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REVIEW

The future Barents Sea—A synthesis of physical, biogeochemical, and ecological changes toward 2050 and 2100

Marius Årthun[1,*], Khuong V. Dinh[2], Jakob Dörr[1], Nicolas Dupont[3], Filippa Fransner[1], Ina Nilsen[4], Paul E. Renaud[5], Morten D. Skogen[4], Philipp Assmy[6], Melissa Chierici[7], Pedro Duarte[6], Agneta Fransson[6], Cecilie Hansen[4], Marcela C. Nascimento[8], Torstein Pedersen[9], Lars H. Smedsrud[1], Øystein Varpe[10,11], and Frida Cnossen[9]

The Barents Sea is a hotspot for ongoing Arctic climate change, manifested in a rapid warming of the ocean and the atmosphere and a strong decline of the winter sea-ice cover. These changes in the physical environment have large consequences for marine ecosystems, including commercial fish populations. In a warmer future climate, both physical and ecological changes are expected to intensify. Here, we provide a first comprehensive overview of future climate change projections for the Barents Sea, and the associated physical, biogeochemical, and ecological consequences based on climate models and end-to-end ecosystem models. We also discuss potential future changes in human activities and their impacts, including changes in shipping activity and contaminants. We analyze results for two time horizons—the near-future (2040–2050) and the far-future (2090–2100)—and for two different emission scenarios: one with moderate future greenhouse gas emissions (SSP2-4.5) and one high-emission scenario (SSP5-8.5). The projections show that the future Barents Sea will be warmer, less ice-covered, more acidic, and more productive, with fish populations and spawning sites moving northward. There are small differences in multi-model mean physical and biogeochemical projections between the two emission scenarios by 2050, while large scenario differences emerge toward the end of the century. The implications of these results are far-reaching, including identifying the sensitivity of ecosystem change to future emissions, informing regional management strategies, and potentially identifying needs for adaptation to changes already likely to occur.

Keywords: Barents Sea, Climate change, Physical environment, Biogeochemistry, Ecological changes, Human impacts

1. Introduction

Nowhere is climate change more evident than in the Arctic with an unprecedented loss of sea ice (Landrum and Holland, 2020) and a warming of nearly four times the global rate (Rantanen et al., 2022), that is, an Arctic amplification of climate change (Cohen et al., 2020). Climate change in the Arctic Ocean is not uniform but is more pronounced in the Barents Sea (**Figure 1**), a region experiencing the strongest decline in winter sea ice (Onarheim et al., 2018), amplified acidification (Ericson et al., 2023), and the most rapid surface warming in the entire Arctic Ocean (Isaksen et al., 2022; Shu et al., 2022; Steiner and Reader, 2024). The transition of the cold (Arctic) northern Barents Sea to a state more closely resembling that of the warm (Atlantic) southern Barents Sea, termed an "Atlantification" of the Barents Sea, has

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[1] Geophysical Institute, University of Bergen, and Bjerknes Centre for Climate Research, Bergen, Norway

[2] Section for Aquatic Biology and Toxicology, Department of Biosciences, University of Oslo, Oslo, Norway

[3] Centre for Ecological and Evolutionary Synthesis, Department of Biosciences, University of Oslo, Oslo, Norway

[4] Institute of Marine Research, Bergen, Norway

[5] Akvaplan-niva, Fram Centre for Climate and the Environment, Tromsø, Norway

[6] Norwegian Polar Institute, Fram Centre, Tromsø, Norway

[7] Institute of Marine Research, Fram Centre, Tromsø, Norway

[8] GEOMAR Helmholtz Centre for Ocean Research Kiel, Marine Evolutionary Ecology Research Division, Kiel, Germany

[9] Department of Arctic and Marine Sciences, Faculty of Biosciences, Fisheries and Economics, UiT The Arctic University of Norway, Norway

[10] Department of Biological Sciences, University of Bergen, and Bjerknes Centre for Climate Research, Bergen, Norway

[11] Norwegian Institute for Nature Research, Bergen, Norway

* Corresponding author:
Email: marius.arthun@uib.no

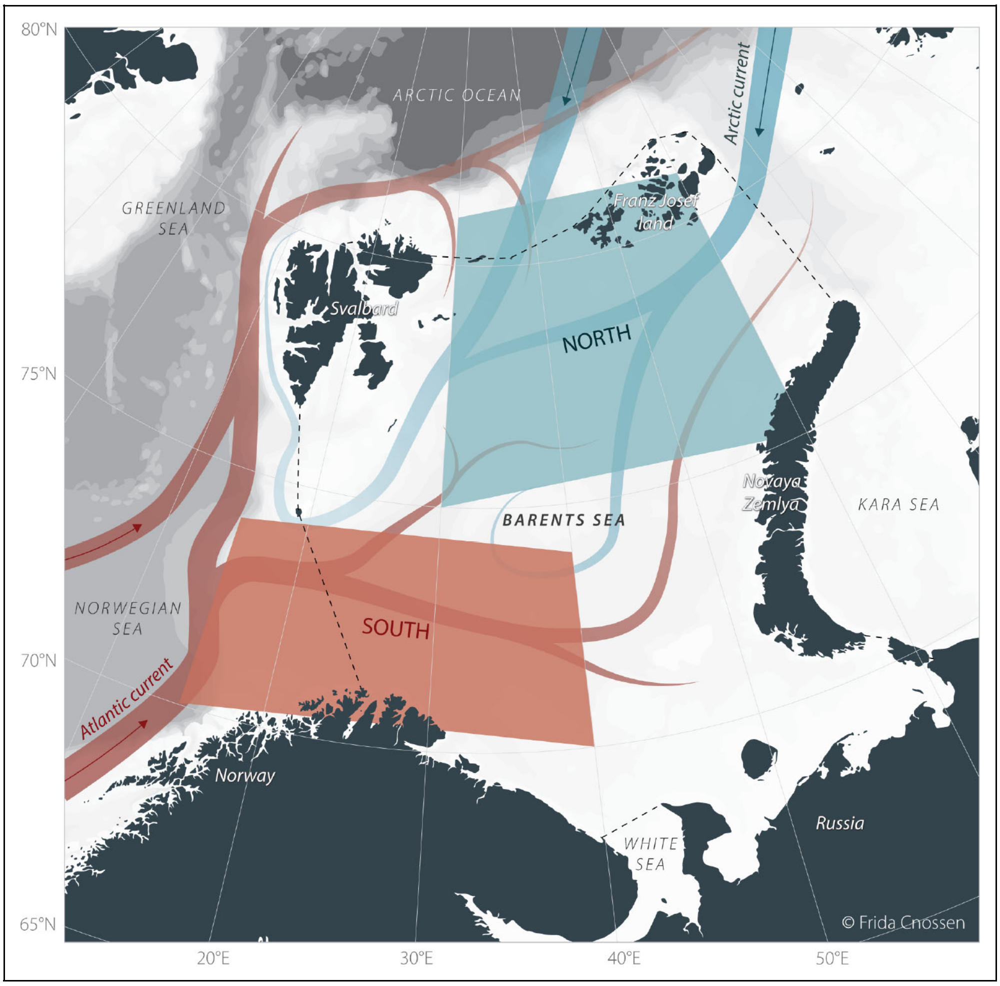

Figure 1. Schematic ocean circulation in the Barents Sea region. The circulation of warm Atlantic waters is indicated by red arrows and cold Arctic waters are indicated by blue arrows. The boxes used to define the southern and northern Barents Sea (see "Data and methods") are also shown.

wide-ranging effects on marine ecosystems (Wassmann et al., 2011; Fossheim et al., 2015; Ingvaldsen et al., 2021; Gerland et al., 2023) and human activities (Smith and Stephenson, 2013; Stocker et al., 2020). Warmer, ice-free conditions lead to the northward expansion of boreal species, a process referred to as "borealization" (Fossheim et al., 2015; Polyakov et al., 2020). As a consequence of borealization and a longer ice-free season, the Barents Sea ecosystem is also under increasing anthropogenic impact from shipping, fishing, and oil exploration, leading to more artificial light, noise, and pollutants (Smith and Stephenson, 2013; Berge et al., 2020; Hansen et al., 2022).

Several comprehensive reviews have described recent changes and the current status of the Barents Sea in terms of physical, biological, and human/social parameters (e.g., Smedsrud et al., 2013; Ingvaldsen et al., 2021; Gerland et al., 2023). A review of future ecosystem status, from physical and chemical drivers to population changes and biological processes, is, however, still lacking. As the Barents Sea is currently the hotspot of Arctic warming and supports critical fisheries and other ecosystem services, a comprehensive overview of future changes in the Barents Sea is important to understand the future Arctic Ocean.

Here, we provide the first integrated assessment of the future Barents Sea based on quantitative projections from CMIP6 climate models, end-to-end ecosystem models, and statistical models of ecological processes. We present these projections for both 2050 and 2100, exploring the consequences of different emissions scenarios. We combine model results with large experimental and observational data to produce the most comprehensive projections of ecosystem changes within the context of developing human activities. These results detailing the timing and character of physical and biological changes in the Barents Sea are important to guide both future research and monitoring priorities and to enable strategic decision-making for adapting to and mitigating change where possible.

2. Data and methods

2.1. CMIP6 models

To assess physical and biogeochemical changes in the future Barents Sea, we turned to projections from the Coupled Model Intercomparison Project, phase 6 (CMIP; Eyring et al., 2016). For CMIP6, nine different Shared Socioeconomic Pathway (SSP) scenarios were designed (Gidden et al., 2019), spanning radiative forcings of 1.9 W m^{-2} to 8.5 W m^{-2} in 2100. In climate change studies (e.g., Kwiatkowski et al., 2020; Khosravi et al., 2022), using one high-emission scenario together with one low- or medium-emission scenario is common to span the scenario uncertainty. In this study, we considered both a medium-emissions scenario, SSP2-4.5, where the global temperature rises to approximately 2.7°C above pre-industrial levels, and a high-emissions scenario, SSP5-8.5, where the temperature rises to approximately 4.4°C above pre-industrial levels (Masson-Delmotte et al., 2021). For both the physical and the biogeochemical variables, we selected models based on the availability of all required variables for the historical and the two future scenarios. The selection yielded a total of 25 models for the physical variables and 10 models for the biogeochemical variables (Table S1). For each model, we included only the first ensemble member available, as to not give too much weight to individual models. Some modeling centers, however, are represented with more than one model (e.g., low- and high-resolution model versions).

We analyzed changes in the annual mean sea-ice concentration (variable *siconc/siconca*), sea-surface temperature (*tos*), surface air temperature (*tas*), mixed-layer depth (*mlotst*), downwelling shortwave radiation (*rsntds*), vertically integrated primary production (*intpp*), nitrate (*no3*), phosphate (*po4*), and CO_2 fluxes (*fgco2*). We additionally calculated the changes in aragonite saturation and pH with the CO_2 chemistry calculator CO2SYS (Lewis and Wallace, 1998) by using monthly output of dissolved inorganic carbon (DIC; *dissic*), total alkalinity (*talk*), temperature (*thetao*), and salinity (*so*). The direct effect of changes in phosphate and silicate concentration on the carbonate system is of minor importance and lower than the detection limit for alkalinity and DIC (Chierici and Fransson, 2009), and they are therefore assumed to be constant (5 μmol l^{-1} and 1 μmol l^{-1}, respectively; Fransner et al., 2020). The pH and aragonite saturation were calculated in each grid cell before making area averages.

Because projected changes are different between the ice-covered northern and the already ice-free southern Barents Sea (Shu et al., 2021), we split the Barents Sea into a northern (75–81°N, 30–60°E) and a southern (70–74°N, 15–40°E) part (**Figure 1**). Water-column averages are based on 0–500 m to exclude waters off the continental shelf in the southwest (the average depth of the Barents Sea is 230 m). To compute future changes by 2050, we first created multi-model averages for the two sub-regions, and then calculated the difference between the 2040s (2040–2049) and a 30-year reference period (climatology; 1980–2009). Likewise, to compute changes by 2100, we computed the difference between 2090s and the reference period. The CMIP6 results presented in this article are based on the multi-model averages. Time series of individual models are shown in Figures S1–S3.

CMIP6 models have been extensively used and evaluated for the Arctic Ocean and the Barents Sea (Khosravi et al., 2022; Wang et al., 2022; Heuzé et al., 2023), and the aim of this study is not to assess model skill. We do, however, provide a comparison between the CMIP6 models and available observations and data from the ERA5 reanalysis in Figures S1, S2, and S5. As also pointed out by Shu et al. (2022), the CMIP6 multi-model mean atmospheric and oceanic temperatures and sea-ice cover are close to observations. Changes in ocean heat transport into the Barents Sea from ocean reanalysis products are also largely reproduced in the CMIP6 multi-model mean (Shu et al., 2022). There is, however, a large spread between the different models for both physical and biogeochemical variables (Figures S1 and S2). This intermodel spread can be attributed to both different natural variability and model uncertainties and biases (Vancoppenolle et al., 2013; Årthun et al., 2021; Bonan et al., 2021; Tagliabue et al., 2021). The projection uncertainty associated with model biases can potentially be reduced by a subselection or weighting of models based on their agreement with observations (e.g., Knutti et al., 2017) or by an emergent constraint approach that relates statistical relationships in the present climate to future changes (e.g., Boé et al., 2009). Such methods are beyond the scope of this article.

2.2. Ecosystem models

Ecosystem projections presented in this article were made based on the results of the following ecosystem models: Norwegian Sea/Barents Sea Atlantis (NoBa Atlantis; Hansen et al., 2016; 2019) and the NORWegian ECOlogical Model system—end-to-end (NORWECOM.E2E; Skogen et al., 2018). Each ecosystem model provides projections toward 2050 and 2100 of the state of different ecological components under two different emission scenarios, SSP2-4.5 and SSP5-8.5, using downscaled projections of oceanographic conditions from the NEMO model. Each model considers different species or assemblages of species referred to as functional groups (based on species similarities in ecological characteristics like diet composition) for which they predict the development of biomass and abundance as a result of future physical conditions, for example, sea-ice cover and ocean temperature. NoBa Atlantis represents 53 different species and functional groups from lower trophic levels to marine mammals and also accounts for the effects of different types of fisheries. NORWECOM.E2E is more limited in its representation of species, representing two groups of primary producers, two groups of secondary producers, and individual-based models for a few selected species.

The two models also have different spatial resolutions. NORWECOM.E2E has relatively high resolution with a spatial representation equivalent to the resolution of the NEMO model (approximately 10 km), while NoBa has relatively low horizontal resolution, dividing the Nordic and Barents Seas into 60 different polygons. Further details about the different ecosystem models and their projections can be found in the respective papers listed above.

Our assessment of future ecological changes is largely based on these two models, and the uncertainty regarding the response of higher trophic level species to climate changes is therefore high. Both ecosystem models also use oceanographic input from the NEMO ocean model which has been shown to simulate larger Arctic climate change, including ocean heat transport and sea ice in the Barents Sea, than other models (Pan et al., 2023). The present ecosystem of the southern Barents Sea is, however, well sampled and understood (Eriksen et al., 2018). This understanding includes how the distribution and abundance of fish stocks change between warm and cold periods (Fossheim et al., 2015), which serves as a valuable benchmark for model projections.

3. The Barents Sea in 2050—A decided future

3.1. Changes in the physical environment

In a future with moderate greenhouse gas emissions (SSP2-4.5), ocean temperatures in the southern and northern Barents Sea are, respectively, 2.1 ± 1.2°C (±1 standard deviation, $n = 20$) and 2.8 ± 1.7°C higher in 2050 than during the recent decades (1980–2009), whereas the atmosphere has warmed by 2.8 ± 1.5°C and 6.2 ± 3.0°C in the southern and northern parts, respectively (**Figure 2**). The warming will result in generally year-round ice-free conditions, although some ice remains in the northern Barents Sea. A more extensive ice cover can also return intermittently during years with lower temperatures or more ice transport from the Arctic Ocean (Rieke et al., 2023). Higher surface temperatures in the southern Barents Sea lead to increased surface stratification (decreased mixed-layer depths; −17 ± 31 m). In contrast, mixed-layer depths increase in the northern Barents Sea (18 ± 22 m), consistent with enhanced surface heat loss and associated convection as a response to the retreating sea-ice cover (Skagseth et al., 2020; Shu et al., 2021). There is very little difference between the medium- and the high-emission scenarios in 2050 (Tables S2 and S3 and Figure S1). Scenario differences are also small if considering the low-emission scenario SSP1-2.6 (Davy and Outten, 2020).

A warmer, less ice-covered future Barents Sea is consistent with previous work based on various climate models and scenarios (Onarheim and Årthun, 2017; Årthun et al., 2021; Drinkwater et al., 2021; Shu et al., 2022; Steiner and Reader, 2024). The increased ocean temperatures also drive an enhanced ocean heat transport into the Barents Sea (Årthun et al., 2019; Dörr et al., 2021). The warming of the ocean extends to the bottom (approximately 2°C warmer in 2050 than 1979–2008) which, together with

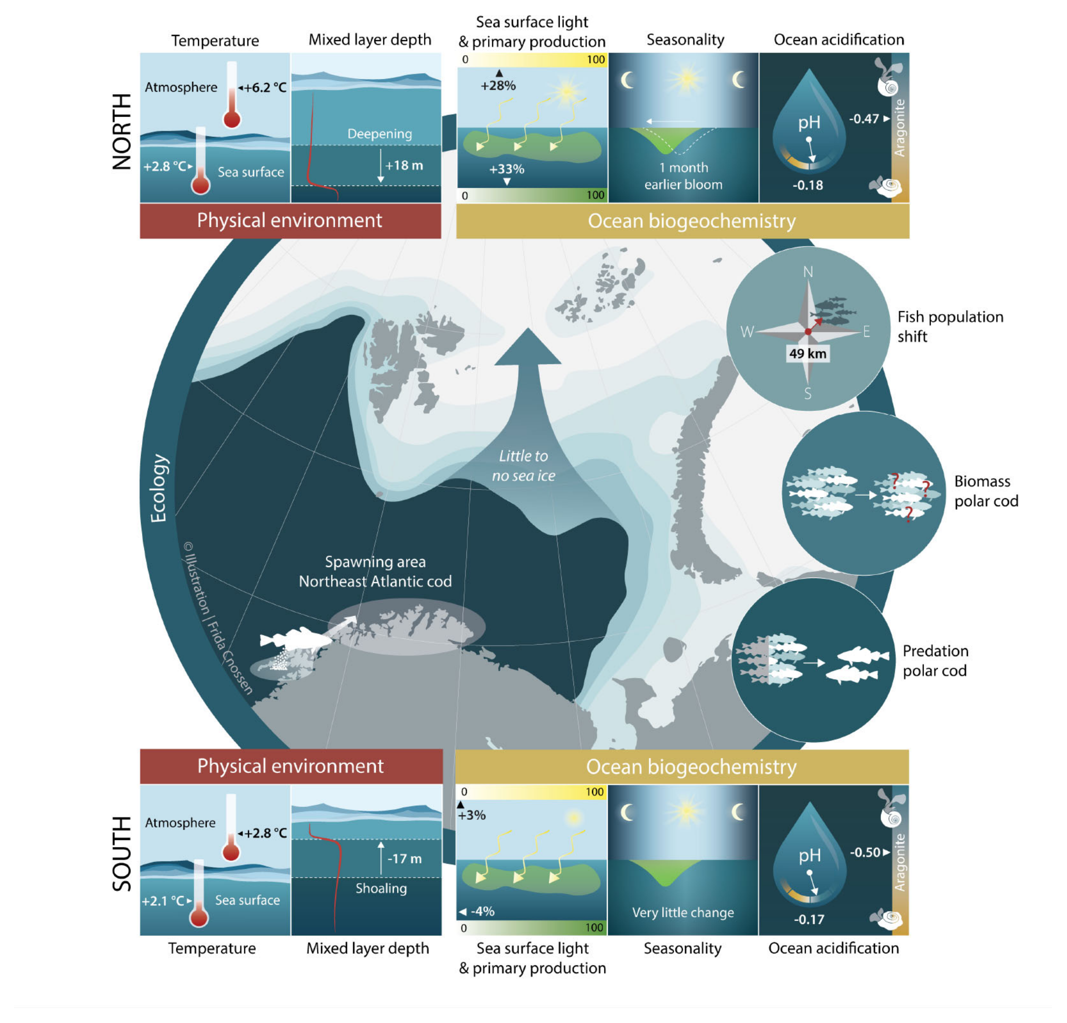

Figure 2. The Barents Sea in 2050. Future changes in the physical environment, ocean biogeochemistry, and ecology for the southern and northern Barents Sea in 2050 under the medium-emission scenario (SSP2-4.5). Numbers indicate changes relative to the period 1980–2009 based on multi-model averages. Changes are highly similar for the high-emission scenario (SSP5-8.5; Tables S2 and S3).

decreased salinities (−0.2), leads to lighter bottom waters exiting the northeastern Barents Sea (Shu et al., 2021). The dense bottom waters from the Barents Sea influence intermediate water masses in the Arctic Ocean (Schauer et al., 1997), and warmer, lighter bottom waters in the future could therefore impact the thermohaline circulation in the Arctic and North Atlantic Oceans.

3.2. Changes in ocean biogeochemistry

3.2.1. Primary production

By 2050, neither the SSP2-4.5 nor the SSP5-8.5 scenario project any pronounced change (−4%) in total integrated primary production in the southern Barents Sea (**Figures 2** and S2 and Table S2), nor in its seasonality (Figure S3). These results are in agreement with results from a regional model run under the RCP4.5 scenario (Sandø et al., 2022). This minor change in total primary production in the model ensemble suggests that the decreasing surface nutrient concentrations (Table S2) have a limited effect on the modeled phytoplankton dynamics. Reduced nutrient concentrations occur over the full water column, suggesting that there is a reduction in the horizontal supply of nutrients (e.g., Vancoppenolle et al., 2013). Surface nutrient concentrations can also decrease because of reduced vertical exchange of nutrients following an increased upper-ocean stratification (e.g., Vancoppenolle et al., 2013; Mousing et al., 2023). The limited effect of decreasing nutrients on primary productivity could be a result of (1) the modeled phytoplankton not being nutrient-limited in the region, or (2) changes in other factors, such as zooplankton grazing or light availability, that are opposing the effect of the decreasing nutrients. Indeed, in contrast to observations (e.g., Dalpadado et al., 2014), some models do not get nutrient-depleted in the summer (Figure S4), suggesting that changes in the nutrient concentrations could have a limited effect on the primary productivity. However, without output of phytoplankton limitation terms and zooplankton grazing, assessing the exact reasons behind the (small) future change in primary productivity in the southern Barents Sea is difficult.

In the northern Barents Sea, there is a 33% and 37% increase (**Figures 2** and S2 and Table S3) in primary production in the SSP2-4.5 and SSP5-8.5 scenarios, respectively, which is consistent with the sea-ice decline and the resulting increase in downwelling solar radiation. Similar effects of decreasing sea ice on primary production have been observed in the same region between 2003 and 2020 (Siwertsson et al., 2023). A simultaneous decline in surface nutrient concentrations is found in the CMIP6 ensemble. An increased primary production can result in an increased export of nutrients in organic matter to the deep water, which can lead to a decrease in the surface nutrient concentrations. However, as for the southern domain, the decline in nutrients occurs over the full water column, suggesting that a reduced horizontal supply plays a major role (Vancoppenolle et al., 2013). The earlier sea-ice break-up also leads to an earlier spring phytoplankton bloom (about a month; Figure S3), in agreement with contemporary pan-Arctic observations (Ji et al., 2013; Siwertsson et al., 2023) and regional projections by Sandø et al. (2022). Future phytoplankton blooms in the northern Barents Sea could thus become more similar in both amplitude and timing to those observed in ice-free areas of the southern Barents Sea (Ardyna et al., 2014; Dalpadado et al., 2020).

The CMIP6 multi-model mean change in total primary production in the northern Barents Sea is larger than that projected by a downscaled NorESM simulation (Sandø et al., 2022), although the decrease in sea-ice concentration is similar. Intermodel differences in nutrient availability have a large impact on the magnitude and sign of future changes in primary production in the Arctic Ocean and the Barents Sea (Mousing et al., 2023; Noh et al., 2023). This impact could partly explain the differences between the CMIP6 ensemble and the results of Sandø et al. (2022), as well as the intermodel spread.

3.2.2. Ocean acidification

A large part of the anthropogenic CO_2 emissions is taken up by the oceans, leading to a reduction in pH and calcium carbonate saturation toward 2050 (Figure S5). There are two types of calcium carbonate, aragonite and calcite. Here, we only analyze aragonite as it has a lower saturation state and is the first one to reach undersaturation (e.g., Fransner et al., 2022). In 2050, the pH in the southern Barents Sea is projected to drop from 8.15 to 7.98 and 7.93 in the SSP2-4.5 and SSP5-8.5 scenarios, respectively (**Figures 2** and S5 and Table S2). These drops correspond to a 47–66% increase in H^+ ion concentration. The whole region is expected to stay oversaturated in aragonite (mean aragonite saturation is estimated to decrease from 2.02 to 1.52 and 1.38, respectively). In the northern Barents Sea, pH is projected to drop from 8.16 to 7.98 and 7.94 (51% and 66% increase in H^+ concentration), respectively, and the aragonite saturation to drop from 1.74 to 1.27 and 1.14, respectively. Considering the volume of water in the southern and northern Barents Sea, the fraction of water undersaturated in aragonite is 1% and 13%, respectively. More open ocean caused by sea-ice loss facilitates enhanced ocean CO_2 uptake (Figure S5 and Table S3), which can speed the acidification (Qi et al., 2022; Ericson et al., 2023).

3.3. Ecological changes

3.3.1. Spatial distribution

Increasing ocean temperatures and decreasing sea-ice cover in the northern Barents Sea are associated with an expansion of boreal demersal species such as the Northeast Arctic (NEA) stock of Atlantic cod (*Gadus morhua*) (**Figure 2**). Arctic-boreal fish species, such as the pelagic capelin (*Mallotus villosus*), have also been predicted to follow the same northward expansion in response to a warmer climate (Huse and Ellingsen, 2008; Roderfeld et al., 2008; Fall et al., 2018). The projected changes in both direction and distance are in agreement with previous observations of changes in the spatial distribution of fish communities between cold and warm years in the Barents Sea (Nascimento et al., 2023). The projected changes in the distribution of boreal and Arctic-boreal species and the decreasing abundance of Arctic marine species suggest potential changes in species interactions (Pecuchet et al., 2020). For example, piscivorous predation is predicted to increase, replacing the strong predation on benthos, which is typical of an Arctic-species-dominated food web (Frainer et al., 2017; Pecuchet et al., 2020). With less sea ice and more light in the water column, increasing prey-detection capacity of fish may contribute to the northward shifts in sub-Arctic species (Varpe et al., 2015). However, for the northern Barents Sea, the polar night may limit the future northern extent of fish species dependent on visual search for prey detection (Langbehn and Varpe, 2017), despite an absence of sea ice.

3.3.2. Spawning areas

Climate change will also likely alter spawning-site selection and the performance of early life stages of fish. Based on the downscaled RCP4.5 scenario, Sandø et al. (2020) predicted a broad shift in spawning sites for NEA cod to the north and east, with localities near Murmansk along the Russian coast shortly after 2050 (**Figure 2**). The projections by Sandø et al. (2020) are based on ocean temperatures exceeding a critical value, and while there is good evidence that temperature is important in spawning-site selection (Langangen et al., 2019), geographical patterns in fishing mortality may also play a role (Opdal and Jørgensen, 2015). Successful spawning in more northern areas, however, may not assure equally successful recruitment in 2050 as we see now. Lower growth rates, exposing smaller larvae to higher predation for longer periods of time, and changes in prey supply may reduce survival of more northerly spawned NEA cod and induce higher interannual variability in early life stage survival (Endo et al., 2023). Clearly, there are many (changing) factors that will determine the success of NEA cod in new spawning areas. However, regardless of the success of eggs spawned along the Barents Sea coast, a shift in spawning area as substantial as that predicted will have considerable impacts on management policies, both for protection of spawning habitats and the likely conflicts with other economic interests in coastal northern Norway. Early studies on capelin suggested an eastward geographical shift of spawning areas and to utilize new spawning areas along Novaya Zemlya as a result of increasing sea temperature (Huse and Ellingsen, 2008). However, in a more recent study, Alrabeei et al. (2021) show that ocean temperature does not have a clear effect on the spatial distribution of capelin spawning areas. Similarly, spawning areas of polar cod (*Boreogadus saida*) are predicted to shift between years, where the importance of the southeastern spawning areas appears to be related to local sea-ice cover (Huserbråten et al., 2019). Although spatial changes in the spawning areas of capelin and polar cod may be expected as a result of foreseeable changes in oceanographic conditions, the details about the changes in their spatial distribution remain to be assessed, as well as the consequences for the species population dynamics (Huserbråten et al., 2019; Alrabeei et al., 2021; Aune et al., 2021).

3.3.3. Biomass

Based on results from the ecosystem models assessed here (NoBa Atlantis and NORWECOM.E2E), projected long-term changes in biomass of several marine populations or subpopulations in the Barents Sea are reported in **Table 1** (results from SSP5-8.5 considering the whole Barents Sea). In NORWECOM.E2E, mackerel (*Scomber scombrus*) and herring (*Clupea harengus*) are projected to increase, while NoBa Atlantis projects increased biomass of blue whiting (*Micromesistius poutassou*) and haddock (*Melanogrammus aeglefinus*). The latter is both a prey and potential competitor of NEA cod, and a future increase could potentially increase competition with NEA cod in the southern areas of the Barents Sea. For other species, however, there is disagreement in the direction of change. NEA cod and capelin are the most striking, as climate warming is anticipated to have both positive and negative impacts on population sizes, depending on the model employed.

Both statistical models and expert opinions in combination with outputs from the NORWECOM.E2E model project a decrease in polar cod populations in the Barents Sea in scenarios with reduced winter sea-ice cover and increased ocean temperature (Gjøsæter, 1998; Dupont et al., 2021; Kjesbu et al., 2022; Geoffroy et al., 2023; **Figure 2**). The NoBa Atlantis ecosystem model projects a small decrease (5% decrease in both biomass and abundance) by 2050 based on both SSP2-4.5 and SSP5-8.5 emission scenarios (Nilsen, 2023). A strong component of the decrease comes from reduced survival of early life stages due to the detrimental effects of high temperatures (Drost et al., 2016; Laurel et al., 2016; Huserbråten et al., 2019; Dupont et al., 2021). In addition, decreasing sea-ice cover may influence the availability of early sympagic food sources as well as increasing exposure of young individuals to predators (Hop and Gjøsæter, 2013). Increased predation related to borealization and extension of large fish predators into the northern Barents Sea may also play a role in the decrease of polar cod abundance by

Table 1. Projected changes for the whole Barents Sea by 2050 in total biomass for major Barents Sea fish stocks based on the high-emission scenario SSP5-8.5

Fish Stock	NORWECOM.E2E[a]	NoBa Atlantis[b]
Blue whiting	Not evaluated	Increase
Haddock	Not evaluated	Increase
Northern shrimp	Not evaluated	Increase
NEA cod	Increase	Decrease
Capelin	Increase	Decrease
Mackerel	Increase	No clear response
Herring	Increase	No clear response
Saithe	Not evaluated	No clear response
Polar cod	Decrease	No clear response

[a] Results from Sandø et al. (2022).

[b] Results from Nilsen (2023).

increasing mortality on older age classes (Dupont et al., 2021). Reduced polar cod abundance could result in lower overall food availability for Arctic top predators, unless replaced by other energy-rich prey items such as capelin.

4. The Barents Sea in 2100—An emissions-dependent future

Next, we will also present a short assessment of projected changes toward 2100. These projections, although useful to strategic decision-making, are outside the time horizon relevant for the management of living marine resources (Tommasi et al., 2017). However, whereas near-future (toward 2050) climate change impacts in the Barents Sea are more or less determined from the emissions we already have committed (i.e., relatively invariant to the climate scenario used), we show that the severity of anthropogenically driven climate change in the longer term is still not decided.

4.1. Changes in the physical environment

At the end of the century (2090–2099), the warming of the Barents Sea and the associated changes in upper-ocean stratification are more pronounced (**Figures 1** and **3** and Tables S2 and S3). Unlike the 2050s, significant differences between emission scenarios have now also emerged. For example, a warming of 7.0 ± 2.5°C ($n = 20$) is projected for surface waters of the northern Barents Sea in the high-emission scenario, while for medium emissions the projected warming is 4.2 ± 2.2°C compared to the reference period.

4.2. Changes in biogeochemistry

Primary production shows a slight decrease in the southern Barents Sea toward the end of the century (Table S2). This decrease, in accordance with the discussion in Siwertsson et al. (2023), is partly related to the increased vertical stratification that reduces the vertical nutrient supply. However, the reduction in nutrients is taking place over the whole water column, suggesting that there is also a decrease in the horizontal supply of nutrients. A reduction in the nutrient supply from the Atlantic was also suggested to be an important factor for a decline in Arctic Ocean nitrate concentration in CMIP5 models (Vancoppenolle et al., 2013). The timing of the spring bloom does not change, indicating a negligible change in the timing of the onset of stratification, although there is a slight increase in integrated primary production at the beginning of the productive season. In the northern Barents Sea, primary production keeps increasing (**Figure 3** and Table S3), but the onset of the spring bloom does not occur earlier compared to the shift that was already projected for the 2050s (Figure S3).

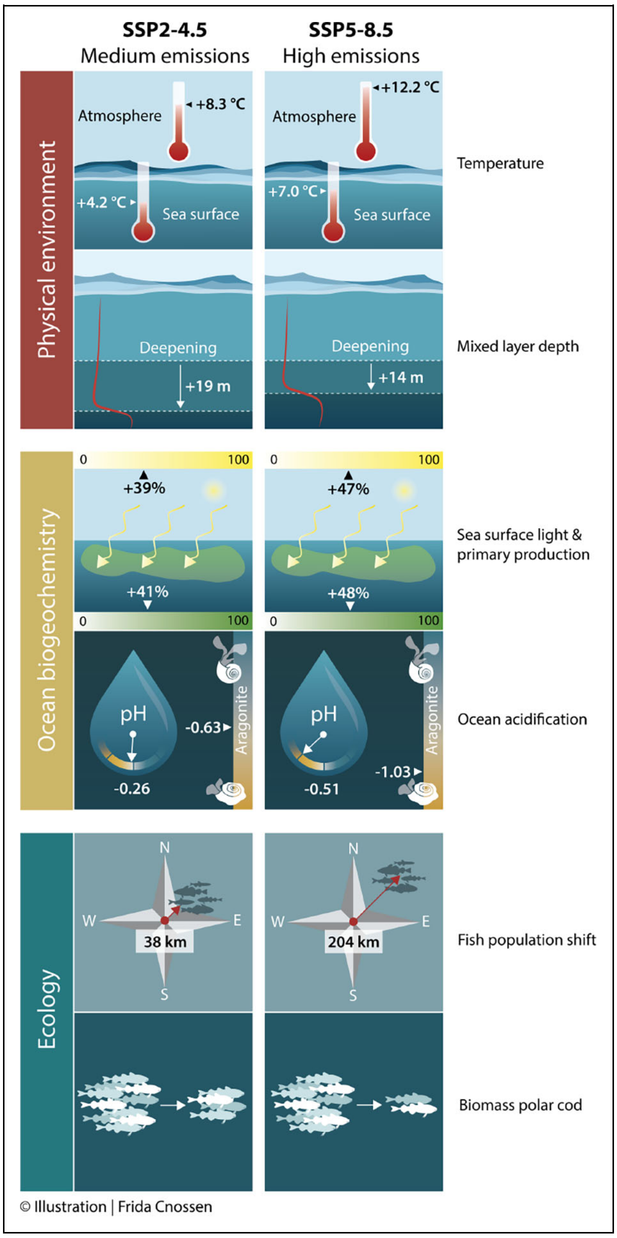

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Figure 3. The northern Barents Sea in 2100. Future changes in the physical environment, ocean biogeochemistry, and ecology for northern Barents Sea in 2100 under the medium- (SSP2-4.5) and high-emission scenario (SSP5-8.5). Numbers indicate changes relative to the period 1980–2009 based on multi-model averages. See text and Tables S2 and S3 for corresponding numbers for the southern Barents Sea.

By the end of the century, scenario differences in pH have emerged in both the southern and the northern Barents Sea (**Figures 3** and S5). The pH has reached values as low as 7.65 (7.67) in the northern (southern) Barents Sea in the SSP5-8.5 scenario. Aragonite reaches undersaturation in both regions (84% and 97% of the water volume in the south and north, respectively), meaning corrosive water and higher energy demand for aragonite shell- and skeleton-forming marine organisms. Decreasing pH and aragonite saturation in a warmer future climate and its sensitivity to emission scenarios are in line with previous studies (Bellerby et al., 2005; Skogen et al., 2014; Fransner et al., 2020; Steiner and Reader, 2024).

Interestingly, the continued decrease in pH and aragonite saturation between 2050 and 2100 is not reflected in the CO_2 fluxes, which show reduced oceanic CO_2 uptake after 2050 in both scenarios (Figure S5). This decrease in ocean carbon uptake toward the end of the century is also seen for the global ocean (Kessler and Tjiputra, 2016) and can be caused by a combination of reduced solubility of CO_2 due to higher temperatures, lowered buffering capacity, as well as a stabilization of the atmospheric CO_2 concentrations for the SSP2-4.5 scenario (Terhaar, 2024). There is also a large advective supply of anthropogenic CO_2 to the Barents Sea from the south that affects both CO_2 fluxes and ocean acidification (Jeansson et al., 2011; Terhaar et al., 2019). The relative roles of ocean advection and air-sea CO_2 fluxes in future changes in pH and calcium carbonate saturation remain to be investigated.

4.3. Ecological changes

Model projections show that some species benefit from higher temperatures (**Table 1**). Species that increase in biomass generally include mid-trophic level species, like northern shrimp, mesopelagic fish, and small pelagic fish. For NEA cod, the models show a different response in biomass to the future warming, increasing in NORWECOM.E2E while decreasing in NoBA Atlantis. In NoBa Atlantis, the reduction in NEA cod comes from the decrease in capelin, which is caused by a decline of large zooplankton in the summer feeding areas (Nilsen, 2023).

Some population and ecosystem models also predict a severe decrease in the polar cod population in the Barents Sea (reduced biomass and abundance) in the high-emission scenario (SSP5-8.5; **Table 1** and **Figure 3**). In a moderate warming scenario (SSP2-4.5), ecosystem models predict a slightly better fate for the polar cod with comparable levels of biomass to current levels.

5. Changes in human activities and impact

Levels of human activities, for example, future levels of pollution and fishing, are more uncertain than the emission scenarios presented above. Future human activities will be responsive to short-term changes in market forces, societal demands, political and regulatory frameworks, as well as regional and international conflicts. Thus, we rely on forecasts of activities from various industry sectors and couple these with empirical relationships between these activities and ecosystem consequences. This approach, however, precludes assigning a clear timeline in most cases, so we chose not to include these changes under the 2050 or 2100 scenarios. Contaminant levels within the ecosystem will depend on ecological responses to modeled climatic changes in the region and projected human activities. Major drivers of potential change in contaminant load and exposure are ship traffic (from fishing, tourism, military, and cargo vessels), biogeographical range extension and expanded migration of boreal species into the Barents Sea region, release of legacy contaminants from the melting cryosphere, and altered contaminant cycles due to climate-driven changes in the marine food web. Projected changes in human activities and their impacts are summarized in **Figure 4**.

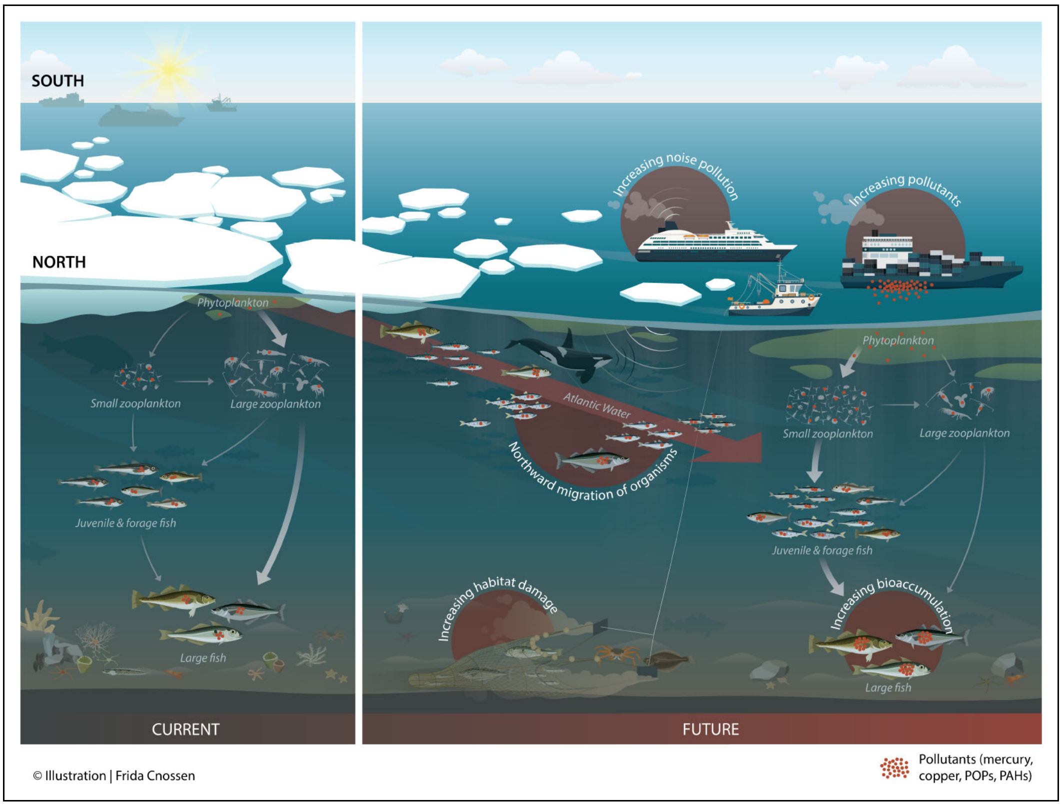

Figure 4. Future changes in human activities in the Barents Sea and their potential impacts. The figure shows how increased human activity in the future can impact the Barents Sea ecosystem. As the northern Barents Sea becomes increasingly ice-free in the future (going from left to right in the figure), increased contaminant load and exposure are expected from ship traffic, northward migration of boreal species into the Barents Sea region, and altered contaminant cycles due to climate-driven changes in the marine food web (see main text for details).

5.1. Human impacts from harvesting

Fisheries remove more than one million tons of fish (primarily cod, haddock, Greenland halibut, capelin, saithe, and redfish) and crustacean (primarily northern shrimp and snow/king crab) biomass from the Barents Sea annually (Skern-Mauritzen et al., 2022). Bilateral (Norway-Russia) management of the Barents Sea fishery has generally been effective in maintaining harvestable stocks and assisting stock recovery after population fluctuations (Eide et al., 2013), and most major stocks are harvested at sustainable levels (Howell et al., 2022). Future stock sizes, and therefore fishing pressure and location of the fishery, are uncertain. Model results are not in agreement on the direction of change in the stock size of the largest fishery, the NEA cod (**Table 1**). The impacts of increases in abundances of other species (mackerel, blue whiting, haddock), along with unknown fluctuations in prey for NEA cod (e.g., northern shrimp, capelin, herring) on future stock sizes, are also difficult to predict.

As waters warm and ice withdraws, fish populations currently centered in the southern area of the Barents Sea are expected to move to the northeast (**Figures 2** and **3**). Snow crab, a non-native species with a rapidly increasing fishery, is also expanding to the west and northwest from Russian waters near the mainland and Novaya Zemlya. These distributional shifts may lead to increased fishing pressure in the northern regions, currently considered areas of special ecological value (Eriksen et al., 2021).

5.2. Shipping activities and contaminants

Between 2012 and 2019, fisheries and cruise traffic have increased, along with a lengthening of the operational season and expanded areas of navigation (Stocker et al., 2020). Despite a prediction that the global maritime traffic may increase substantially by 2050 (Sardain et al., 2019), realized changes in the number of cargo ships in the Barents Sea may be at the low end of this range, at least until 2050, due to the lack of services and infrastructure, high insurance and escort fees, and other socio-political and economic considerations (Smith and Stephenson, 2013). The peak shipping season is predicted to be in late summer, most likely in September (Smith and Stephenson, 2013).

Ship traffic increases the risk of chronic and acute pollution, particularly from scrubber water which contains various metals (copper, mercury), petroleum products such as polycyclic aromatic hydrocarbons (PAHs), sulfur compounds (Stokstad, 2021), and persistent organic pollutants (POPs; Miller and Ruiz, 2014), as well as being vectors for species introductions. A warming climate can volatilize POPs into the atmosphere (Ma et al., 2011), which may increase the accumulation and magnification in the Arctic food web. While the concentrations of individual chemicals may be low, mixtures of contaminants have shown detrimental effects on sub-Arctic species (Thor et al., 2021).

PAHs are common pollutants from shipping and oil exploitation that are increasing concerns for the future as the Arctic has the world's largest remaining prospective reservoirs of oil and gas (Gautier et al., 2009). Studies on the effects of PAHs or crude oil on physiology, grazing, reproduction, and survival of Arctic zooplankton have indicated reduced survival, grazing, reproduction, and hatching success of *Calanus* species (Dinh et al., 2019; Toxværd et al., 2019). Impacts of oil pollution may further interact with additional stressors such as warming and freshening (Rist et al., 2024). The potential outcome of reduced survival and reproduction will affect the population growth and dynamics directly and also lower the copepod biomass available for higher trophic levels (e.g., polar cod). In fish, oil-exposed polar cod may induce early spawning (Strople et al., 2023) with unknown consequences for the offspring generation; early-life stages of polar cod may also be particularly sensitive to PAH levels (Nahrgang et al., 2016).

The ongoing warming of the Barents Sea, as well as altered fishing pressure and the potential for species introductions (Cottier-Cook et al., 2024), can impact the food web, leading to altered contaminant transfer (Borgå et al., 2022; De Wit et al., 2022). A poleward extension of boreal species could, for example, present a threat as these species act as vectors transporting contaminants (Pedro et al., 2017) and disease (Varpe and Bauer, 2022) from more industrialized southern areas of their range. Furthermore, in a warmer Arctic, top predators may be approximately one trophic level higher in the food chain than they have been historically (Mueter et al., 2021). Increase in maximum trophic level of the Barents Sea food web may change the bioaccumulation in highest trophic levels substantially. For example, concentrations of a wide variety of POPs increased by 50–600% in predatory fish inhabiting a system where they fed at 1–2 trophic levels above that of a control area (Evenset et al., 2004).

The interaction between, for example, ocean warming and acidification can have knock-on effects on the uptake, fate, and effects of POPs and other contaminants in Arctic marine organisms (Borgå et al., 2022; Dinh et al., 2022). This interaction can result in antagonistic, additive or synergistic effects depending on the species, life stage, and the magnitude and duration of stressor exposure (Dinh et al., 2022; Rist et al., 2024). Identifying possible ecological tipping points of Arctic marine species and food webs in complex interactions of climate change and other anthropogenic stressors is crucial for more comprehensive ecological risk assessments and management.

6. Projection uncertainty

Projections of the future are inherently uncertain. The uncertainty comes from the choice of emission scenario, internal variability, and from differences in model structure and biases (Vancoppenolle et al., 2013; Årthun et al., 2021; Tagliabue et al., 2021; Khosravi et al., 2022; Nilsen et al., 2022). Combined, these uncertainties lead to a large intermodel spread in projections of the future Barents Sea (Figures S1, S2, and S5). The relative importance of the different sources of uncertainty depends on the projection horizon of interest. In the Barents Sea, internal variability dominates projection uncertainty in the next few decades (Bonan et al., 2021). Predictions and advice for the next decade thus need to be mindful of internal variability, for example, by taking advantage of the recent developments in seasonal to decadal forecasts from dynamical prediction models (Tommasi et al., 2017; Payne et al., 2022; Fransner et al., 2023).

Beyond the next few decades, scenario and model uncertainty dominate the total uncertainty (Bonan et al., 2021). This uncertainty is manifested in the large inter-model spread for both physical and biogeochemical variables (Figures S1, S2, and S5). Coupled climate models are known to have mean-state biases in Arctic hydrography (Khosravi et al., 2022; Heuzé et al., 2023) and, hence, upper-ocean stratification and vertical mixing. Models also differ in their ability to simulate correctly ocean heat transport into the Barents Sea, which is reflected in the present sea-ice cover and its future change (Li et al., 2017; Dörr et al., 2024).

Biases in the simulated physical environment are in turn translated to uncertainties in biogeochemical projections as, for example, upper-ocean stratification and sea-ice cover exert a strong influence on primary production (Vancoppenolle et al., 2013; Tagliabue et al., 2021; Mousing et al., 2023; **Figures 2** and **3**). Uncertainties in biogeochemical projections also come from inadequate representation of biogeochemical processes in climate models (Laufkötter et al., 2015; Séférian et al., 2020; Steiner and Reader, 2024). For example, CMIP6 models do not include modules for sea-ice biogeochemistry. Potential changes in sea-ice primary production (Hegseth, 1998) are thus not considered in the model projections presented here. The absence of sea-ice biogeochemistry also implies that the effect of sea-ice alkalinity and carbon storage on seawater carbonate chemistry (Rysgaard et al., 2009; Fransson et al., 2017) is not taken into account. This lack of accounting can result in an underestimation of the future ocean carbon uptake by 5–15% (Richaud et al., 2023).

Uncertainties in ecological projections are related to structural uncertainty of the ecosystem model, how species respond to climate change (e.g., their thermal tolerance), and uncertainties regarding projections of the physical environment (including scenario differences). Ecological uncertainty can be addressed by using multiple ecological models (Nilsen et al., 2022). Using different models with different complexities (as in **Table 1**) can reveal species showing consistent results across the models, suggesting higher confidence in the projections. In contrast, species responding differently to climate change in different models would suggest that more research is needed. Improved understanding of ecological model uncertainty can also be achieved by targeted sensitivity experiments where model parameters and parameterizations (e.g., recruitment and mortality) are perturbed to see how different species respond (Hansen et al., 2019).

7. Conclusions and implications

The Barents Sea is currently undergoing a transition from cold, Arctic climate conditions to a warmer, more Atlantic-like climate (Gerland et al., 2023). This "Atlantification" of the Barents Sea has already had a wide range of physical and ecological impacts (Ingvaldsen et al., 2021). In this study, we have combined climate, biogeochemical, and ecosystem model runs to provide a holistic view of the Barents Sea in 2050 and 2100, and how this may vary depending on emissions scenario. We find that:

- The future Barents Sea is characterized by warmer, ice-free conditions. Upper-ocean stratification increases in the southern Barents Sea, while it decreases in the north.
- A warmer, less ice-covered northern Barents Sea more exposed to solar radiation leads to increased primary production and improved conditions for visually searching predators. Primary production increases in the northern parts but not in the southern Barents Sea.
- More open areas in the north facilitate enhanced uptake of atmospheric CO_2 which contributes to decreased pH and aragonite saturation (ocean acidification).
- A warmer, less ice-covered Barents Sea leads to a northward expansion of sub-Arctic demersal species such as NEA cod. Spatial changes in spawning areas are also expected, although less certain. The biomass of several marine populations or subpopulations are projected to change, the direction of change varying between species and models.
- There is large potential for increases in contaminant load, introduction of alien species, and fisheries-related impacts on biotic communities and the habitat itself.

One key finding is the small scenario differences for physical and biogeochemical projections by 2050. Importantly, the small scenario differences we identify in a wide variety of physical, biogeochemical, and ecosystem models suggest that most of the changes projected for 2050 are already locked in due to the inertia of the earth-ocean system. This implies that managing the Barents Sea toward 2050 must move from prevention and mitigation to adaptation.

In contrast to 2050, the severity of climate change in the Barents Sea toward the end of the century scales directly with future emissions. The warming of the surface ocean in the northern Barents Sea in 2100 is, for example, approximately 3°C higher in the high-emission scenario (SSP5-8.5) than in the medium-emission scenario (SSP2-4.5). Higher emissions also lead to more severe changes in fish populations and ocean acidification. To avoid these consequences, lowering emissions to Paris Agreement levels within the next couple of decades is vital in order to stabilize changes around the 2050 levels, or possibly reverse some of the changes we will experience by then.

The poleward displacement of boreal species, both for commercial stocks (e.g., NEA cod, mackerel, blue whiting) and other fish species with the potential for substantial food-web changes, presents new challenges for monitoring and management. Projected northward and then eastward shifts in the spawning grounds of capelin and NEA cod introduce the potential for novel area-use conflicts as the need for protection of spawning grounds can challenge expected growth of aquaculture and other coastal industries in northern Norway. A northeastward shift in spawning grounds and commercial stocks also underscores the continued need for strong bilateral fisheries management efforts between Norway and Russia.

Physical and ecological impacts of Arctic climate change are not restricted to the Barents Sea and are currently expanding along the eastern Eurasian Basin (Polyakov et al., 2017; 2020). A sustained incursion of Atlantic waters into the Eurasian Basin throughout the century will result in the retreat of the sea-ice edge beyond the Barents Sea (Årthun et al., 2019; Dörr et al., 2021). Future changes in the Barents Sea, as detailed in this article, may therefore serve as precursors for changes in other Arctic seas.

Data accessibility statement

CMIP6 data analyzed here are available from the Earth System Grid Federation (ESGF; Eyring et al., 2016), ERA5 from Hersbach et al. (2020), Global Ocean Colour primary production data from CMS (2024); in-situ measurements of nutrients from the Barents Sea Opening are available from Gundersen et al. (2022) and observation-based CO_2 fluxes from Jersild et al. (2024). Observed pH and aragonite saturation were calculated from in-situ measurements of total alkalinity, dissolved inorganic carbon, temperature, and salinity extracted from the GLODAPv2 database (Lauvset et al., 2023). Data from NORWECOM.E2E (Hordoir and Skogen, 2024) and NoBA Atlantis (Nilsen et al., 2024) are available through the Norwegian Marine Data Centre.

Supplemental files

The supplemental files for this article can be found as follows:

Barents_Sea_2050_Supp_Mat_Elementa (PDF)

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Competing interest

All authors declare that they have no competing interests.

Author contributions

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Contributed to analysis and interpretation of data: All authors.

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