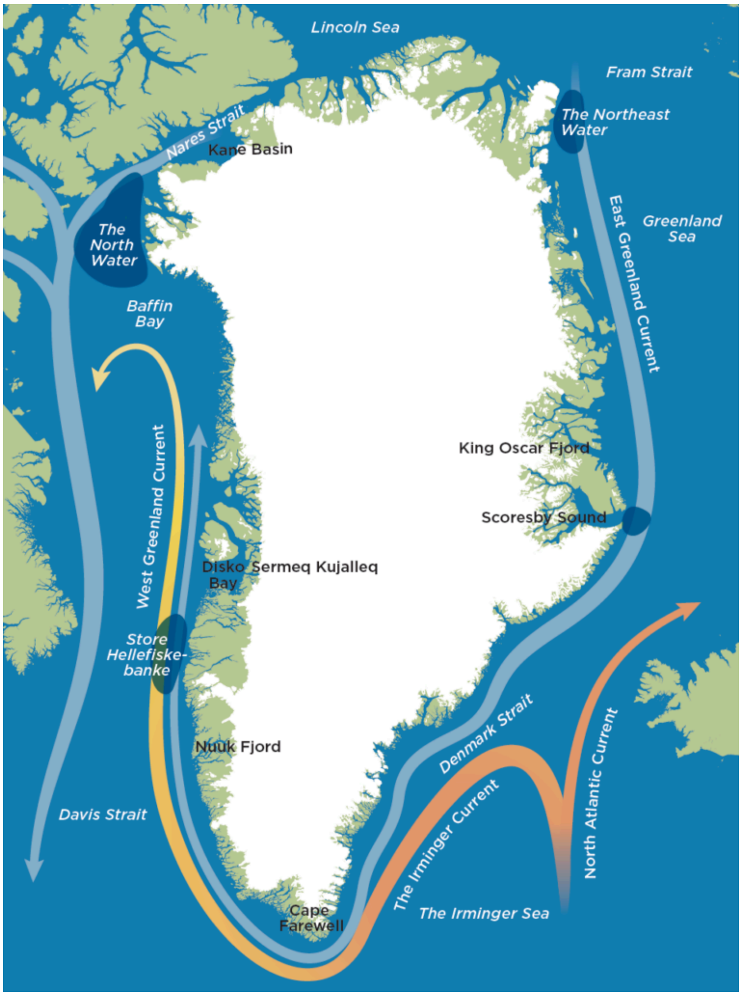


Figure 10. The main currents around Greenland. Cold ocean currents from the Arctic Ocean are shown in light blue and the relatively warm North Atlantic Current in orange fading to yellow. From Professor Mads Peter Heide-Jørgensen, Greenland Institute for Natural Resources and Trap Greenland (https://trap.gl/en/natur-og-landskab/havet-og-fjordene/)

Physical and biogeochemical changes

During the past decades, Greenland has experienced rapid warming, with consequences for e.g. the ice cap melt rate, ocean temperature and ecosystem structure. Changes that are projected to continue over the coming century.

The CMIP6 earth system models project that air temperature over Greenland will increase by more than 5 °C at the end of the century in the (extreme) SSP5-8.5 scenario, and precipitation will likewise increase significantly (Zhang et al. 2024). The globally increasing atmospheric temperature has implications for the water temperature, for which the CMIP6 multi-model mean shows an increase that exceeds 2 °C at the end of the century in the low SSP1-2.6 scenario, and 5 °C in the SSP5-8.5 scenario (Kwiatkowski et al. 2020). The glacier volume loss is projected to reach 67% in the SSP5-8.5 scenario (Kang et al. 2024).

The combination of increased precipitation and glacier melt leads to increasing freshwater runoff from land to the seas around Greenland. For the SSP1-2.6 scenario, the runoff volume is projected to peak in 2037, while more severe scenarios lead to progressively later peaks in runoff (e.g. year 2083 for SSP5-8.5). The change in runoff has a strong seasonal signal, and is projected to increase the most during summer, in July and August (Kang et al. 2024). With regards to nutrient supply, marine terminating glaciers currently induce upwelling of nutrient-rich water from below, thus playing an important role in sustaining the marine coastal ecosystem (Hopwood et al. 2020). However, as glaciers retreat inland, this mechanism will no longer occur, likely with large ecosystem implications locally. Meltwater from the Greenland Ice Sheet further provides smaller concentrations of bioavailable iron, phosphorus and silica (Hawkings et al. 2014, 2016 and 2017), while also nitrate appears to be supplied by meltwater (Wadham et al. 2016). Ocean simulations show that runoff from east Greenland will be transported to the Labrador Sea, while runoff from West Greenland will be moved toward Baffin Bay, thus bringing nutrients and increasing stratification in these areas (Luo et al. 2016). Meltwater has already been shown to reduce light limitation for phytoplankton in open waters, through shallowing of the pycnocline, and thus reduced light limitation in the Labrador Sea (Oliver et al. 2018). Future changes in the mixed layer depth (MLD) depend on the balance between increased wind mixing and stronger stratification due to increased freshwater runoff, leading to large variability between models in both CMIP5 (Steiner et al. 2014) and CMIP 6 (Kwiatkowski et al. 2020), but overall the model means show a small tendency toward shallower MLD around Greenland.

Primary production

Currently, marine primary productivity around Greenland follows a pattern of higher productivity south, southwest and southeast of Greenland, areas which are warmer and predominantly ice-free year-round at present time. CMIP6 projections show that these southern areas will experience a decrease in productivity, associated with stronger stratification and nutrient limitation. In the northern areas, Baffin Bay and the eastern parts of the Greenland Sea, productivity is projected to increase to a decrease in ice cover, and thus less light limitation (Kwiatkowski et al. 2020, Tittensor et al. 2021). Compared to the earlier CMIP5 projections, the changes in CMIP6 are similar in direction, but with a stronger trend. In the Greenland Sea, northeast of Greenland, projections show a significant *increase* in productivity (Popova et al. 2014, Tittensor et al. 2021). This increase can be attributed to a combination of increased light availability due to a smaller sea-ice extent, and increased vertical mixing of nutrients (Popova et al. 2014). While the overall trend in primary productivity is similar between the earth system models, the strength and timing of change differs. However, productivity is changing in relation to both duration, strength and timing of blooms, as well as species composition.

CMIP5 and CMIP6 projections show that over the coming decade CO_2 uptake will act to decrease pH in the waters around Greenland, with potential implications for organisms with calcium carbonate shells (Popova et al. 2014, Steiner et al. 2014, AMAP 2018). CMIP6 projections show that the waters around southern Greenland will experience significant reductions in the aragonite saturation state, which will be corrosive (<1) year-round by 2100 in SSP2-4.5, and more severe in SSP5-8.5. The drop in pH and saturation state is smaller towards the north in Baffin Bay and at the east coast north of Greenland. Here, productivity is projected to increase, thus counteracting acidification (Popova et al. 2014, Steiner et al. 2024).

Secondary production

The CMIP6 multi-model mean shows a decrease in zooplankton biomass in the waters southwest, south and southeast of Greenland, areas that currently are ice free and have higher phytoplankton and zooplankton biomass than waters toward the north (Tittensor et al. 2021). However, the calculation of zooplankton grazing on phytoplankton is a large source of uncertainty in CMIP6 models (Rohr et al. 2023).

The copepod *Calanus glacialis* is a nutritious food source and thus a key species for the marine food web in Greenlandic waters. However, changes in sea ice cover and temperature has caused the smaller and less fatty *C. finmarchicus* to move northward from the Atlantic Ocean with warming water, currently dominating the

Calanus biomass in Disko Bay (Møller et al. 2020). This change in species composition has implications for the food web as the mean lipid content of the *Calanus* females has decreased by 34% due to the change in species composition (Møller et al. 2020). A model study shows that *C. glacialis* has moved northward in Baffin Bay over the past 30 years (Feng et al. 2018), brought on by changing conditions in the northern parts. Changes in ice cover and temperature have led to a prolonged growth and feeding season, as well as increased food availability. This study thus suggests that the poleward movement of *C. glacialis* will continue, as current changes with regards to ice cover, temperature and primary productivity are projected to continue (Tittensor et al. 2021). Similarly, Freer et al. (2022) showed that habitats for *C. finmarchicus* are moving northward in the Greenland Sea.

Benthic plants and animals

In the Arctic, the pelagic and benthic productivity is closely coupled (Grebmeier et al. 2015). Consequently, benthic biomass and the variety of species living on the surface of the seabed decreases with latitude, ice cover and depth along the west Greenland shelf (Maier et al., 2024). Given the projected decrease in ice-cover and increase in primary productivity in poleward areas around Greenland, an increased flux of organic matter to the seafloor is likewise expected. In the northern areas of both the west coast and east coast of Greenland, increased food availability for epifauna (Rysgaard et al., 2007), including bivalves (Sejr et al. 2009), is therefore expected, indicating increased benthic biomass in the future.

Further, bottom temperature has increased by more than one degree from 1990 in the water off west Greenland, leading to poleward expansion of communities especially west of Greenland, a tendency which is likely to continue with continuing ocean warming over the coming decades (Renaud et al. 2015). Species of macroalgae from the intertidal zone have likewise expanded poleward along the west coast of Greenland, e.g. *F. vesiculosus,* which moved from 73 to 76N over a period of 40 years from 1970. However, no similar trends have been observed on the east coast, possibly due to the southward current here (Krause-Jensen et al. 2020). In Jungsund, the growth rate of kelp (*Saccharina latissima*) correlates with the increasing ice-free period (Krause-Jensen et al. 2020).

Factors that may affect communities in a negative direction are, e.g., acidification, which is especially projected to affect the shelves, bottom trawling, and Walrus feeding on benthic communities. The latter may increase as the ice coverage decreases in northern areas, making feeding more accessible (Węsławski et al. 2011).

In western Greenland, shrimp (*Pandalus borealis*, also known as northern prawn or deepwater prawn) play an important role for the economy and local employment, and are a key food source for fish and birds (AMAP 2018). Shrimp habitats currently include the continental shelves of southern Greenland, south of Iceland in the east, and south of 75 °N on the west coast, but with changing temperature shrimp are increasingly observed also north of 69.3 °N (AMAP 2018). The shrimp fishery takes place both in coastal and offshore waters. The shrimp life cycle is closely coupled to the physical and biological environment, with e.g. larvae hatching time co-occurring with the phytoplankton spring bloom. As climate change is projected to change the timing and strength of the phytoplankton bloom, the feeding of shrimp may also be affected in the future. Additionally, warming is likely to impact stress sensitivity. Higher temperatures are known to reduce recruitment, but they may also benefit shrimp (Richards et al. 2015). Shrimp seem to be able to internally counteract the effects of acidification (AMAP 2018), though their taste may be affected negatively (Dupont et al. 2014). In summary, the combined effect of increasing stress on shrimp due to climate change is not well understood, and more studies are needed to understand how the Greenlandic shrimp stock will change in the future.

Fish

The fish around Greenland are currently already affected by increasing temperature and decreasing ice cover, leading to changes in optimal habitats, food availability, and predation pressure, as primary and secondary production is changing, and new species are migrating north.

The fish model intercomparison in CMIP5 and CMIP6 project a global decline in animal biomass by the end of the century (Lotze et al. 2019). However, in the areas around Greenland that are currently ice-covered during winter, e.g. Baffin Bay and the east Greenland Sea, the multi-model mean projects an increase in animal biomass by up to 50% in 2100 under SSP5-8.5. This is mainly brought on by decreased ice cover, increased temperature, and shallowing mixed layer depth, combined with increased primary production. In the sea south of Greenland, animal biomass projections show minor to no decline (Lotze et al., 2019). In CMIP6, the area of positive change in biomass is further north, while the southern area shows a larger decline than what was projected in CMIP5 (Tittensor et al. 2021). The future fish stocks are affected also by changes in other human pressures, something that is not addressed in the simulations, neither are changes in species composition.

Given the large importance of fisheries for Greenlandic society, changes in fish stocks are currently monitored by researchers and fishermen alike (Jacobsen et al. 2023). In waters off south and east Greenland, changes in sea ice distribution, duration and thickness affect the availability of habitats. Here, poleward expansion of distributions of boreal generalists is currently happening with increasing temperature, opening new habitats for mobile pelagic species such as saithe (Post et al. 2020). Further mackerel and tuna appear to be moving poleward, but with fluctuations over the years (Heide-Jørgensen et al. 2022). At the same time, a decrease in Arctic bottom dwelling benthivores and demersal fish has occurred. However, the loss of species with Arctic traits was not compensated by the number of new species, leading to a functional diversity decline in waters southeast of Greenland (Emblemsvåg et al. 2022a). An example is the subarctic capelin, which has moved closer to the east Greenland shelf due to changed temperatures (Heide-Jørgensen et al. 2022).

The deep-water flatfish Greenland halibut is an important species for fisheries in west Greenland. Given the deep habitat of the species, only little is known about the distribution. However, studies have shown that the seasonal and interannual distribution is affected by variations in temperature (Boje et al. 2014, Wheeland and Morgan 2019). Additionally, the distribution of fisheries along the west coast shows how the halibut has moved northward, with halibut fisheries having been common in Ilullissat (69 °N) for 100 years, in Uummaanaq (71 °N) for 70 years and in Upernavik (73 °N) for 30 years (Jacobsen et al. 2023). In general, the fishermen in northwest Greenland experienced increasing fishing opportunities with decreasing sea ice (Jacobsen et al., 2023).

All in all, current experiences with increasing fisheries west of Greenland, combined with projected continued warming of the water, reduction in summer sea ice and increased primary productivity suggests that a borealisation in southern parts of west Greenland, while a poleward expansion of Arctic species, is likely to continue.

Seabirds

Greenlandic seabirds are expected to be affected by factors such as changes in temperature and sea ice extent and thickness, which will lead to shifts in spatial distribution of prey species, affecting timing of prey availability. Physical and ecosystem changes brought on by climate change are expected to impact specialized Arctic species, while generalists will be more likely to adapt to, or even take advantage of, new conditions.

An example of an Arctic specialist is the ivory gull in east Greenland, which forages at the ice edge throughout the year. The ivory gull breeds in northeast Greenland, while the ability to obtain sufficient food to raise young depends on the distance to the ice edge. The population trend in Greenland is unknown due to the remote habitat but is thought to decline south of 70 °N e.g. due to loss of sea ice habitat (Gilg et al. 2009). Similarly, the Canadian population has declined by 80% from 1980 to 2002 (Gilchrist et al. 2005), and the Svalbard population by 40% from 2006 to 2019 (Strøm et al. 2020). In northeast Greenland, the projected change in ice extent over the coming century is small compared to the rest of the Arctic, and it is thus possible that the population here will remain stable in the future (Gilg et al. 2009). However, winter-habitats for the ivory gull are found around the ice-edge south of the Polar Circle (66 °N), mainly in the Labrador Sea, due to the need for light to forage. Consequently, if the ice edge moves too far north, the winter habitats will be lost, likely causing a decline in the populations and ultimately extinction (Kuletz et al. 2024).

Little auk is the most abundant seabird in the Atlantic Arctic, playing an important role in the ecosystem by transporting organic matter from the sea to land, where it breeds exclusively on rocky coasts of the high Arctic, especially in northwest and east Greenland (Wojczulanis-Jakubas et al.,2022). Little auk is dependent on Arctic copepods with high fat content, and it is thought that the increased temperature over the past century, combined with poleward movement of e.g. *C. glacialis*, has contributed to a decline in the population in southeast Greenland, though other factors may also contribute (Jakubas et al. 2024). The habitats of the Arctic copepods are expected to continue the poleward displacement, likewise, pushing the habitat for little auk northward.

However, some Greenlandic seabirds, such as the common eider and great black-backed Gull, benefit from warmer conditions and have expanded their habitats northward (Boertmann et al. 2016; Boertmann and Frederiksen, 2020). Additionally, opportunistic species, such as the lesser black-backed gull, which were previously limited in northward movement by e.g. temperature, ice or prey availability, are likely to increasingly move north to southern Greenland (Boertmann and Frederiksen 2016). Further, some birds which currently do not have a strong presence in southern Greenland, such as the herring gull, may move north to Greenland in the future (Boertmann and Frederiksen 2016).

Marine mammals

In addition to the importance of marine mammal hunting for Inuit communities, marine mammals are apex predators in Greenlandic waters, and their distribution thus provides information on the state of the ecosystem. Species such as narwhal, walrus and hooded and ringed seals rely on ice and cold temperatures for their habitats and are thus likely to be affected by the changes in the environment. A study combining CMIP6 earth system models with long-term time-series of the distribution of three Arctic ice-dependent whale species (bowhead whale, beluga, and narwhal) around Greenland, has assessed the projected habitat changes for these cetaceans (Chambault et al. 2022). The study showed a major loss of summer habitats for all three species both west and east of Greenland, especially in the SSP5-8.5 scenario, except for narwhal habitat east of Greenland, which was increased in Scoresbysund in the projections. In winter, an overall gain of habitat was projected for Bowhead whales, especially in the Canadian Archipelago, though a loss habitat was projected east of Greenland. Narwhals likewise lost habitat during winter both in Baffin Bay and east of Greenland (Chambault et al. 2022).

Narwhals have a preferred feeding temperature of <2C, and it has been shown that southward migration takes place later in the season during warmer years with increased meltwater runoff and delayed ice formation, suggesting that narwhal habitats are currently being pushed north- and westward as their habitats are reduced due to less sea ice (Laidre et al. 2024). However, currently no trend in the number of narwhals is observed at Melville Bay in west Greenland. In east Greenland, a decline has been observed due to e.g. changed temperature and ice conditions (Heide-Jørgensen et al. 2023).

Walrus habitats include the coasts of northwest and northeast Greenland where they rely on ice for resting and nursing their young. In recent years, the number of walruses caught in northwest and west Greenland has declined, partly due to sea ice decline, which has moved walrus habitats westward with the Baffin Bay pack ice (Born et al. 2017). However, walruses have a good heat tolerance, and longer ice-free periods may also be positive for Atlantic walrus, giving prolonged access to foraging and access to terrestrial haul-outs. In addition, primary production and thus benthic growth is thought to increase in the north toward 2100. Hence walrus may thrive in a future climate, provided other human pressures are kept down (Born et al. 2021).

In southeast Greenland, the number of boreal cetaceans, such as pilot whale, dolphin and killer whale, has increased since 1980 with decreasing summer ice cover. At the same time, the number of walrus and narwhals has declined in the area (Heide-Jørgensen et al. 2023). The loss of summer ice can be considered a tipping point that has led to major habitat changes, and which is not likely to be reversed under current climate scenarios.

Holistic ecosystem considerations

The Arctic has been identified as an area experiencing climate change at a rate faster than the global average, and climate change impacts are already altering the ecosystem around Greenland. In the northern regions both east and west of Greenland, the trend of an increase in temperature and a decrease in sea ice extent, duration and thickness over the past decades is projected to continue until the year 2100. For Arctic species adapted to low temperature and sea ice, such as the copepod *G. glacialis* and the narwhal, habitats are moving northward thus also causing a poleward movement of these species which is likely to continue with future changes. However, the CMIP6 multi-model mean also projects increases in primary and secondary production due to, e.g., increased light, higher temperatures and nutrients from runoff, leading to increased primary and secondary production, and thus an increased flux of organic matter to the sea floor, and increased benthic biomass. Likewise, the projections show that fish biomass will increase in the northern areas around Greenland. These projections do, however, not have information about changes in species composition. Current observations show that economically important species, such as shrimp and halibut, can be fished progressively further north as temperature increases. Especially on the west coast of Greenland, fisheries are important for the economy, and the northward movement of fish opens up new opportunities in the northern locations, such as Upernavik and Qaannaaq.

Further towards the south, in the areas that do not currently have summer sea ice, CMIP6 projections show an increase in temperature, stronger stratification and a small decrease in primary and secondary production, as well as animal biomass by the year 2100. However, south, southwest and southeast of Greenland, the warmer water has seen an increase in boreal species over the later years. For fish, the boreal species are generally characterized by being pelagic generalists that are able to move to new locations, such as mackerel and tuna, while Arctic demersal fish are increasingly moving northward. Also, cetaceans, such as pilot whales and dolphins, have been observed in the area. Especially the region southeast of Greenland is relatively well connected to Iceland, making it possible for species to move northward to Greenland, suggesting that the fisheries there might become increasingly successful in the future.

Changed trophic interactions may have both negative and positive impacts that are difficult to predict on, e.g., fisheries. IPCC (2019, 2022) generally predict mainly negative impacts for Greenlandic society. Given the large importance of fisheries and hunting for the local economy and culture, communities are generally adaptable to new possibilities, making it important to identify, e.g., new harvestable fish species. However, the ability to adapt to changes depends on several factors, including the existence of infrastructure, such as local piers and fish factories, and political decisions, such as fish quotas and export prohibitions (e.g., narwhal tusk and walrus ivory). Thus, local communities, government and private companies all play a role in the resilience and adaptability in Greenland.

Another change brought on by decreasing ice extent and improved infrastructure is an increasing number of tourists, filmmakers and researchers visiting even remote areas of Greenland. This provides new possibilities in terms of earning money servicing the visitors, something that may widen the gap between those who can take advantage of new options and those who cannot, e.g., English language is becoming more important in communicating with tourists (Hayashi and Delaney 2024).

The Barents Sea

Geir Ottersen, Institute of Marine Research, Norway and
Thorsten Blenckner, Stockholm Resilience Centre, Sweden

The effects of climate change are of particular importance in the Arctic due to the temperature increase there, resulting in a fundamental change from a seasonally ice-covered to a permanently open ocean system. The northern and eastern parts of the Barents Sea (BS) are essentially of arctic nature. They have been, and to a large degree still are, seasonally ice-covered, with a long and dark Arctic winter and strongly light limited production. The southwestern part of the BS is boreal, but the boundary between the two regimes is not locked into latitude or longitude but shifts with the water masses (Fig. 11).

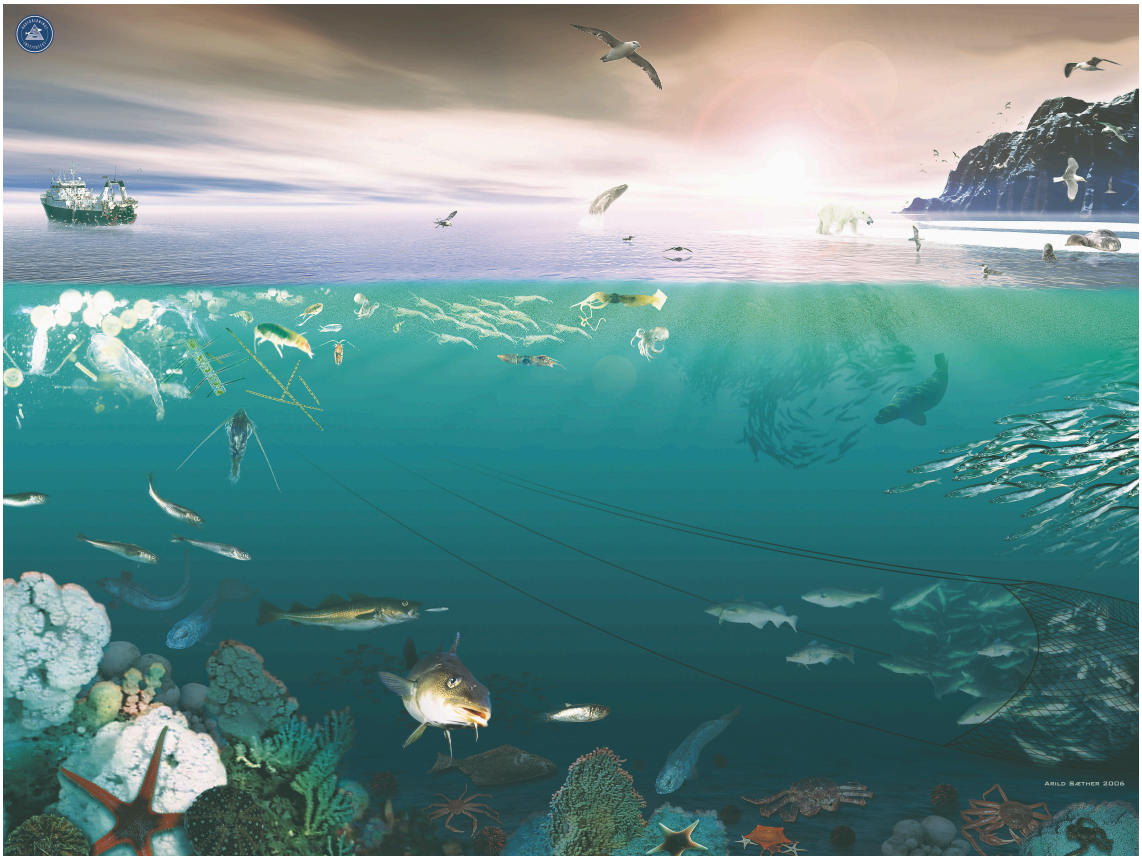


Figure 11. An artist's view of the southern Barents Sea. Credit: Institute of Marine Research, Norway.

As briefly described earlier, by absorbing large quantities of CO_2 from the atmosphere, ocean chemistry is changing and especially the surface layer is becoming more acidic (IPCC, 2019). Ocean acidification may become a threat by affecting fish eggs and larvae or through phytoplankton, but too little is yet known to draw any conclusions. Lack of oxygen is generally not considered to be a threat in the open Barents Sea.

Primary Production

Primary production, mainly phytoplankton, lays the foundation for much of marine life. How climate change affects this production will be important for everything from zooplankton to fish and whales. Primary production depends on nutrients reaching the upper layers where there is light. Thus, future production depends a lot on the availability of nutrients, which is regulated by the degree of the stratification of the sea and wind conditions. Strong stratification hinders nutrients entering the upper photic zone, thus reducing primary production. On the other hand, increased windiness will reduce the layering, mix up water from below and increase the nutrient levels in the upper layer. At high latitudes a large proportion of the yearly primary production is coupled to the phytoplankton bloom happening when the sea-ice retreats in the spring. These areas now undergo major changes related to diminishing ice coverage, changes that are expected to strengthen with further climate change. A future (more or less) ice-free BS will likely lead to significant changes in spring bloom dynamics and seasonality more generally, total productivity, and ecosystem structure (Sandø et al. 2021). Retreating ice will in large areas drive a transition from a system dominated by ice-algal production to one dominated by open-water phytoplankton blooms with an overall marked decrease in ice algae and increase in open-water phytoplankton production (Mueter et al. 2021). However, the development is complicated as the expected warming of surface seawater and increased freshwater from precipitation and (for a period) ice-melt leads to stronger stratification, while, acting to the contrary, stronger winds and increased storminess can have a positive effect on plankton production through weaker layering and thus increased upward mixing of nutrients.

Further, significant positive relationships have been found between ice-free conditions (open water area and duration) and net primary production (NPP; Arrigo and Donald 2020). The estimated annual NPP for the Barents Sea more than doubled over the 1998–2017 period, from around 40 to over 100 Tg C (teragrams, million tonnes of carbon); Dalpadado et al., 2020). The strong increase in NPP is the result of reduction of sea ice, extending both the area and period available for phytoplankton production. Over this ca 20-year period, the spring and summer phytoplankton blooms expanded and shifted to the north and east (Dalpadado et al. 2020).

In areas where ice extent has decreased, satellite-derived measurements of chlorophyll *a* show that the timing of the peak spring phytoplankton bloom has advanced by over a month. Using satellite ocean colour data, Renaut et al. (2018) observed a significant increase in primary productivity of phytoplankton spring blooms in the Barents Sea. A northward expansion of these blooms at a rate of 1° per decade driven by the Barents and the Kara regions was also detected. Satellite-based results confirm information from other sources that phytoplankton dynamics in the Barents Sea ecosystem have been changing rapidly and that this is driven mainly by bottom-up climatic processes (Renaut et al. (2018, Dalpadado et al. 2020).

The study by Sandø et al. (2021) examined how future variability and trends in temperature, sea-ice extent, light and wind-induced mixing in the BS will affect the lower trophic levels in the marine ecosystem. They combined downscaling of the NorESM1-M earth system model for the IPCC RCP4.5 scenario by means of the Regional Ocean Model System (ROMS) with the coupled physical–chemical–biological model system NORWegian ECOlogical Model system end-to-end, NORWECOM.E2E (Aksnes et al. 1995, Skogen and Søiland 1998). They projected that during the period 2010-2070 the northernmost parts of the BS gained increased access to light during the productive season due to decreased sea-ice extent, leading to increased primary and secondary production in periods of low sea ice concentrations. In the southern parts, variable access to nutrients as a function of wind-induced mixing and mixed layer depth were found to be the most dominating factors controlling variability in primary production (Sandø et al. 2021).

Projections by NORWECOM.E2E and evaluations by an expert panel were further used to project future primary production (and other variables) in the Barents Sea by Sandø et al. (2024). They estimated accumulated directional effects of climate change on primary production during 2015-2100 as a function of climate exposure and sensitivity attributes under the three IPCC climate scenarios SSP1-2.6 (low emission), SSP2-4.5 (moderate emission), and SSP5-8.5 (extremely high emission; Fig. 12).

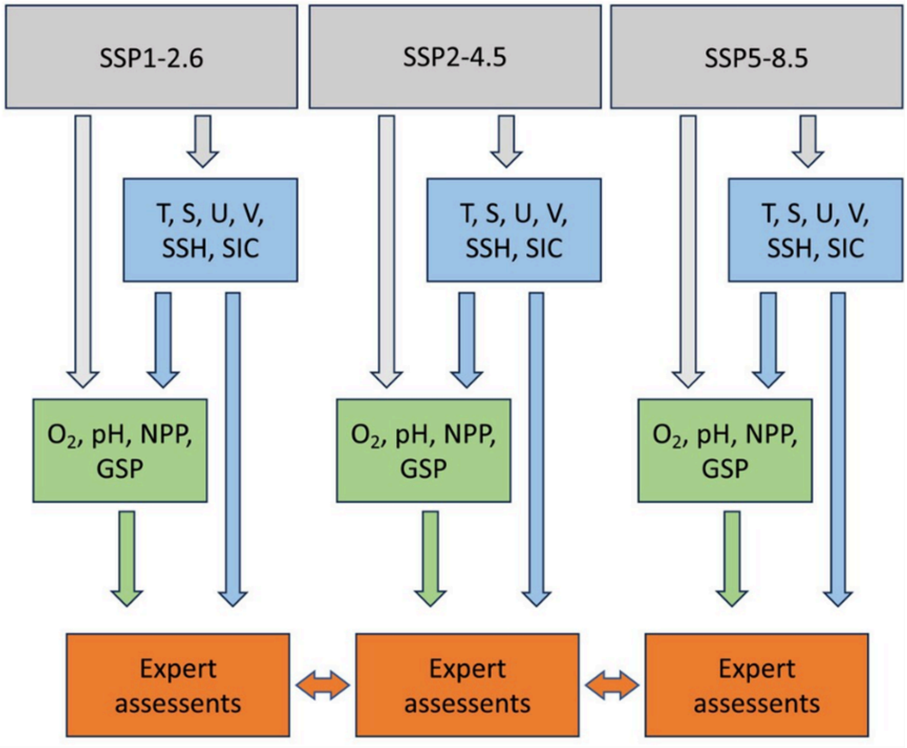


Figure 12. Rough outline of the approach behind the assessments of climate change impact on plankton and fish undertaken by Sandø et al. (2024). The Norwegian Earth System Model (NorESM) produces atmospheric forcing and boundary conditions for ocean downscaling within each of three scenarios (upper grey boxes). Regionally downscaled scenarios from the regional ocean model NEMO-NAA10km produces hydrography and ocean currents, sea surface height and sea ice extent within each of the same scenarios (blue boxes). The ecosystem model NORWECOM.E2E produces biogeochemical variables for each scenario (green boxes). Finally, based on the above and knowledge on selected sensitivity attributes expert assessments are conducted to estimate accumulated directional effects on plankton and a wide selection of fish (bottom orange boxes). From Sandø et al. (2024).

Sandø et al. (2024) evaluated four parts of the BS separately, Polar (coldest and most northerly), Arctic, Atlantic, and Coastal. For SSP2-4.5 and even more so in SSP5-8.5 an increase in net primary production was found for the Polar, Arctic, and Coastal regions. Within SSP1-2.6 the projected changes were very small for all four regions, as were they for the Atlantic region within all scenarios (Sandø et al. 2024). Results are here shown for the Arctic and Atlantic parts of the BS (Fig. 13).

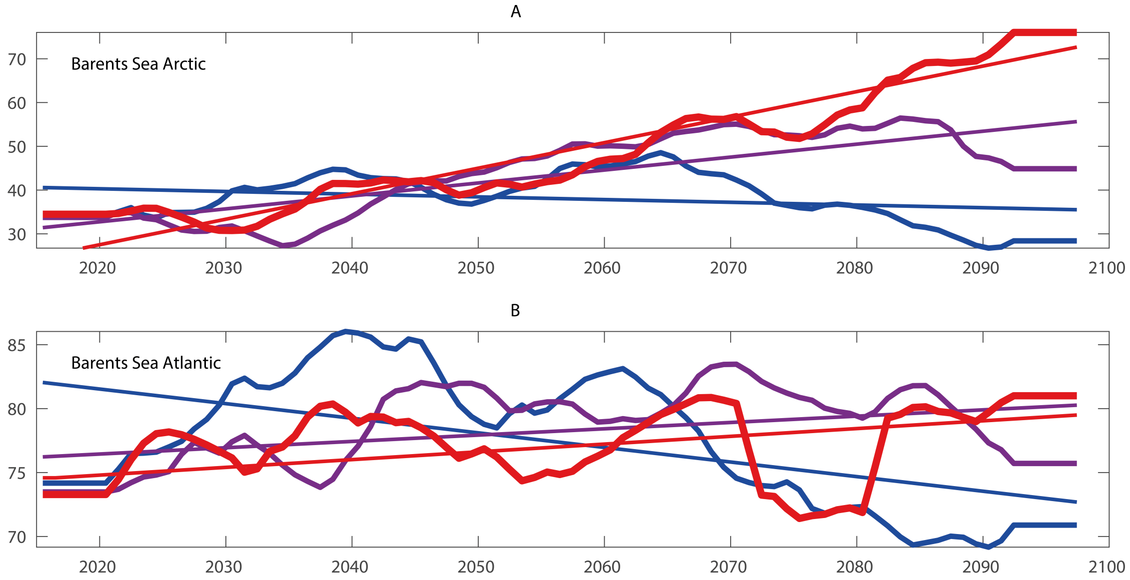


Figure 13. Projected annually averaged Net Primary Production in Tg C (y-axes) in the Barents Sea for the period 2015–2100 in (A) Arctic, and (B) Atlantic region. Coloured time series indicate the scenarios SSP1-2.6 (blue), SSP2-4.5 (purple), and SSP5-8.5 (red), and corresponding straight lines their trends.

Secondary production - zooplankton

In the Northern, seasonally ice-covered, part of the Barents Sea, primary production has been strongly light limited. A short and geographically limited phytoplankton bloom has also limited the zooplankton potential to utilize the existing particulate organic material due to low (phytoplankton) prey density. Future decrease in ice coverage will increase available light and expand and prolong the secondary production significantly as compared to the present. This change is particularly pronounced under the SSP8.5 scenario. For the polar region of the BS the annually averaged April–July Gross secondary production (GSP) has been projected to increase by on average more than 50 g/cm^2 over the period 2015–2100, in some smaller areas even more. Also for the Arctic and Atlantic regions the projected changes under the SSP8.5 scenario are pronounced (Fig. 14; Sandø et al. 2024).

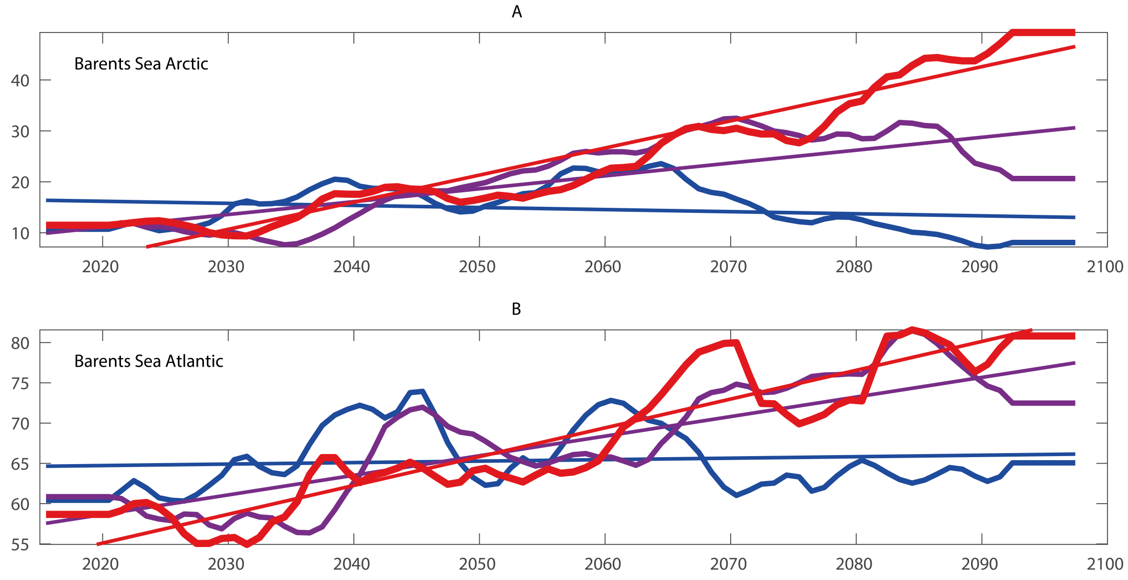


Figure 14. Projected annually averaged Gross Secondary Production (in g/cm^2; y-axes) in the Barents Sea for the period 2015-2100 in (A) Arctic, and (B) Atlantic region. Coloured time series indicate the scenarios SSP1-2.6 (blue), SSP2-4.5 (purple), and SSP5-8.5 (red), and corresponding straight lines their trends.

The transition from ice-algae to open water plankton blooms also affects the size and species composition of zooplankton communities, with a shift from large-bodied and typically lipid-rich zooplankton, whose early life stages are associated with the ice, to smaller and often less nutritious zooplankton species in the absence of ice (Aarflot et al. 2018, Mueter et al. 2021). Such changes in the size structure of lower trophic levels have been supported by laboratory studies and models.

In the western part of the Barents Sea, Aarflot et al (2018) observed indications of borealization of the zooplankton community, with a decreasing proportion of the Arctic *C. glacialis* from around year 2000 onwards and increase of the smaller boreal/North Atlantic *C. finmarchicus* during the same period. This is likely linked to increasing temperatures in the area and the pattern may strengthen with future more permanent warming.

Such species replacement within the Calanus complex has caused concern for ecosystem functioning and energy transfer to higher trophic levels. Calanus species store large quantities of lipids, making these zooplankton a critical link in marine food-webs. The Arctic Calanus species are usually larger and, importantly, have been suggested to contain disproportionately larger lipid stores than their boreal congeners. As pointed to above, there are already shifts from the larger, lipid-rich Arctic species *C. glacialis* and *C. hyperboreus*, toward *C. finmarchicus* in the

European Arctic, including the Barents Sea. Continued climate warming and subsequent changes in primary production regimes are expected to strengthen this development. It has been argued by several authors that there will be severe negative consequences, e.g., Mueter et al (2021) state that this will have detrimental effects on fishes that depend on high-lipid prey for overwinter survival as well as seabirds. However, this is debated. Renaud et al. (2018) suggest that lipid content is closely related to body size for all three species. Following this line of argument, lipid content is not a species-specific trait, and further, there is considerable overlap in size between C. *finmarchicus* and C. *glacialis*. This suggests that climate driven shifts in dominant Calanus species may not negatively impact their consumers in the Barents Sea.

Benthic plants and animals

The bottom-dwelling organisms in the Barents Sea have adapted to the temperatures in their living areas. Species in the southwest are thus adapted to warmer Atlantic climate and will be able to spread northwards with expanding Atlantic water masses. Contrary, Arctic species in the northeast may become more vulnerable, especially species that prefer stable cold temperatures. This is similar as for Barents Sea fish, but benthic animals are typically sessile species and individuals cannot swim away from warmer water. The populations can move, but only gradually through, for example, larval dispersal.

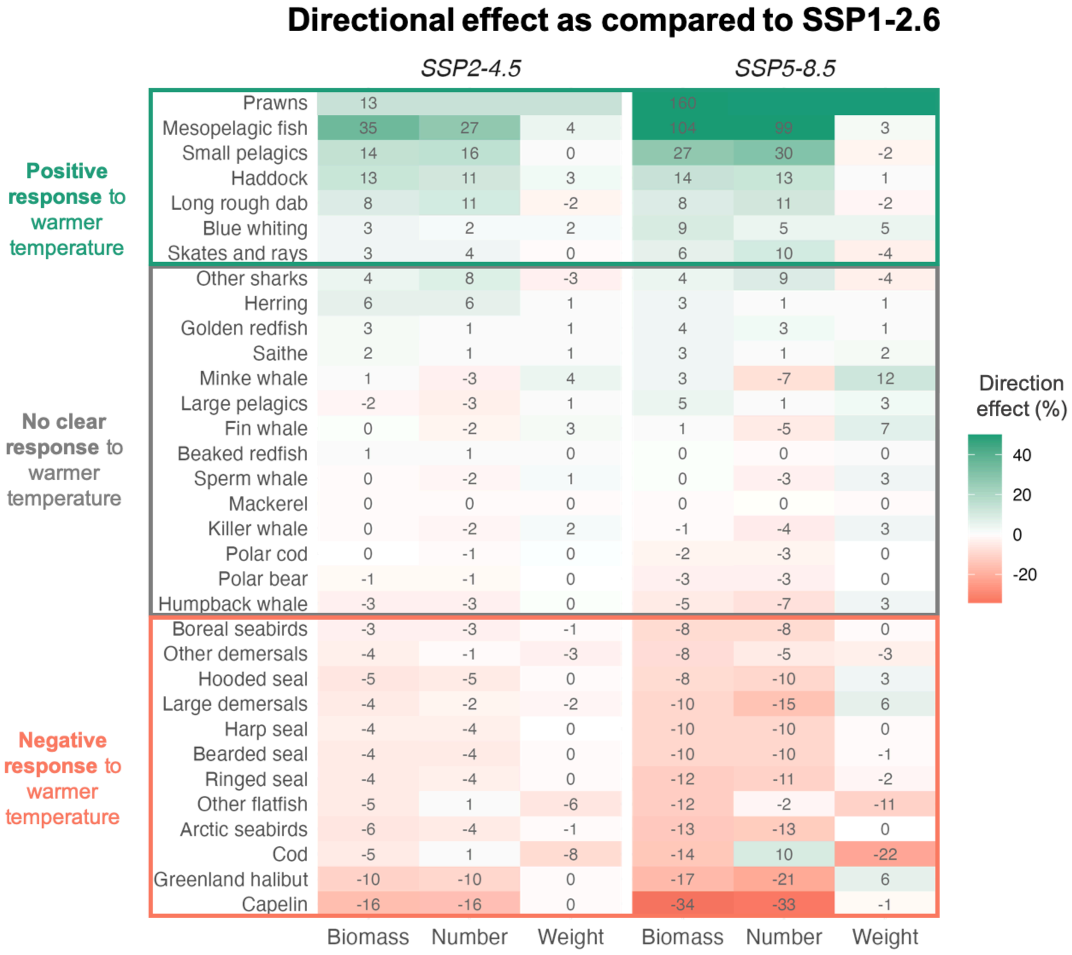
Further, in connection with the expected increasing sea temperatures sea ice will retreat northwards. This will lead to expansion or movement of the distribution not only of commercially targeted fish species, but also fisheries. Therefore, bottom living animals and plants in areas that were previously unaffected, may now come under pressure from fisheries, especially bottom trawling (Miljøstatus 2024).

Some bottom-oriented animals can indeed move actively, like crabs. The red king crab was introduced to the Barents Sea during the 1960 as a consequence of a Russian initiative to establish a new fishable resource. The crabs have since their release locally in the Murmansk fjord expanded to cover most of the near-coastal zone of the Barents Sea. No clear link between this development and changes in climate have so far been detected. However, it has been suggested that with increased warming the king crab may spread northwards and further offshore from its current near-coastal distribution (Christiansen et al. 2015).

The other numerous and expanding crab species in the Barents Sea is the snow crab. Although some observations were made from the mid-1990s onwards, snow crab is reckoned to be established as a species in the Barents Sea from around 2005. Their numbers have since increased significantly (Lorentzen et al. 2018). This is not clearly linked to climate. It has earlier been argued that future spreading of the snow crab in the Barents Sea will depend on warming (Pavlov and Sokolov

2003, Bakanev 2015). Mueter et al (2021) investigated a broad range of future scenarios for Subarctic and Arctic marine ecosystems. They envisage that snow crab will contract in the Subarctic but increase on Arctic shelves, the Barents Sea included in the latter. They argue that higher temperatures, combined with increased predation from expanding predator populations, reduces the survival of early stages of snow crab at the southern end of their current distribution. However, longer ice-free season and warming in more northern regions create favourable conditions for growth (Mueter et al. 2021). This is in accordance with Tao et al. (2024), who examined the impact of climate change on snow crabs and their fishery, including in the Barents Sea. They point to Arctic sea ice extent as a crucial climate factor affecting snow crab biomass and harvests.

Although northern prawns spend significant time in the water column, they are generally considered benthic. In their projections for the Barents and Norwegian Sea with the NoBa Atlantis ecosystem model, Nilsen et al. (2024) examined the directional response of a range of species to the three climate scenarios SSP1-2.6 (low), SSP2-4.5 (intermediate), and SSP5-8.5 (extremely high). Of all the species the prawns were found to have the most positive response to the strong warming under SSP5-8.5 but also responded more positively to SSP2-4.5 as compared to SSP1-2.6 (Fig. 15).



	SSP2-4.5			SSP5-8.5		
	Biomass	Number	Weight	Biomass	Number	Weight
Prawns	13			160		
Mesopelagic fish	35	27	4	104	99	3
Small pelagics	14	16	0	27	30	-2
Haddock	13	11	3	14	13	1
Long rough dab	8	11	-2	8	11	-2
Blue whiting	3	2	2	9	5	5
Skates and rays	3	4	0	6	10	-4
Other sharks	4	8	-3	4	9	-4
Herring	6	6	1	3	1	1
Golden redfish	3	1	1	4	3	1
Saithe	2	1	1	3	1	2
Minke whale	1	-3	4	3	-7	12
Large pelagics	-2	-3	1	5	1	3
Fin whale	0	-2	3	1	-5	7
Beaked redfish	1	1	0	0	0	0
Sperm whale	0	-2	1	0	-3	3
Mackerel	0	0	0	0	0	0
Killer whale	0	-2	2	-1	-4	3
Polar cod	0	-1	0	-2	-3	0
Polar bear	-1	-1	0	-3	-3	0
Humpback whale	-3	-3	0	-5	-7	3
Boreal seabirds	-3	-3	-1	-8	-8	0
Other demersals	-4	-1	-3	-8	-5	-3
Hooded seal	-5	-5	0	-8	-10	3
Large demersals	-4	-2	-2	-10	-15	6
Harp seal	-4	-4	0	-10	-10	0
Bearded seal	-4	-4	0	-10	-10	-1
Ringed seal	-4	-4	0	-12	-11	-2
Other flatfish	-5	1	-6	-12	-2	-11
Arctic seabirds	-6	-4	-1	-13	-13	0
Cod	-5	1	-8	-14	10	-22
Greenland halibut	-10	-10	0	-17	-21	6
Capelin	-16	-16	0	-34	-33	-1

Figure 15. 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).

Fish

It is well documented that throughout the historical record fish in the Barents Sea have been and are significantly affected by variability in their environment, particularly sea temperature, both at the single population (Hjort 1914; Ottersen et al. 2014) and community level (Fossheim et al. 2015; Ingvaldsen et al. 2021). Environmental pressures may act both directly on the fish's physiology or indirectly through predators or prey. Impacts on individual fish may lead to responses at the population level, affecting distribution, seasonal migration patterns, and recruitment success (see recent review by Gerland et al. 2023, also Mueter et al. 2021 and Skjoldal et al. 2022)

Higher temperature, retreating sea ice, and changes in prey availability during the decade 2004–2014 affected fish especially in the northern Barents Sea. Here higher temperatures expanded suitable feeding areas for boreal/subarctic species towards the typically cold north and east and contributed to strongly increased Atlantic cod production (Kjesbu et al. 2014). In contrast, the small-sized, slow growing arctic fish species that usually dominates the region were affected negatively by a shortened ice-covered season and reduced sea ice extent through loss of spawning habitat and shelter, increased predatory pressure, reduced prey availability, and impaired growth and reproductive success (Kortsch et al., 2015; Dupont et al. 2024). The population size of the Atlantic cod is now strongly reduced and distribution retreated to "normal" areas. Still, this period of climate induced structural change over large spatial scales, leading to a borealization or 'Atlantification' of the European Arctic biological communities (Fossheim et al. 2015, Meredith et al. 2019, Årthun et al. 2025) may be taken as a forewarning of what will happen when more permanent climate change sets in (Fig. 16).

Figure 16. Alternative futures of Barents Sea fish with climate change (with OpenAI DALL· E 3).

It is yet difficult to distinguish between impacts of natural environmental variability, anthropogenic climate change, and other human pressures, like fishing, on the Barents Sea fish stocks. In the future, climate change will play a more dominant role, and fisheries will need to adjust to the prevailing situation (Skern-Mauritzen et al. 2016, Ottersen et al. 2025). The most significant ecological impacts from climate change on Barents Sea fish will, as many other places, be through higher sea temperatures. Temperature changes will decrease both ice cover and thickness, and affect mixed layer depth, in most cases decreasing it. This and other effects of temperature change will likely alter nutrient mixing and availability. Recent results by Sandø et al. (2024) show that future changes in mixed layer depth are a main driver for changes in NPP. Future changes in primary and secondary production will affect fish stocks, some negatively and some positively, and thus alter ecosystem dynamics in many ways. Following Sandø et al. (2024) projected increase in GSP in the Barents Sea might positively impact recruitment of boreal species like Atlantic cod and haddock and allow them to expand their distribution northwards and eastwards again.

The degree, and in some cases also the direction of change, is however, highly different not only between scenarios, which is to be expected, but more problematically also between different model approaches. While Sandø et al. (2024), as we just described, projected a positive development for Atlantic cod in a warmer ocean and Kjesbu et al. (2021) had similar results, the study by Nilsen et al. (2024) concluded differently. Their very recently published projections for the BS conducted with the NoBA Atlantis model are the first with an end-to-end model using downscaled regional physical forcing. The negative responses to warming in Atlantic cod and capelin and the unclear response of polar cod found in the NoBa Atlantis projections contrasts with the findings of Kjesbu et al. (2021) and Sandø et al. (2024). This highlights the complexity and uncertainty in present state-of-the-art long-term projections for higher trophic levels, like fish stocks.

Seabirds

Seabirds are typically at the top of the marine food web. Predicting the effects of climate variability on and through the different trophic levels is a major challenge, increasing in complexity at successively higher food web levels up to seabirds. As summarized in Ottersen et al. (2023) and reported earlier in this report for other areas, seabirds can be affected by changing climate both directly, for example if extreme weather becomes more frequent, or indirectly, through changes in their food supply. There is substantial literature pointing towards indirect effects most often being the more important of the two.

The islands around the Barents Sea (i.e., Svalbard, Franz Josef Land, and Novaya Zemlya) are the nesting places for large numbers of seabirds. Estimates of numbers are, naturally, somewhat uncertain, but likely about six million pairs from 36 seabird species breed regularly in the Barents Sea. Including also immature birds and non-breeders, the total number of seabirds in the area during spring and summer is about 20 million individuals. Note that although many species are present, 90% of the birds belong to only 5 species: Brünnich's guillemot, little auk, Atlantic puffin, northern fulmar and black-legged kittiwake (BarentsPortal 2020). The birds feed on different pelagic ecosystem components, including zooplankton and fish. Because seabirds typically depend on rather specific prey, they may be vulnerable to changes, and function as indicators for ecosystem status (Gerland et al. 2023).

Ramirez et al. (2017) find that interannual changes in phenology, the seasonal patterns of marine productivity, may have a cascading effect on seabirds around Svalbard. In particular, they showed that increasing temporal lag between sea-ice melting, i.e. the physical process driving the annual bloom of sea ice algae, and the bloom of pelagic phytoplankton resulted in rapidly decreasing breeding performance for little auks and Brünnich's guillemots, two of the most important and abundant species in the Barents Sea region. The timing of these two productivity pulses is considered as an essential driver of recruitment, and hence abundance. The advancement in ice breakup may result in an earlier onset of the pelagic phytoplankton bloom. This may negatively impact the seabirds both through reducing food abundance/availability and by causing a temporal mismatch between seasonal patterns in food availability and their reproductive requirements (Ramirez et al. 2017).

While the abundance of black-legged kittiwakes remains stable in most of the monitored colonies on Bjørnøya and Spitsbergen, it is declining rapidly in mainland Norway. Since 2021 they are classified as Endangered (mainland) and Near threatened (Svalbard) on the Norwegian Red List. The causes of changes in kittiwake populations are not fully known, but similar changes in populations across larger geographical areas suggest there are coinciding causal patterns. These are likely linked to changes in food availability, which are mainly related to climate, in particular changes in ocean temperature. Generally, with increasing sea temperatures and declining sea ice coverage a northward shift in Barents Sea seabird distribution is expected. This is substantiated by clear such trends for numerous species from 2009–2019 (Miljøstatus 2024).

Nilsen et al. (2024), studying future scenarios, did not focus much on seabirds, but their results for the Arctic seabirds group in the Nordic and Barents Seas as a whole point towards a rather clear negative response to warming (Fig. 15).

Marine mammals

Arctic marine mammals are large, warm-blooded and highly mobile animals that are adapted to experience significant variation in their environments. They have physiological capacities that make them quite robust to direct effects of climate change (Haug et al. 2017). Still, predicted reductions in sea ice are likely to affect seals and walruses negatively, in particular by directly reducing or removing their established breeding habitats and more indirectly by shifting the general location and timing of lower trophic level productivity (Kovacs and Lydersen 2008, Haug et al 2017).

The warming observed in the Barents Sea ca 2004–2012 had negative impact on several particularly sensitive seal species (Eriksen et al. 2021, also reported in Ottersen et al. 2023). Less ice and poorer ice quality can lead to a further decline in the populations of Greenland- and hooded seals (Eriksen et al. 2021) as well as ringed seals (Stenson et al. 2020). After the drastic changes in ice conditions that started in 2006, which could be termed a "tipping point", the behaviour of ringed seals around Svalbard has changed a great deal. This applies to both those who migrate out and those who remain close to the coast. They now spend much more time diving and less for resting; everything indicates they are working harder to find food (Hamilton et al. 2015). Further, ice retraction from the shallow (100–350 m) shelf to the deep polar basin reduces access to bottom-associated prey species for harp seals (Haug et al. 2021) and walrus (Gerland et al. 2023). Further ahead, fertility rates, mortality rates, foraging success, and pup survival may be negatively affected for several populations of endemic Arctic marine mammals (Hamilton et al. 2015; Gerland et al. 2023).

Seals, both hooded, harp, bearded, and ringed, are projected to respond negatively to higher temperatures, thus more pronounced decline under SSP5-8.5 compared to SSP2-4.5 and especially to SSP1-2.6 is expected (Fig. 15; Nilsen et al 2024). This is directly linked to temperatures exceeding tolerated levels. However, marine mammals that depend on sea ice, especially several seal species, are also expected to decline due to habitat loss. Sea ice is important also for Polar bears in the region, still no clear response to future warming was found by Nilsen et al (2024).

The effects of warming are more uncertain for most whale species. This was stated already by Kovacs and Lydersen (2008) and clearly illustrated by Nilsen et al (2024) where all the five whale species are grouped under "No clear response" (Fig. 15). However, when projecting changes in projected core habitat for bowhead whales, Chambault et al. (2022) generally project losses over the eastern distribution region north of Svalbard to Franz Joseph Land. Between the present and 2100, their models project a significant contraction in habitat, with the most marked habitat loss suggested under scenario SSP5-8.5 (Fig. 17). The bowheads are projected to lose most of their current eastern habitat under the SSP5-8.5 scenario, while under SSP1-2.6 projections show some new habitat becoming available in the northeast (Chambault et al. 2022).

Eriksen et al. (2021) point to challenges during the early 21st century warming for beluga whales due to reduced sea ice, to bowhead whales owing to increased sea temperature and reduction in ice extent and to narwhals related to both their specialised deep-diving eating behaviour, ice dependence, and already limited distribution area.

Further, temperate whale species, including minke whales, are showing northward expansions of their ranges, which is likely to cause competition with endemic Arctic species, as well as increasing their risk of predation and diseases. Also, whale species endemic to the Arctic may face increasing competition from intensified use of (sub)Arctic habitats by seasonally migrant species, like large baleen whales (Moore and Huntington 2008, Haug et al. 2017).

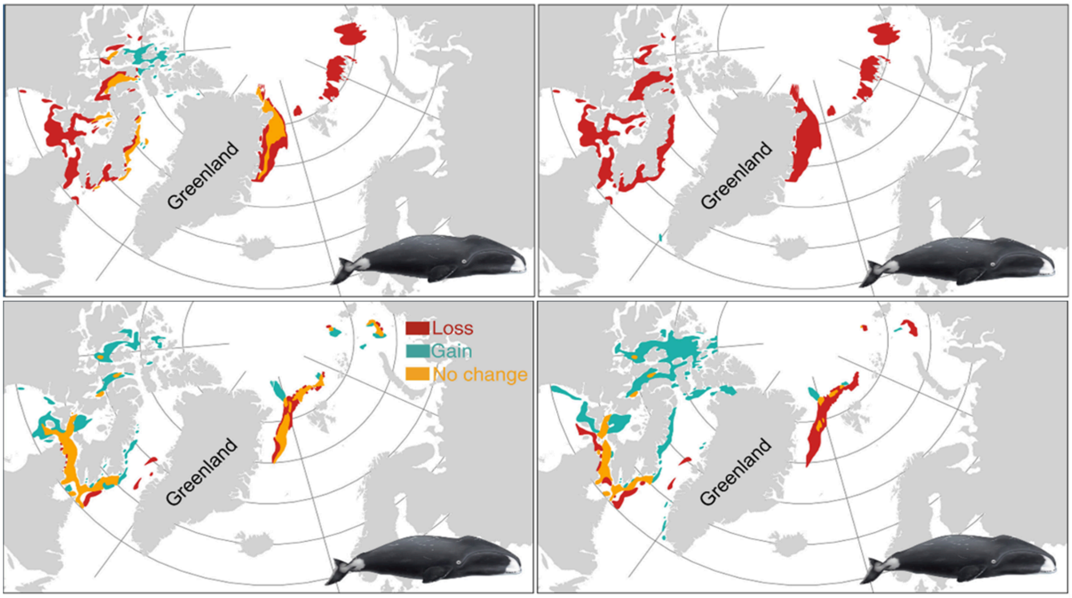


Figure 17. Changes in projected summer (upper panels) and winter (lower panels) core habitats (probabilities >0.5) by the year 2100 for Bowhead whales for the scenarios SSP1-2.6 (left) and SSP5-8.5 (right). Areas with projected losses by 2100 in red, areas expected to remain unchanged in orange, and areas with projected increases in habitat in green. Adapted from Chambault et al. 2022. Bowhead whale illustration by Uko Gorter.

Holistic ecosystem considerations

The physical changes expected in the Barents Sea are among the globally most significant. Consequently, substantial ecosystem changes are expected to arise. During the warming period from ca 2004–2012 major shifts took place, with the Atlantic fish community from the southern BS (mainly Atlantic cod and haddock) expanding towards northeast at the cost of the resident local Arctic species. A similar ecosystem change occurred for benthic populations. There was a shift northward in the amount of benthic animals and temperate benthic communities. For example, changes in benthic biodiversity was seen in the Svalbard area, again an increase in boreal and withdrawal of Arctic species. With persistent future warming such changes may become permanent in both benthic and pelagic ecosystems, for boreal fish also related to projected increase in zooplankton production (Sandø et al. 2024, Ottersen et al. 2025).

The most significant ecological impacts from climate change in the Barents Sea (as many other places) are through higher sea temperatures. Rising temperatures will reduce ice cover, thickness, and typically decrease mixed layer depth. This and other effects of temperature change will likely alter nutrient mixing and availability. In the

Barents Sea, new results from the NorScen project show that change in mixed layer depth is a main driver for changes in NPP (Ottersen et al. 2025). Such changes in NPP will propagate upwards in the food web, influencing zooplankton and fish stocks. Some species and populations will be negatively affected and some positively, the ecosystem dynamics will thus be altered in many ways (Sandø et al. 2024, Nilsen et al 2024, Ottersen et al. 2025). Note that the degree, and in some cases also the direction, of change for the various species, is highly different between scenarios up to 2100.

With temperature increase, Marine heat waves (MHWs) are generally expected to become more frequent, longer lasting, and more intense. Relatively little work has been done on MHWs in the Barents sea area, but recent and ongoing research points to increasing number and severity of both surface and near-bottom events over large parts of the region (Mohamed et al 2022, Ottersen et al. 2025, S. Gonzalez, IMR work in progress). Such abrupt events may sweep through the ecosystem, causing non-linear effects that are difficult to predict or project. Although writing on the Arctic region more as a whole, the conclusions of Gou et al. (2025) are highly relevant also for the Barents Sea. They underline that the extreme temperature variations and increased stratification associated with MHWs will pose substantial challenges for Arctic ecosystems. These changes may adversely affect food webs both through direct temperature effects on physiology and indirectly by influencing nutrient supply and causing shifts in species taxonomy (Gou et al. 2025).

As high-level predators, seabird populations depend upon lower trophic levels in the ecosystem and have in high-latitude regions like the Barents Sea, evolved to fit production cycles. Climate change thus poses a particular threat to seabirds since it can disrupt the critical timing between when they need to feed and when their food sources are available (match becomes mismatch). As a result, the well-being and even survival of a seabird populations will depend heavily on the locations and timing of fish spawning, as well as the abundance of zooplankton.

Projections recently conducted with the NoBA Atlantis model are the first with an end-to-end ecosystem model using downscaled regional physical forcing (Nilsen et al. 2024). It should be noted that the negative response in cod and capelin and the unclear response of the polar cod found in the NoBa Atlantis projections by Nilsen et al. (2024) contrast with the findings in the other expert-based studies on the region (Kjesbu et al. 2021, Sandø et al. 2024). This highlights the complexity and uncertainty in long-term projections for higher trophic levels, which depend on developments in other parts of the ecosystem.

A key message from the recent extensive review by Årthun et al. (2025) is that the inter-scenario differences first become substantial late in the century. Mitigation is of great consequence for the long-term development of the ecosystems, but if most of the changes projected for 2050 are already locked in due to the inertia of the earth-ocean system, adaptation should also be an important part of management (Årthun et al. 2025). While this is written for the Barents Sea, it is likely a general conclusion and recommendation.

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What are the largest climate change related threats to marine ecosystems in the Nordic region – views from policy makers and managers

We here map which impacts from climate change policy makers and managers in the environmental sector from Nordic countries consider to be the largest treats for marine ecosystems in the region. This is in fulfilment of NorMECC's Subgoal 2 (Deliverable 4 and 5). The overview is based upon direct communication with selected policy makers and managers underpinned by additional information from relevant recent marine ecosystem management plans from Nordic countries. We did not conduct a formal survey, and no statistical or other quantitative analysis was conducted. Still, our clear impression is that the opinions given are representative. We consider the findings to be highly relevant towards the main goal of this report and the NorMECC project, i.e., to obtain and make available a good overview of observed and expected impacts of climate change on a wide range of marine species in Nordic waters. While our results should provide guidance towards topics of priority, this should not be taken to imply that pressures not highlighted necessarily are of no importance in the future. Our findings in this part of the report are presented briefly, we do not explain underlying mechanisms or refer to supporting literature. Such information is provided in the first part of the report and in-depth in the scientific papers referred to there.

We divide our presentation into two: *Important pressures* (including very brief comments on effects) and *Means to further develop Nordic cooperation*.

Pressures considered to be of high importance

Climate change related pressures and challenges brought up as especially important are summarised in Table 5 and briefly described afterwards.

Table 5. Climate change related pressures and challenges brought up as especially important

Pressures and challenges	Region
Rising Sea Temperatures	All
More frequent and intense Marine Heat Waves	All, but impact perhaps most severe in the warmer parts of the Nordic sea areas
Retreating Sea ice	Barents Sea, northern part of Nordic Seas and the Baltic
Sea level rise	All, but highly varying impact. Specifically mentioned for Baltic regions.
Changes in freshwater runoff	Coastal areas in general, Baltic
Browning (increase in dissolved organic matter)	Coastal areas
Eutrophication	Especially the Baltic, but also southern North Sea and some coastal areas
Oxygen depletion	Baltic, locally in other regions (like in some fjords)
Harmful algal blooms	All, but especially mentioned for the Baltic
Biodiversity loss	Especially northern Barents Sea and Baltic

Rising Sea Temperatures

This pressure is brought up by "everyone" and "everywhere" and is undoubtedly considered to be among the most important impacts of climate change on marine species and ecosystems in the Nordic region. Warming is affecting and will further affect all regions, although both mechanisms and consequences differ. For instance, rise in the mean sea surface temperatures have been consistently observed in the Baltic over recent decades. Both surface and deeper water layers are showing warming. Overall, the Baltic Sea is warming faster than the global oceans. In the Norwegian and Barents seas the temperatures have fluctuated, but the warm period ca 2004–2012 had significant ecosystem impact, with expanding distributions of mackerel and cod.

Marine Heatwaves

Marine heatwaves are becoming more frequent throughout the Nordic region. In Norwegian waters the greatest concern for these effects is so far in southerly areas, e.g. linked to kelp forests being heavily impacted and reduced since the 1990s. In Norway there have also been warm-water episodes that have been detrimental to salmon farming, both in the south and in the summer of 2024 when salmon lice for the first time became a severe issue far north. Also in the Baltic MHWs now occur more often. In response and preparedness, The Finnish Meteorological Institute (FMI) provide an indicator to track marine heatwaves in the Finnish coastal areas (FMI Ocean Indicator).

Decreasing sea ice

The largest overall decrease and most striking pictures are from the high Arctic circumpolarly, including the northern Barents Sea and the area around Svalbard. However, the sea extent, thickness and length of ice season have over recent decades decreased also in the Baltic Sea. The ice winters there are becoming milder, and the probability of severe ice winters has decreased. The average length of the ice winter is projected to shorten 6 days per decade in the Bothnian Bay during this century based on RCP4.5 scenarios.

Sea Level Rise

In this context Sea level rise (SLR) was pointed to as an issue relevant for the Baltic. It is of course a global problem, but with geographically different magnitude and consequence. The effects of SLR will increase with time, more so in the case of weak greenhouse gas release mitigation. The impacts om marine life will naturally be most pronounced close to shore. The Nordic region is still "recovering" from the last ice age, causing differentiated rates of sea level vs land uplift. The Baltic Sea was covered by more ice than the Oslo area, which in turn had more ice than western Norway. Thus, for instance along the Finnish coast the land uplift still protects the coast from eustatic sea level rise. However, in the future the effects will not be sufficient to fully compensate the sea level rise. On the Gulf of Bothnia coast, the decreasing trend in the relative mean sea level will slow down. Still, from present until 2100 RCP4.5 scenarios show 20 – 30 cm ***decrease*** in the relative mean sea level in the Bothnian Bay and 20 – 30 cm ***increase*** in the Gulf of Finland. Similarly, the estimated sea level rise for the period from 1986–2005 to 2100 under the RCP4.5 scenario is estimated to be 38 cm in Stavanger on the SW coast of Norway, but 0 in Oslo.

Eutrophication and biogeochemical changes challenge biodiversity and ecosystems

Although reported to be of concern also in southern Norwegian sea areas and fjord systems, eutrophication "over fertilising" is particularly problematic in the Baltic Sea. Here eutrophication and climate change are often stated to be the worst problems, which in turn exacerbate other phenomena, such as changes in biogeochemistry including oxygen levels. Land-use activities such as agriculture and forestry practices are considered to be the biggest culprits.

Human land-use practices are challenging and will further challenge biodiversity especially coastally. In addition to eutrophication, coastal browning and changes in freshwater runoff (e.g., with more intense rainstorms) were mentioned as important. Profound effects are observed and expected on marine life in, e.g., southern Norwegian sea areas and fjord systems where especially the Oslofjord is impacted by runoff and wastewater from a large catchment area.

Trophic mismatch and ecosystem disruption

Climate change may cause mismatch between phytoplankton, zooplankton and fish production. Effects in this category occur in, e.g., Norwegian waters and could be expected to intensify, following a too heavy burden from cumulative impacts. Mismatch in time between young stages of fish and their zooplankton prey e.g. affect seabird populations through lack of food in critical stages of especially the breeding season, when the populations are confined to search for food in areas reachable from the breeding colonies.

Impacts on industries and society

Some effects of climate change on marine species are expected to propagate to industries and society. There are both direct and indirect effects. Fisheries would be expected to be the most heavily affected, due to the dependence on sustainable harvesting from the natural production of wild-living stocks of fish, crustaceans and molluscs. Without measures counteracting ecosystem impacts and stress, and increasing ecosystem resilience and robustness, yields from harvesting may become increasingly uncertain over time. For example, in Finnish waters fisheries are affected by adverse environmental states and economically less valuable fish increasing in abundance at the cost of other more appreciated species. In Limfjorden, the most productive area for both mussel fishery (bottom) and aquaculture (suspended cultures) in Denmark, major changes are expected. In particular due to decreases in bottom oxygen, wild mussels will suffer – more so under the more severe climate change scenarios. On the other hand, harvest of farmed mussels (in the water column) is expected to increase significantly in all scenarios. The degree of nutrient regulation through a Water Management plan also is of high importance. Tourism and recreational activities like swimming or spending time by the sea is/will likely be negatively affected by algal blooms and other non-pleasing environmental conditions. Generally, it was pointed to that legislation, permits for activities and more will affect the development.

Means to further develop Nordic cooperation across national borders to sustainably solve common environmental challenges

This section is a follow-up to questions to a panel debate at the final conference of the Nordic Council of Ministers Vision Project *Marine Management and Climate* in Gothenburg, November 2024.

To enhance the foundation for successful internation cooperation, it is important to establish a platform where all necessary data is accessible to relevant countries, so well-balanced decisions between harvesting and conservation can be made. Furthermore, enhancing public awareness both locally and nationally is significant, so that both threats and solutions to the impacts on the ocean is made clear. It is about getting people aware and involved.

Marine Protected Areas

The importance of marine protected areas (MPAs) was highlighted by respondents. It was said that by including MPAs more actively into marine management, one would provide for safeguarding of important ecological functions and resilient ecosystems. When designating MPAs, it is important to account also for the ongoing alterations in the environment and ecosystems due to climate change, ensuring that these MPAs are resilient to anticipated impacts. While the development of MPAs has come quite far in the Nordic region, this latter aspect still seems to be considered only to little degree. There are, however, processes moving in this direction in some countries (Finland was mentioned). In parallel to developing MPAs, one should identify what areas are available to fisheries and other industries – promoting stronger predictability for both the sustained delivery of ecosystem services and the industries' activity and long-term value creation.

Environmental managers further argued that more coordinated work should be done towards establishing cross-border MPAs in shared Nordic waters. In theory at least, larger, strictly protected areas could enable habitats to be more resilient to climate change. Cross-national MPAs would demand good practices for exchanging relevant information between countries. To enhance this, and in support of well-founded decisions for appointing an MPA, a platform, like that mentioned above, should include all necessary information/data for selection of MPA areas. Further, common management plans for larger cross-border MPAs should be developed. It was underlined that there already exist international bodies working on conservation planning, like HELCOM in the Baltic. Still, it was suggested that a (new or existing) body could operate on a more holistic and cross-border level and have a larger mandate to make decisions. Ultimately, a network of MPAs could be established in Nordic waters, including MPAs that cross national boundaries where it makes sense in an environment and ecosystem conservation context.

Sustainable use and conservation of marine ecosystems

Collaboration between managers and scientists was proposed as an important measure in future ocean management to maintain and improve environmental conditions while facilitating value creation in Nordic marine areas. Such collaboration can enhance the understanding of the challenges there are on both sides. However, from a conservation point of view far stronger measures are likely needed. One respondent stated that (s)he is in favour of "nature first", implying strict limitation of human activities. We should at least safeguard some sort of "baseline" before even considering economic activities. Following this reasoning, for something to be sustainably utilised, the resource should first exist on a sustainable level, i.e., conservation comes before economic exploitation, and the exploitation is directed at the "surplus" beyond the sustainable level. Although the respondent sees the need for a reasonable balance, to account for e.g., livelihoods, (s)he argues that with climate change, biodiversity loss, and more the above is additionally important.

Restoration

The Convention on Biological Diversity emphasized at COP16 the connection between climate (change) and nature (degradation). There should be little doubt that enabling climate change adaptation is highly relevant for nature conservation. Within this complex a relevant question, asked at the Gothenburg conference, is if restoration of ecosystems can help us strengthen marine nature's resilience to climate change. Our conservation-oriented responded does not disagree but sees restoration as a last resort. Deteriorating ecosystems to the degree of requiring restoration should be avoided, as restoration can be very costly, compared to not deteriorating it in the first place. Moreover, restoring single ecosystem features or ensembles has a limited ability to mitigate climate change (as they are relatively small-scale compared to human activity), and first and foremost human activity should be limited. On a more local level, perhaps a restored habitat may function as a sort of refuge for species, but the benefits will likely be offset by human activities either elsewhere or at least on a larger scale.

However, another respondent sees restoration of ecosystems in a more positive light (the apparent disagreement may be related to scale considered). Following this respondent, restoration could be expected to improve marine nature's resilience against climate change – and to give good long-term results. Giving space and time for processes like natural rewilding would be an important approach in this respect.

About this publication

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