


Trivial gain of downscaling in future projections of higher trophic levels in the Nordic and Barents Seas

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Funding information

This work was funded by the Research Council of Norway (RCN) through the project The Nansen Legacy (AeN, RCN 276730).

Abstract

Downscaling physical forcing from global climate models is both time consuming and labor demanding and can delay or limit the physical forcing available for regional marine ecosystem modelers. Earlier studies have shown that downscaled physics is necessary for capturing the dynamics of primary production and lower trophic levels; however, it is not clear how higher trophic levels respond to the coarse resolution physics of global models. Here, we apply the Nordic and Barents Seas Atlantis ecosystem model (NoBa) to study the consequences of using physical forcing from global climate models versus using that from regional models. The study is therefore (i) a comparison between a regional model and its driving global model to investigate the extent to which a global climate model can be used for regional ecosystem predictions and (ii) a study of the impact of future climate change in the Nordic and Barents Seas. We found that few higher trophic level species were affected by using forcing from a global versus a regional model, and there was a general agreement in future biomass trends and distribution patterns. However, the slight difference in temperature between the models dramatically impacted Northeast Arctic cod (*Gadus morhua*), which highlights how species projection uncertainty could arise from poor physical representation of the physical forcing, in addition to uncertainty in the ecosystem model parameterization.

KEYWORDS

Atlantis, Barents Sea, climate change, downscaling, ecosystem modeling, Northeast Arctic cod

1 | INTRODUCTION

Global warming is already causing large-scale impacts in sub-Arctic and Arctic Ocean regions, with temperatures quickly rising and sea ice receding (Comiso, 2012; Smedsrud et al., 2013). These changes are altering the ecosystem by displacing southern, boreal species further north, while arctic species are retreating and declining (Fosheim et al., 2015; Frainer et al., 2017; Kjesbu et al., 2022, 2014). With the

increasing number of marine environmental stressors (Henson et al., 2017), there is an urgent need to understand how marine ecosystems will respond to these changes (Fagundes et al., 2020).

The only process-based tools available to study the implications of future climate change are models. To study potential responses in ecosystem function and structure to climate change, output from climate models is often used as forcing for ecosystem models (Lotze et al., 2019; Tittensor et al., 2021). Over the past few years, the

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Intergovernmental Panel on Climate Change (IPCC) has developed five SSP narratives to describe alternative pathways for future society (IPCC, 2022). The SSPs contain a range of baseline scenarios spanning between 1.9 and 8.5 W/m² of radiative forcing by 2100 and play an important role in facilitating integrated research across multiple climate modeling communities (O'Neill et al., 2016).

Global climate models, such as those used in the IPCC reports (IPCC, 2022), are generally capable of reproducing the observed long-term trends at a global scale. However, due to their global coverage, even with increasing computational power, their spatial resolution and parameterizations remain insufficient at regional scales that are relevant for marine ecosystems (Melsom et al., 2009; Tjiputra et al., 2007). This can lead to biases relative to observational data and inaccuracies in regional details (Skogen et al., 2018).

A way to improve such biases is through downscaling, where a high-resolution regional ocean circulation model is initiated from, and/or nested into, a global climate model (Skogen et al., 2018). This is done to translate coarse global information into finer scale resolution in order to simulate more accurate regional processes and obtain climate information on scales that are relevant to society (Ekström et al., 2015). Regional models also have the advantage of better-calibrated parameterizations targeted for the study regions (Hordoir et al., 2022).

Previous studies have explored the impact of increased model resolution and found that higher resolution physical forcing produces results closer to observations and provides a better representation of ocean dynamics and variability. Increased resolution has been found to improve the representation of physical processes such as the northward transport of heat and salt (Langehaug et al., 2019), frontal regions (Kirtman et al., 2012), and deep convection (Busecke et al., 2019). Improving these processes results in temperatures and salinity closer to observations (Melsom et al., 2009; Sandø et al., 2014; Skogen et al., 2018) and improves the timing of spring bloom and estimates of net primary production (Hansen & Samuelsen, 2009; Skogen et al., 2018).

However, the process of downscaling physical forcing from global models is both time consuming and labor demanding, which can delay or limit the physical forcing available for ecosystem modelers. Some ecosystem models have coarse resolution grids with few or only one grid cell. Examples for the Nordic and Barents Seas include Ecosim with Ecosim (Pedersen et al., 2021), Gompertz (Nilsen et al., 2022; Stige et al., 2019), NDND (Planque et al., 2014), RCaN (Planque et al., 2022), Gadget (Lindstrøm et al., 2009), and NoBa Atlantis (Hansen et al., 2016), where only the last one has more than two grid cells. The coarse resolution will cause these models to lose the details provided by the high-resolution models. However, differences in physics might still be reflected in the mean values used as forcing. If this is the case, how large are these differences, and would they impact not only the lower trophic levels but also higher?

Several studies have used ecosystem models to study how species in the Nordic and Barents Seas might respond to future climate changes, from lower trophic levels to complex systems including several trophic levels. Skogen et al. (2018) used physical forcing from climate models of various resolution and found no trends in future nutrient levels or primary production. Hansen, Nash, et al. (2019)

studied the effect of changes in management strategies in combination with climate changes and found an increased vulnerability in pelagic and demersal functional groups when harvesting a higher number of species. Cheung et al. (2010) showed that high-latitude areas such as the Norwegian and Barents Seas are likely to experience an increase in total catch potential in the future, based on calculations of future primary production, trophic level, and geographic range. This is supported by observations from the Barents Sea over the last decades, where increasing temperatures have been beneficial for, for example, Northeast Arctic cod (*Gadus morhua*) (Kjesbu et al., 2022, 2014).

In this study, we aim to focus on the higher trophic level species, and the goal is twofold: (1) to study how much we gain, if anything, when applying downscaled forcing compared to forcing from a global climate model in a coarse resolution end-to-end ecosystem model simulation, and (2) to evaluate expected ecosystem changes in the Nordic and Barents Seas under the future climate changes with the two different types of forcing.

2 | MODELS AND SIMULATIONS

To investigate how much we gain from downscaling, we study ecosystem responses to applying physical forcing from a global circulation model and from a downscaled regional model in the Nordic and Barents Seas Atlantis model. We will also investigate how sensitive the projections of the Barents Sea ecosystem are to the underlying physical forcing.

2.1 | Models

We use physical forcing taken directly from the ocean component of a global climate model (NorESM2) and as downscaled with a regional ocean circulation model (Nemo-NAA10km) and apply them to an ecosystem model (NoBa Atlantis). The concept is illustrated in Figure 1 and a short description of the two oceanographic models and the ecosystem model follows below. Figure 1 also shows a comparison of the sea surface temperature as projected for the Nordic Seas and parts of the Arctic Ocean by NorESM2 and Nemo-NAA10km. Clearly, the RCM appears to capture spatial aspects in greater detail, including the northward flowing Atlantic Water and circulation along the coasts.

2.1.1 | NorESM2

The Norwegian Earth System Model version 2 (NorESM2-MM; Seland et al., 2020; Tjiputra et al., 2020) is a fully coupled Earth system Model developed in Norway in collaboration with the National Center for Atmospheric Research (NCAR) in the United States. The model is an important tool for Norwegian climate researchers in the study of the past, present and future climate and was recently updated from its original version NorESM1 (Bentsen et al., 2013; Tjiputra et al., 2013). The NorESM2-MM has contributed to the Coupled Model Intercomparison Project phase 6 (CMIP6) and to the latest assessment report

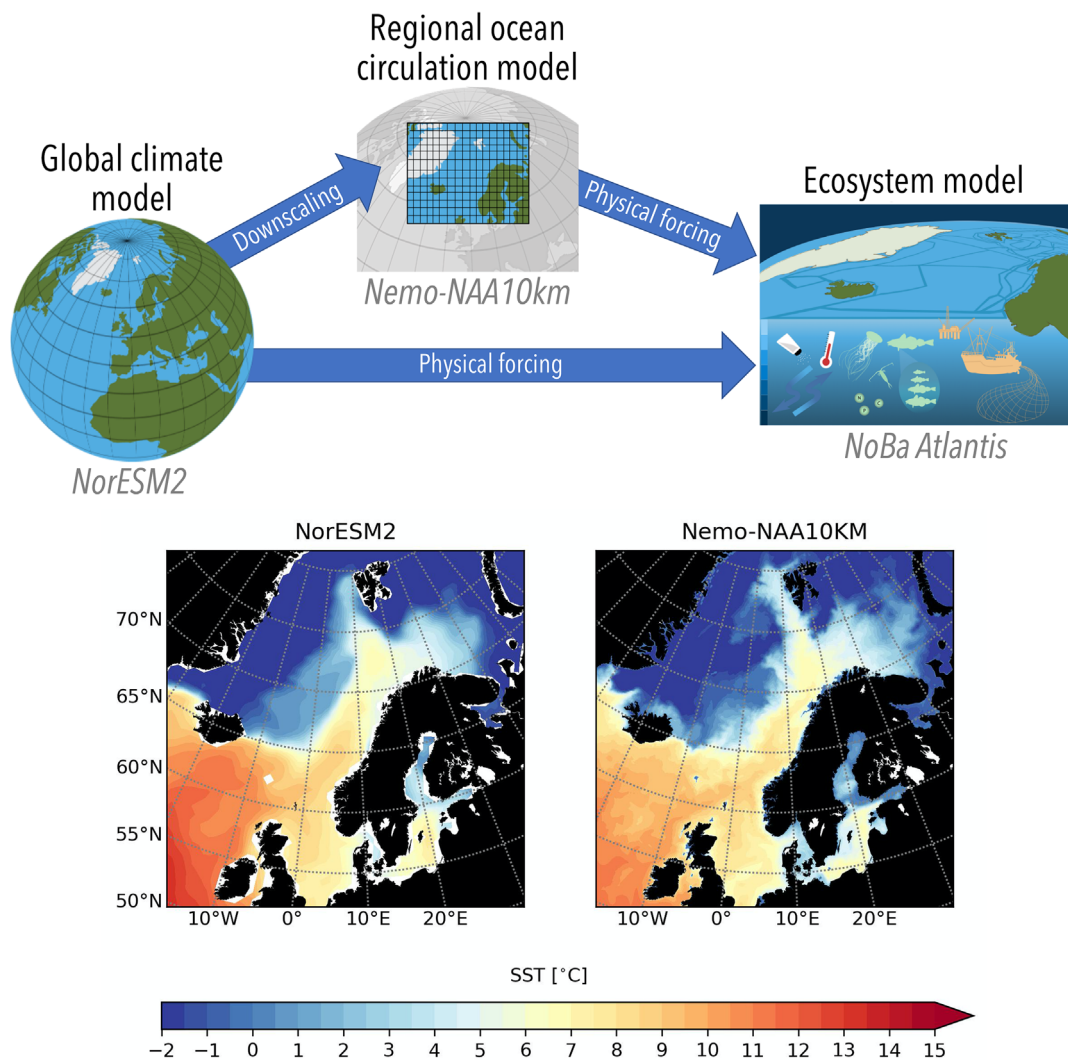


FIGURE 1 An overview of the experiment configurations in the study where physical forcing from a global climate model and from a regional ocean circulation model are applied to an ecosystem model. Note that the regional extent of Nemo does not correspond to the one in the figure. The lower part of the figure illustrates the effects of downscaling, here visualized by showing projected mean sea surface temperatures (SSTs) from January 2000 directly from NorESM2 and as downscaled by Nemo-NAA10km.

of IPCC-AR6. It consists of the atmospheric model CAM6-Nor, the ocean physical model BLOM (Bentsen, 2021), the ocean biogeochemistry model iHAMOCC (Tjiputra et al., 2020), the sea ice model (CICE5.1.2), land model (CLM5), and river runoff model (MOSART). BLOM has a horizontal resolution of $\sim 1^\circ$ and 53 vertical isopycnic layers. CAM6-Nor has a horizontal resolution of $\sim 1^\circ$ on 32 vertical layers. The NorESM2-MM will hereafter be referred to just as “NorESM,” and a full description including an evaluation of its key climatic and biogeochemical features is available in Seland et al. (2020) and Tjiputra et al. (2020).

2.1.2 | Nemo-NAA10km downscaling

The Norwegian Institute of Marine Research's regional ocean model Nemo-NAA10km (Hordoir et al., 2022) covers a major part of the North Atlantic and of the Arctic Oceans. This model is used for

studying ocean processes in a changing climate; it is based on the NEMO ocean engine for both representing ocean and sea ice dynamics. The model works in forced mode at its surface and open boundary conditions. The model can be forced either by an atmospheric/oceanic reanalysis such as the ERA5 reanalysis (Hersbach et al., 2020) for the atmosphere, or the GLORYS reanalysis (Egbert & Erofeeva, 2002) for the ocean. The model can also be forced by a climate model both for the atmosphere and the ocean (climate downscaling), which allows for a better representation of ocean processes than that represented in climate models due to the higher resolution available. Nemo-NAA10km has been forced by the NorESM2 climate model for several emission scenarios (including SSP5-8.5 which is applied here).

Nemo-NAA10km is a forced model but runs without any kind of restoring in salinity nor in temperature. This enables a representation of the inter-annual variability of the thermohaline structure of the ocean. More information about this can be found in the Supporting Information and in Hordoir et al. (2022).

2.1.3 | NoBa Atlantis (ecosystem model)

The Atlantis modeling framework (Audzijonyte et al., 2019; Fulton et al., 2011) is one of the most complex marine end-to-end ecosystem models in the world (Plagányi, 2007). In this study, the version implemented in the Nordic and Barents Seas (hereafter NoBa) (Hansen, Drinkwater, et al., 2019; Hansen et al., 2016) will be used.

The NoBa model contains 53 key species and functional groups (hereafter components) that are connected through a diet matrix. Most vertebrate species are age-structured while invertebrates are gathered into biomass pools. The model simulates spatial variation and is divided into 60 polygons with up to seven depth layers depending on total water column depth (Hansen et al., 2016). The species can move between polygons and layers either actively through swimming or passively transported by currents (e.g., plankton, egg, larvae, and nutrients). The majority of the vertebrate species have forced migration to ensure seasonal movement patterns throughout the year. The species are however free to distribute themselves (e.g., based on food availability and temperature preference) within these given polygons. A thorough description of the updates of this version of the NoBa model following the Overview, Design concepts, Details (ODD) protocol (Grimm et al., 2020, 2006) is included in the Supporting Information.

2.2 | Forcing

NoBa is forced by daily inputs of temperature, salinity, sea ice in each polygon, and also the net transport of water (m^3/s) between the polygons. In this study, monthly output from NorESM2 or 5-day mean forcing from Nemo-NAA10km was used to create the physical forcing for NoBa. To create the forcing files, an average value (of temperature, salinity, or sea ice concentration) was calculated over all grid cells (either Nemo-NAA10km or NorESM2) included in each of the 60 polygons of NoBa Atlantis. In the vertical, the average was calculated over the layers from the physical models which were within the depth levels of NoBa. Net transport was calculated across each face of the polygons (253 in total) for all depth levels. Linear interpolation was used to create daily fields from the monthly and 5-day means from NorESM2 and Nemo-NAA10km, respectively.

NoBa explicitly simulates concentrations of nutrients through nitrate which depends on primary production, remineralization (Murray & Parslow, 1997), horizontal transport, and vertical exchange between layers and sediments. Light is also calculated within the model for each of the polygons. Primary production is determined by a maximum growth rate and by limiting factors such as nutrients, light, and an eddy scalar (to facilitate vertical mixing between the layers).

After the forcing from NorESM2 and Nemo-NAA10km was fitted to the NoBa grid we refer to the simulations using the two various sets of forcing as just “NorESM” and “Nemo” respectively to avoid confusion.

2.3 | Simulations

Following the application of new forcing, the commercially exploited species in NoBa had to be calibrated to fit better to observations. This was done in order to ensure that the biomasses and the catches would be at observed levels and thereby represent the current situation. The same tuning was applied for both simulations, that is, Nemo-NAA10km and NorESM2 forced (Table S1), and the model was initiated from year 1980 and included a 24-year spin-up period where the same physical state of the year 1980 was repeated. The change in forcing started after the spin-up. Historical fishing levels were applied for the hindcast period (year 1980–2020) using assessment catches and total stock biomass data (International Council for the Exploration of the Sea [ICES], 2021, 2020). After this, the fishing mortality in the last year (year 2020) was applied and maintained throughout the rest of the simulation. More information about the parameters that were tuned and the results of the tuning can be found in Table S1 and Figure S1.

In this study, we use the SSP5-8.5 scenario, which represents the highest emissions no-policy baseline scenario with fossil-fueled development and a growing economy. Although the SSP5-8.5 is the “worst-case scenario” and might not represent the most realistic future (Mohr et al., 2015; Wang et al., 2017), we decided to use this high-end baseline scenario to explore what “could” happen, as it offers the largest signal-to-noise ratio, which was of interest in our study.

To compare the impact of physical forcing from the two models, eight simulations were set up (Table 1). In these simulations, we used forcing from either Nemo-NAA10km or NorESM2 (Nemo_ref, NorESM_ref) and then turned on the thermal niche of the species (Nemo_temp, NorESM_temp), included ice as forcing (Nemo_ice, NorESM_ice), or included both ice as forcing and the thermal niche (Nemo_ice_t, NorESM_ice_t). These scenarios were set up to study how the distinct parameter settings affected the species.

TABLE 1 Overview of the NoBa simulations conducted in this study.

No	Name	Description
1	Nemo_ref	Forcing from Nemo-NAA10km
2	NorESM_ref	Forcing from NorESM2
3	Nemo_temp	Forcing from Nemo-NAA10km, thermal niche turned on
4	NorESM_temp	Forcing from NorESM2, thermal niche turned on
5	Nemo_ice	Forcing from Nemo-NAA10km, including ice forcing
6	NorESM_ice	Forcing from NorESM2, including ice forcing
7	Nemo_ice_t	Forcing from Nemo-NAA10km, including ice forcing and thermal niche turned on
8	NorESM_ice_t	Forcing from NorESM2, including ice forcing and thermal niche turned on

Turning on the thermal niche restricts the species to spawn or reside in polygons within their tolerated temperature range. Hence, if the temperature in the polygon is below or above the species' temperature range, the species cannot inhabit or spawn in that polygon when the thermal niche is turned on. However, the temperature still affects the species when the thermal niche is turned off as it is included in both growth and consumption equations (Audzijonyte et al., 2017). The temperature ranges set in NoBa were based on literature (Hansen et al., 2016).

Using ice as forcing was important since the Barents Sea is largely covered by ice during winter and early spring. Including ice also affects the distribution of the species, as some species don't tolerate being under ice, while others thrive being on, in or under the ice. The ice cover also affects the primary production by limiting the availability of light in the water underneath it.

2.4 | Data analysis

To compare both the forcing from the models and the results from the NoBa simulations, two different periods of 15 years, an early (year 2005–2020) and a late (year 2085–2100), were chosen. These periods were used to examine the trends throughout the simulation and compare potential future levels to the present.

The temperature, salinity, and ice of the entire model area were estimated by accounting for the area and depth of the polygons and layers. For temperature and salinity, the median values over all polygons were used for comparison since the distribution of values was somewhat skewed and had some clear outliers. Total ice cover was estimated by summarizing the areas covered with ice concentration >30%. Monthly and yearly means of the physical forcing were calculated based on snapshots taken every fifth day throughout the year.

To study the effects of the physical forcing on the ecosystem, the difference in biomass (%) in NorESM simulations compared to Nemo was used. We considered any difference exceeding 15% to be significant based on uncertainty limits used in the ICES reports (ICES, 2021). The biomass estimates were based on five snapshots throughout the year to capture seasonal variation, and a yearly mean was calculated based on this. It should be noted that haddock (*Melanogrammus aeglefinus*), snow crab (*Chionoecetes opilio*), and king crab (*Paralithodes camtschaticus*) were removed from the results, as these species are either collapsing or increasing to unrealistically high levels. There is no obvious reason to believe this would happen in the real world, such that this behavior is in all likelihood a consequence of model artifacts. The species were sorted by trophic levels (Fishbase, 2022) to investigate the effect of the physical forcing on the different parts of the food chain. Species with trophic levels >3 were considered high trophic level species (Pauly & Watson, 2005).

When studying the sensitivity to future climate changes in NoBa, all species and groups were gathered into 11 categories (Table S2). The biomasses of the species within each category were summarized to study how the total biomass varied compared to the mean biomass in the early period (year 2005–2020) in the scenarios. The groups of

bacteria and benthos were not plotted for these future studies as these contain large functional groups and the parameterization of these is more uncertain.

The spatial distribution of the commercial species was also investigated to evaluate how it is affected by the difference in physical forcing. This was calculated by estimating the center of gravity of the distribution, based on the mean longitude and latitude coordinates where the greatest portion of the stock resides throughout the seasons. We then explored the change in this point, either between the scenarios with different physical forcing or from early period to late period. To evaluate the change, we decided that the change in distribution point was considered significant when the distance was equal to or more than 10 km, which is a relatively small distance compared to observed changes in distribution, but due to the coarse resolution of the model and the fact that it was based on mean changes over a 15-year period, it would still provide insight into projected movement.

All figures were created using “R studio” (RStudio Team, 2020), version 4.1.2.

3 | RESULTS

The results are separated into three sections. The first summarizes how the physics from the two oceanographic models differed after being fitted to the NoBa polygons, the second evaluates the sensitivity of the NoBa Atlantis ecosystem simulations to the difference in physics, and the third uses the different scenarios and forcings to study impacts of future climate change on the Nordic and Barents Sea ecosystem.

3.1 | Differences in temperature, salinity, and ice cover

The monthly climatology of temperature and salinity from Nemo and NorESM above and below 150 m for the early (year 2005–2020) and late (year 2085–2100) periods were compared after being fitted to the NoBa grid (Figure 2). For temperature, the difference largely depended on what part of the water column we compared. In the upper 150 m, Nemo projected a higher overall median temperature throughout the year, both for the early- (3.3°C compared to 3.0°C) and the late period (5.0°C compared to 4.6°C; Figure 2a). Below 150 m, however, Nemo projected lower temperatures, both for the early (1.9°C compared to 2.2°C) and the late period (2.9°C compared to 3.2°C; Figure 2a). While Nemo projected warmer temperatures in the shallower parts of the water column mainly around Svalbard and in the Barents Sea, NorESM projected warmer temperatures in the deeper layers of the Norwegian Sea (Figure S2). Accounting for the volume of the polygons, the overall temperature was higher in NorESM, but the greatest differences between the two models were observed in the sea surface layer where Nemo was warmest (up to 6°C). The difference in the upper layers was highest in September (>1°C) for both periods, while for the lower part of the water column the difference was more or less the same

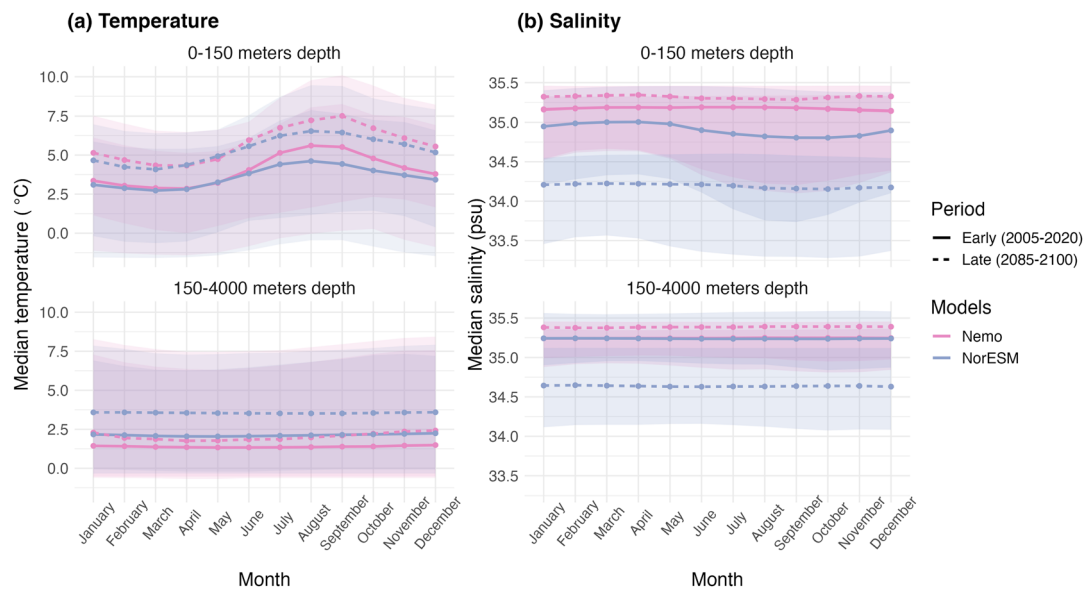


FIGURE 2 Monthly climatology of temperature and salinity above and below 150 m of the water column throughout the entire model when using Nemo (pink) or NorESM (purple) as forcing. The solid lines show the early period (2005–2020), while dotted lines show the late period (2085–2100), and the shaded bands shows the 95% confidence interval.

throughout the year. Between 2005 and 2020 and 2085–2100, the median temperatures throughout the entire water column increased by 1.4°C and 1.2°C in NorESM and Nemo, respectively. The overall difference between the two also increased as the median difference went from 0.3°C to 0.5°C.

For salinity, the situation was somewhat different (Figure 2b). The difference in salinity was uniformly distributed across all polygons and layers (but with a slightly greater difference in the layers closest to the surface for the early period) (Figure S3). The biggest difference here was temporal rather than spatial as NorESM projected a clear decline in the salinity throughout the simulation, while Nemo was quite stable and slightly increasing. For the early period, NorESM projected marginally lower salinity than Nemo (median -0.1 compared to Nemo), while towards the end of the simulation the salinity was substantially lower (median -0.93 compared to Nemo). From the early period to the late, NorESM projected a decrease in median salinity from 35.1 to 34.4, while Nemo had a slight increase from 35.2 to 35.4. The difference in salinity was largest in the upper 150 m of the water column in both periods.

The NoBa-fitted sea ice cover from Nemo and NorESM was compared, focusing on the area with sea ice concentration $>30\%$. The seasonal ice cover was calculated as a mean and compared for the early and late periods. The results showed a consistent decrease in ice concentration from the early to the late period in both models. In Nemo, the ice cover extended further southward along eastern Greenland, compared to NorESM where the ice cover was mostly confined to the northeastern Barents Sea (Figure 3). The total area covered with ice throughout the entire year was approximately the same for Nemo and NorESM in the early period, while in the late period the area was slightly greater (20%) in NorESM compared to Nemo. When comparing the monthly sea ice cover (Figure S4) for the early period, Nemo

projected more ice in the spring (February–May), while NorESM projected more during the rest of the year, especially in the late summer (July–September). In the late period, NorESM projected more ice than Nemo in all months except April and December.

3.2 | Species responses to forcing from Nemo or NorESM

The biomasses of all components in NoBa were compared to explore how they responded to the two sets of physical forcing (Figure 4). This was done for the two 15-year periods defined as early and late, which allowed for comparison between the two physical forcings and how this difference varied through time. The components were sorted by trophic levels to investigate the effect of the physical forcing on the different parts of the food chain.

The majority of the species in the model were not notably impacted by using NorESM as physical forcing instead of Nemo. The species and groups that were most impacted were lower trophic levels species such as the phytoplankton and zooplankton groups, prawns, and mesopelagic fish.

However, some higher trophic level species were also impacted in the simulations, in particular long rough dab (*Hippoglossoides platessoides*) and Greenland halibut (*Reinhardtius hippoglossoides*). Both species responded when turning on the thermal niche, and the difference was the same whether ice was included as forcing or not, indicating that the thermal niche was the main driver for this response. The biomass of long rough dab was reduced in NorESM compared to Nemo both in the early (-18%) and late (-20%) periods. The reduction in biomass was caused by a reduction in numbers rather than weight and occurred first in Age Class 1 at the start of the simulation indicating a reduction in

FIGURE 3 Mean seasonal sea ice cover (%) from Nemo and NorESM and how they varied throughout the year, when interpolated into NoBa grids (polygon outlines). The sea ice cover was given as concentration averaged over the (a) early (year 2005–2020) and (b) late (year 2085–2100) periods.

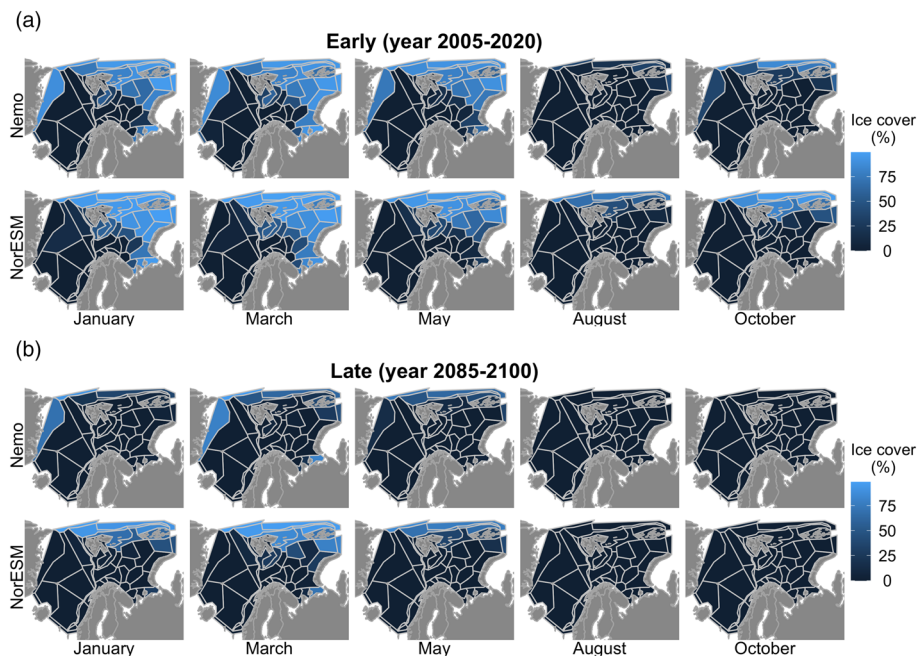


FIGURE 4 Difference in biomass for the components in NoBa when using physics from NorESM compared to Nemo. The difference in mean biomass for two 15-year periods was compared: an early (year 2005–2020) and a late period (year 2085–2100). Green cells indicate a higher biomass in NorESM compared to Nemo, while red cells indicate a lower biomass in NorESM, and differences >15% are given as values.

recruitment. Greenland halibut, on the other hand, increased in biomass (by 22%) in NorESM compared to Nemo in the late period when the thermal niche was turned on. The increase in biomass was also here caused by a higher abundance and occurred in the first age class.

When comparing the early period to the late, it was evident that the difference in biomass between the NorESM and Nemo simulations was apparent for more species in the late period compared to

the early. Another tendency was that higher trophic level species also responded more strongly to the difference in physical forcing when the thermal niche was turned on.

We also investigated which traits might influence stability of biomass to environmental change (Figure S5). The changes in biomass in NorESM compared to Nemo from Figure 4 were converted to absolute values as a measure of variability. This variability was plotted for all

species and separately only for vertebrates, against trophic level, lifespan (a proxy for population growth rate or population productivity), temperature sensitivity (the width of the thermal niche), and core area (size of occupied habitat at model initialization for vertebrates). Results showed a negative correlation between variability and trophic level and lifespan. When focusing only on vertebrates, there was also a significant negative correlation between variability and thermal niche, as well as the area occupied area at model initialization.

How the different sets of physical forcing affected the distribution of the commercial species was also studied. The distributions were not notably altered when using different physical forcing (i.e., Nemo vs. NorESM). The only changes were observed when the thermal niche was turned on, and occurred in herring, which was displaced between 24 and 11 km (depending on the seasons) to the East in NorESM compared to Nemo in the late period, and Northeast Arctic cod (*G. morhua*), hereafter cod, which was relocated 18 km southwest in NorESM in the spring. However, these displacements were relatively small compared to the size of the polygons and were considered negligible.

3.3 | Species responses to future climate changes

Using two sets of physical forcing and various temperature and ice sensitivity settings offered the opportunity to include uncertainty in the projections when studying the ecosystem responses to climate

changes. The species in NoBa were grouped into categories, and the change in total biomass within each category throughout the simulation was plotted (Figure 5).

For most of the categories the overall trend was the same for all simulations, while the biomass levels varied slightly. The groups of whales and mesopelagic species had positive biomass trends and increased by 30% to 40% towards year 2100, while other mammals and seabirds decreased by 10% to 20%. The pelagic species first decreased and then increased before stabilizing. The zooplankton and phytoplankton groups were highly variable, but the overall level was stable throughout the run. The sharks and the demersal species had a stable mean, but the various simulations projected different trends. For sharks, the simulations with the thermal niche turned on projected a slight positive increase of 5% to 10% towards the end of the simulation, while the runs without the thermal niche projected a slight decrease of ~5%.

The most striking effect of climate change was in the demersal group where projections displayed two big drops in biomass depending on the different scenarios. Investigating the species within this group revealed that cod was causing most of this variation (Figure 6). The cod stock experienced two severe declines in biomass in year 2032 and 2060, happening only in the scenarios where NorESM was used as forcing and the thermal niche was turned on (NorESM_temp and NorESM_ice_t). The biomass in these years was reduced by ~60% with catches reduced to ~50% compared to current levels (year 2005–2020).

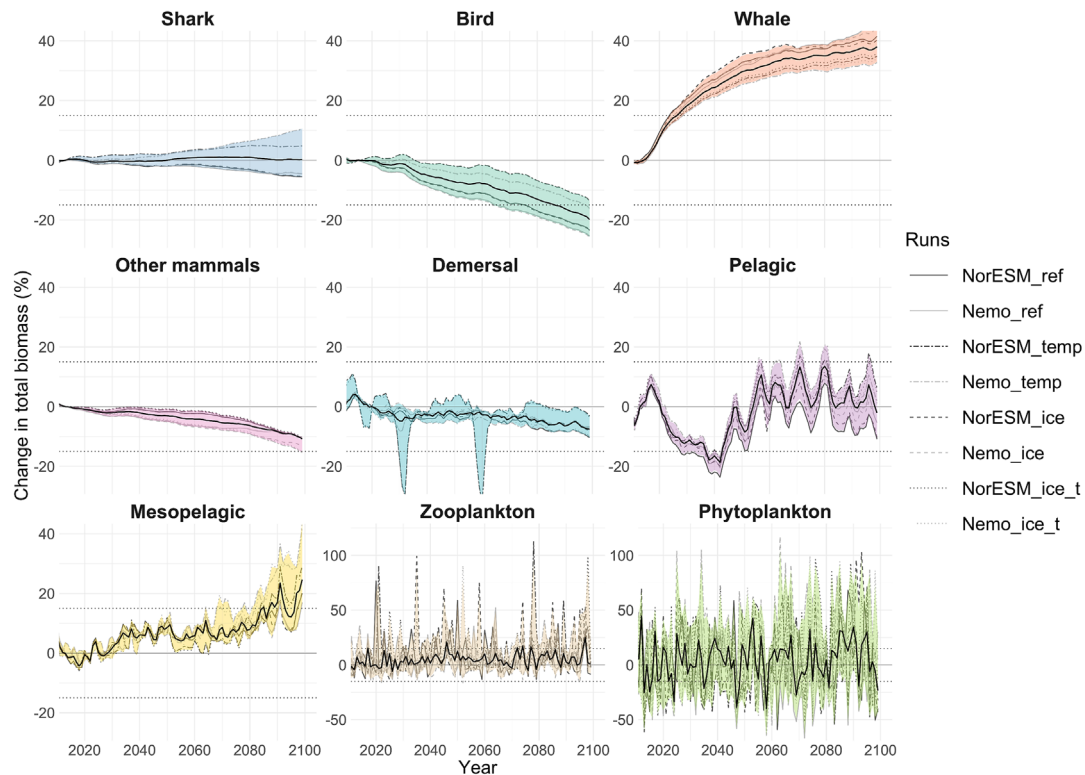


FIGURE 5 Projected changes in total biomass for various species groups. Grey lines represent the projected biomass from the different simulations, while black solid line shows median, and shaded area shows the 95% confidence interval. Horizontal dotted lines indicate changes greater than 15%. Please note that the number of species within each category varies and that the y-axes for the zooplankton and phytoplankton groups differ from the others.

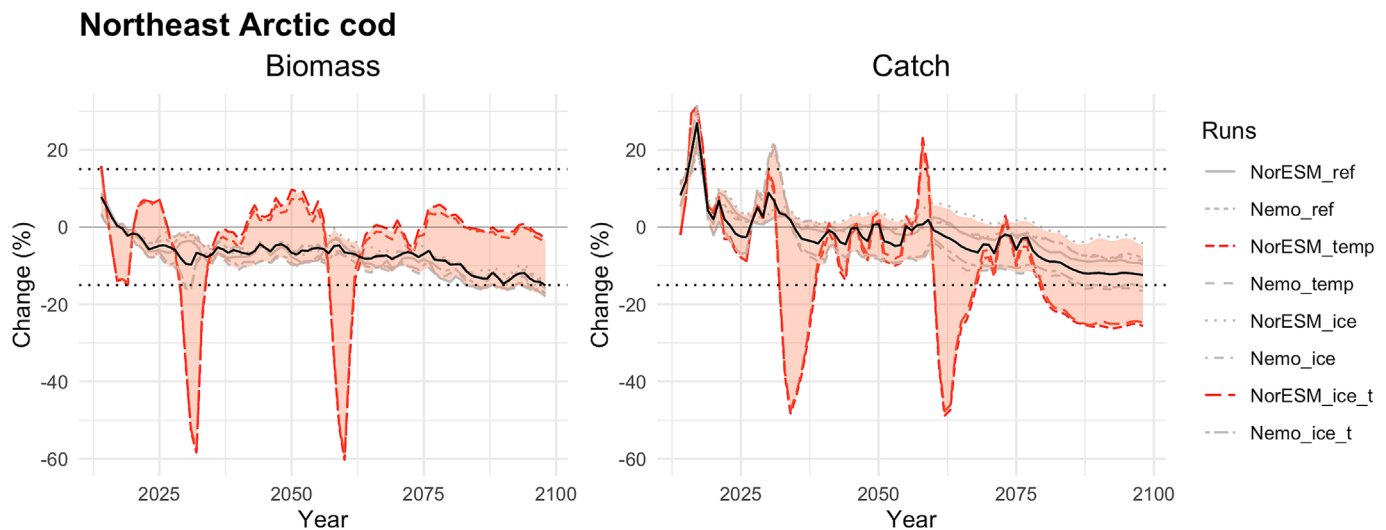


FIGURE 6 Projected changes in Northeast Arctic cod biomass and annual catches in scenarios with various physical forcing and parameter settings showed several drops in biomass. Grey lines represent the projected biomass from the different scenarios with the two projections resulting in collapse marked as red. The black solid line shows median biomass, and shaded area shows the 95% confidence interval. Lines indicating changes greater than 15% was marked as horizontal dotted lines.

Investigating the collapses further revealed that the temperatures in the spawning areas of cod were lower in NorESM compared to Nemo. The minimum spawning temperature of cod was set to 4°C based on literature (Bergstad et al., 1987; Höffle et al., 2014; Langangen et al., 2019; Righton et al., 2010; Sandø et al., 2020), and temperature in NorESM was thereby below the tolerated temperature for cod to spawn, resulting in recruitment failure. This could clearly be observed as intermittent declines in temperature in the spawning area were followed by stock collapses and occurred when NorESM had particularly low temperatures. Although the temperatures from Nemo also occasionally dropped below 4°C, the durations of these events were generally much shorter. The individual species within each category were investigated separately to reveal if this was happening in any of the other species as well (Figure S6), but this mainly occurred with cod.

Comparing the early period to the late period showed that both models projected notable changes in distribution for the different commercial species, especially for herring (*Clupea harengus*), saithe (*Pollachius virens*), cod, golden redfish (*Sebastes norvegicus*), and Greenland halibut. All these species moved in a northeastern direction, with the exception of saithe, which moved northwest. Turning on the thermal niche slightly increased the change in distribution, but the overall results were more or less the same for all the scenarios. The change in distribution also appeared gradually for these species, as opposed to a sudden shift in distribution. A summary of the distance between the early and the late period can be found in Table S3.

4 | DISCUSSION

In this study, we had two objectives. First, to study how much we gain when applying downscaled forcing compared to forcing from a global

climate model in a coarse resolution end-to-end ecosystem model simulation. And second, to evaluate expected ecosystem changes in the Nordic and Barents Seas under future climate changes with the two different types of forcing.

What we gain from downscaled physics was interpreted at the resolution of our ecosystem model, NoBa, and therefore, the translation from Nemo-NAA10km and NorESM2 onto NoBa was critical. Comparing the physical forcing in Nemo and NorESM revealed that the temperature and ice cover varied between the two models even after being converted to the coarse NoBa grid. Nemo projected higher temperatures in the upper water column around Svalbard, while NorESM projected higher temperatures below 150 m in the Norwegian Sea (Figure 2a). The temperature difference slightly increased throughout the simulation. The sea ice cover in terms of area with ice concentration >30% was similar in the two models for the early period, while in the late period Nemo projected less ice than NorESM. The distributions of the sea ice cover also differed between the models with Nemo projecting more ice east of Greenland compared to NorESM (Figure 3).

A large part of the differences between NorESM and Nemo was most likely a result of the different horizontal resolutions of NorESM2 and Nemo-NAA10km. It is well known that the representation of currents, fronts, and sites of deep convection are improved with an increased horizontal resolution of ocean models (Busecke et al., 2019; Kirtman et al., 2012; Langehaug et al., 2019). In the Nordic and Barents Seas, increased resolution typically leads to an increased northward transport of heat and salt (Langehaug et al., 2019), which brings the simulated temperature and salinity closer to the observed. NorESM2 and Nemo-NAA10km further have different vertical coordinate systems, vertical resolution, and physical parameterizations, which all have an impact on the representation of vertical mixing and the bottom boundary currents. Also, the river forcing and the sea ice

modules differ between the models, which can give rise to differences in the freshwater budget. To get around problems with biases in the physical forcing, adopting an anomaly approach could be a possible solution, that is, where the ecosystem model is forced with modeled changes from present climatology, instead of the modeled full field hydrography. Similar approaches are used for example in data assimilation (Bethke et al., 2021), and in acidification studies (Fransner et al., 2022), and could be applied to future ecosystem studies. A detailed investigation of the inter-model differences would require an extensive analysis of the simulated ocean dynamics and additional sensitivity runs and is beyond the scope of this paper.

The lower trophic levels in NoBa responded quickly to changes in physics and were generally more variable than the higher trophic levels.

The results of the study were therefore in line with the findings that the lower trophic levels were more sensitive to the resolution of the physical forcing (Hansen & Samuelsen, 2009; Lee et al., 2016; Skogen et al., 2018), although a direct comparison is not easy as NoBa has a coarse resolution and is better at capturing the dynamics of higher trophic level species. While variable, the projected lower trophic level biomass showed no clear trend with time in the various simulations. This could be due to the fact that the planktonic groups in NoBa are divided based on size rather than species, where the size classes have wide temperature ranges and will therefore not be constrained by the thermal niche. Generally, high-latitude spring-bloom ecosystems should benefit from higher temperatures giving increased production, but other factors like changes in mixed-layer-depth may alter this (Skogen et al., 2018). Other recent papers have also found uncertainty in projections of future trends in plankton and net primary production, but more agreement across models and stronger impacts regarding the effects of climate change on higher trophic levels (Heneghan et al., 2021; Lotze et al., 2019; Skogen et al., 2018; Tittensor et al., 2021).

Generally, few species responded differently to using forcing from NorESM2 compared to Nemo-NAA10km (Figure 4). The high trophic level species that stood out in our results were cod, long rough dab, and Greenland halibut, where all three had in common that they responded in the simulations where the thermal niche was turned on. Cod had the most dramatic response where events of massive recruitment failure occurred in NorESM, leading to collapses in total biomass and greatly reduced catches (Figure 6). This was due to the temperature in NorESM occasionally falling below the tolerated spawning temperature of cod. Investigating the temperature in the polygons where the adult long rough dab spawned revealed that, similar to cod, the temperature in NorESM was occasionally below their tolerated spawning temperature in several of the polygons, leading to a reduced recruitment. Greenland halibut, on the other hand, responded positively in the NorESM scenario as opposed to the other two. This response was due to the reduction in long rough dab (and partly cod) as these prey on the same species and overlap in distribution.

Investigating which traits might influence stability showed that species with short lifespans were more variable in the model. Lower trophic level species and species with narrower thermal niches

experienced higher variability, although the significance of this correlation depended on whether all species were studied or just vertebrates were included. Vertebrate species also experienced higher variability when occupying a smaller habitat at model initialization. Lower trophic levels, which consistently responded more strongly to changes in physical forcing, include a temperature correction in the growth rates. The correction is higher for phytoplankton than other species (Hansen et al., 2016) and might lead to stronger responses in phytoplankton-feeding organisms (like zooplankton) which in turn could impact other zooplankton-feeding species (such as prawns). The response to this variability is dampened through the system (Bracis et al., 2020; Hansen, Drinkwater, et al., 2019; Pantus, 2007). In addition, plankton and other invertebrates use all their energy to grow (in our model formulation), while vertebrates devote energy to reproduction. Furthermore, our results suggest that for vertebrates in particular, traits such as lifespan, thermal niche, and area occupied influence stability.

Turning on the thermal niche had a larger effect on the species when comparing the scenarios, both in terms of how the species responded to the physical forcing from NorESM or Nemo, and their projections in a future warmer climate. The temperature ranges that were set in NoBa were based on literature, but species temperature tolerance is uncertain, and in our model especially for the functional groups and non-commercial species where information is scarce. Even for cod, the tolerated temperature range for spawning grounds has been discussed in several studies (Bergstad et al., 1987; Höffle et al., 2014; Langangen et al., 2019; Righton et al., 2010; Sandø et al., 2020) with minimum temperature ranging from 2.0°C to 6.5°C. The lowest tolerated temperature for cod spawning was set to 4°C in NoBa, but this divergence reflects the uncertainty regarding the species' tolerated temperature ranges. Another issue was that due to the coarse spatial resolution of NoBa, the temperature range of several species had to be adjusted to allow them to be in areas where they had been observed historically (Table S1). The thermal niche also affected the species in such a way that if the temperature was outside the species range it could not spawn or inhabit that polygon. Given the coarse resolution of NoBa, future studies might benefit from adjusting this parameter to first *reduce* the spawning or habitat quality before inhibiting it when the temperature is outside the tolerated range.

Adding ice as forcing had a weaker effect on the species compared to the thermal niche, especially for the higher trophic level species discussed above. However, many Arctic species are known to be highly dependent on ice (Kearney et al., 2021). Polar cod (*Boreogadus saida*) is an example of such a species, where the reduction in ice cover projected by the SSP5-8.5 scenario is expected to severely impair their recruitment and habitat conditions (Gjøsæter et al., 2020; Kjesbu et al., 2022). The fact that polar cod was not negatively affected in our projections suggests that further development of the ice parameters in the NoBa model is needed, as the link between the species and their dependence on ice might be too weak. This was the first attempt at applying ice in an Atlantis model, and for future studies, the link between the survival of a species and its dependency on ice should be revised.

There was a Northeastern shift in some species throughout the simulations. The same trends were observed in Nemo and NorESM and occurred independent of whether the various settings were turned on. As most vertebrate species in NoBa are restricted to seasonal migrations, the species cannot move into completely new areas, but how the stock is distributed within the given polygons can change. When the thermal niche is turned off, the distribution depends on migration pattern and food availability. Since the trends were observed in all scenarios, this indicates that the Northeastern shift was caused by a change in food availability. The primary production in NoBa is affected by light and nutrients, and the reduced ice coverage in NorESM and Nemo would therefore lead to increased production further north which can explain the shift in distribution. These results are consistent with other studies indicating increased primary production in the Arctic Ocean (Steinacher et al., 2010; Vancoppenolle et al., 2013) and species moving further North (Fossheim et al., 2015; Frainer et al., 2017).

Another trend in response to future climate changes was that whales and mesopelagic species were increasing, while sea birds and other marine mammals were declining. Sea birds are expected to decline under future climate changes (Dias et al., 2019; Mitchell et al., 2020) due to a higher frequency of extreme weather events and lower food supply. Marine mammals that depend on ice (such as polar bear and seals included in the “other mammals” group) are also expected to decline due to habitat loss, while the effects on whales are more uncertain (Kovacs & Lydersen, 2008). Mesopelagic species are less studied but are expected to be positively impacted based on assessment reports (Kraft et al., 2021). The projected trends are therefore in line with what other studies have suggested.

Overall, most of the higher trophic level species did not respond notably to using physics from the global model compared to the regional. The NoBa simulations also mostly agreed on the sign of future changes with both sets of forcing. Our results therefore indicate that for modelers lacking available downscaled physical forcing, using physics from a global model could be sufficient to study climate effects on higher trophic level species. This is in line with Drenkard et al. (2021) who have suggested a pragmatic approach when considering if downscaling is needed for ecosystem studies. They argue that the primary objective of downscaling should be to resolve ocean features (e.g., mesoscale activity and upwelling; Small et al., 2015) that are important for the species that are being studied, which are not captured by the global climate model.

The case of cod illustrates such an ocean feature, in this case the temperature at spawning grounds, that must be downscaled properly given what we know about that species and how it is represented in the ecosystem model. The future state of the cod stock and potential consequences for fisheries are uncertain. A warmer climate might increase suitable feeding areas for cod (Kjesbu et al., 2022), while at the same time cause potential negative effects on its prey species (Gjøsæter et al., 2020). However, the collapses of the cod stock in our results were caused by cooler temperatures, not warmer. Although the stock has been at low levels before (ICES, 2021), sudden collapses, like the ones projected in the scenarios using NorESM and turning on the thermal niche, have not been reported and seem rather unlikely.

To analyze the results and determine the effects of the different physical forcing on the species we chose to set certain boundaries. Whether the species were regarded as impacted, or if the change in distribution point was significant depended on the boundaries set prior to the study, as well as the periods that were chosen to study changes throughout the simulation. All of these choices inevitably affect the results and how we interpret them. A crucial uncertainty regarding the results of this study is where we set these limits, as well as the assumptions within the models. The temperature ranges set for the thermal niche, as discussed above, are also uncertain and demonstrate another boundary setting that should be treated with caution. It should also be noted that the species were not parameterized to be affected by the salinity (which differed greatly between Nemo and NorESM) and were only marginally affected by ice. The results could therefore have been entirely different if the dependency on salinity and ice were strengthened. There were also species that were excluded which could have impacted the results, including haddock, snow crab, and king crab. The recruitment of haddock strongly depends on variability in lower trophic levels, which results in high variability in biomass and makes it unrealistically sensitive to any perturbations (Olsen et al., 2019). Snow crab larval dispersion was not parameterized correctly in this study which caused it to collapse, while king crab is currently represented as biomass pools instead of individuals which leads to unrealistic behavior, and the group is therefore in the process of being reparameterized as a vertebrate.

Using ensembles of ecosystem models (Heneghan et al., 2021; Lotze et al., 2019; Tittensor et al., 2021) or multiple climate models and projections (IPCC, 2022) to deal with uncertainty is commonly applied, but this study also highlights the benefits of using multiple sets of physical forcing to deal with uncertainty.

5 | CONCLUSIONS

This study focused on investigating ecosystem changes in the Nordic and Barents Seas under the future climate, as well as how much we gain from applying downscaled forcing compared to forcing from a global model in a coarse resolution ecosystem model. Most commercial species were projected to move further north as a response to future temperature change, which is consistent with previous studies suggesting a borealization of the Arctic Ocean/Barents Sea with climate change (Fossheim et al., 2015; Frainer et al., 2017). Whales and mesopelagic species were increasing, while sea birds and other marine mammals were declining, which is also in line with former studies (Dias et al., 2019; Kovacs & Lydersen, 2008; Mitchell et al., 2020).

Higher trophic levels were generally not particularly impacted by using downscaled physics compared to physics from a global model. This suggests that physical forcing from global models in many cases is sufficient to study higher trophic levels. However, cod illustrates an exception to this, and we demonstrated how even minor differences in temperature may impact the modeled species. The reason behind cod being particularly sensitive was that the temperature in the spawning areas was below the tolerated temperature range. This

highlights the need for higher precision when dealing with species with higher sensitivity to the physical environment, in which cases downscaling can become of importance. Without access to the down-scaled physical forcing the results would project collapses in the future cod stock, which would be of huge importance as cod is the most valuable stock in the Norwegian economy.

AUTHOR CONTRIBUTIONS

The study was conceptualized by Ina Nilsen, Cecilie Hansen, and Are Olsen and methods developed by all authors. Modeling, analysis, and interpretation of results were carried out by Ina Nilsen, Cecilie Hansen, Are Olsen, Filippa Fransner, Jerry Tjiputra, and Robinson Hordoir. The manuscript was drafted by Ina Nilsen, while all authors contributed to the review and approval of the manuscript.

ACKNOWLEDGMENTS

This work was funded by the Research Council of Norway (RCN) through the project The Nansen Legacy (AeN, RCN 276730). We also want to thank Isaac Kaplan for constructive comments on a previous version of the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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REFERENCES

- Audzijonyte, A., Gorton, R., Kaplan, I. C., & Fulton, E. A. (2017). Atlantis User's Guide Part I: General Overview, Physics & Ecology
- Audzijonyte, A., Pethybridge, H., Porobic, J., Gorton, R., Kaplan, I., & Fulton, E. A. (2019). Atlantis: A spatially explicit end-to-end marine ecosystem model with dynamically integrated physics, ecology and socio-economic modules. *Methods in Ecology and Evolution*, 10, 1814–1819. <https://doi.org/10.1111/2041-210X.13272>
- Bentsen. (2021). BLOM (Bergen Layered Ocean Model), Model Item, OpenGMS. <https://geomodeling.njnu.edu.cn/modelitem/6e2fc63b-5013-4c75-babf-3d413ded5b1f>
- Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., Roelandt, C., Seierstad, I. A., Hoose, C., & Kristjánsson, J. E. (2013). The Norwegian Earth System Model, NorESM1-M— Part 1: Description and basic evaluation of the physical climate. *Geoscientific Model Development*, 6, 687–720. <https://doi.org/10.5194/gmd-6-687-2013>
- Bergstad, O. A., Jørgensen, T., & Dragesund, O. (1987). Life history and ecology of the gadoid resources of the Barents Sea. *Fisheries Research*, 5, 119–161. [https://doi.org/10.1016/0165-7836\(87\)90037-3](https://doi.org/10.1016/0165-7836(87)90037-3)
- Bethke, I., Wang, Y., Counillon, F., Keenlyside, N., Kimmritz, M., Fransner, F., Samuelsen, A., Langehaug, H., Svendsen, L., Chiu, P.-G., Passos, L., Bentsen, M., Guo, C., Gupta, A., Tjiputra, J., Kirkevåg, A., Olivie, D., Seland, Ø., Solsvik Vågane, J., ... Eldevik, T. (2021). NorCPM1 and its contribution to CMIP6 DCP. *Geoscientific Model Development*, 14, 7073–7116. <https://doi.org/10.5194/gmd-14-7073-2021>
- Bracis, C., Lehuta, S., Savina-Rolland, M., Travers-Trolet, M., & Girardin, R. (2020). Improving confidence in complex ecosystem models: The sensitivity analysis of an Atlantis ecosystem model. *Ecological Modelling*, 431, 109133. <https://doi.org/10.1016/j.ecolmodel.2020.109133>
- Busecke, J. J. M., Resplandy, L., & Dunne, J. P. (2019). The equatorial undercurrent and the oxygen minimum zone in the Pacific. *Geophysical Research Letters*, 46, 6716–6725. <https://doi.org/10.1029/2019GL082692>
- Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R., Zeller, D., & Pauly, D. (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, 16, 24–35. <https://doi.org/10.1111/j.1365-2486.2009.01995.x>
- Comiso, J. C. (2012). Large decadal decline of the Arctic multiyear ice cover. *Journal of Climate*, 25, 1176–1193. <https://doi.org/10.1175/JCLI-D-11-00113.1>
- Dias, M. P., Martin, R., Pearmain, E. J., Burfield, I. J., Small, C., Phillips, R. A., Yates, O., Lascelles, B., Borboroglu, P. G., & Croxall, J. P. (2019). Threats to seabirds: A global assessment. *Biological Conservation*, 237, 525–537. <https://doi.org/10.1016/j.biocon.2019.06.033>
- Drenkard, E. J., Stock, C., Ross, A. C., Dixon, K. W., Adcroft, A., Alexander, M., Balaji, V., Bograd, S. J., Butenschön, M., Cheng, W., Churchtser, E., Lorenzo, E. D., Dussin, R., Haynie, A. C., Harrison, M., Hermann, A., Hollowed, A., Holsman, K., Holt, J., ... Wang, M. (2021). Next-generation regional ocean projections for living marine resource management in a changing climate. *ICES Journal of Marine Science*, 78, 1969–1987. <https://doi.org/10.1093/icesjms/fsab100>
- Egbert, G. D., & Erofeeva, S. Y. (2002). Efficient inverse modeling of barotropic ocean tides. *Journal of Atmospheric and Oceanic Technology*, 19, 183–204. [https://doi.org/10.1175/1520-0426\(2002\)019<0183:EIMOBO>2.0.CO;2](https://doi.org/10.1175/1520-0426(2002)019<0183:EIMOBO>2.0.CO;2)
- Ekström, M., Grose, M. R., & Whetton, P. H. (2015). An appraisal of downscaling methods used in climate change research. *WIREs Climate Change*, 6, 301–319. <https://doi.org/10.1002/wcc.339>
- Fagundes, M., Litvin, S. Y., Micheli, F., De Leo, G., Boch, C. A., Barry, J. P., Omidvar, S., & Woodson, C. B. (2020). Downscaling global ocean climate models improves estimates of exposure regimes in coastal environments. *Scientific Reports*, 10, 14227. <https://doi.org/10.1038/s41598-020-71169-6>
- Fishbase. (2022). World Wide Web electronic publication. www.fishbase.org
- Fossheim, M., Primicerio, R., Johannesen, E., Ingvaldsen, R., Aschan, M., & Dolgov, A. (2015). Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nature Climate Change*, 5, 673–677. <https://doi.org/10.1038/nclimate2647>
- Frainer, A., Primicerio, R., Kortsch, S., Aune, M., Dolgov, A. V., Fossheim, M., & Aschan, M. M. (2017). Climate-driven changes in functional biogeography of Arctic marine fish communities. *PNAS*, 114, 12202–12207. <https://doi.org/10.1073/pnas.1706080114>
- Fransner, F., Fröb, F., Tjiputra, J., Goris, N., Lauvset, S. K., Skjelvan, I., Jeansson, E., Omar, A., Chierici, M., Jones, E., Fransson, A., Ólafsdóttir, S. R., Johannesen, T., & Olsen, A. (2022). Acidification of the Nordic Seas. *Biogeosciences*, 19, 979–1012. <https://doi.org/10.5194/bg-19-979-2022>
- Fulton, E. A., Link, J. S., Kaplan, I. C., Savina-Rolland, M., Johnson, P., Ainsworth, C., Horne, P., Gorton, R., Gamble, R. J., Smith, A. D. M., & Smith, D. C. (2011). Lessons in modelling and management of marine ecosystems: The Atlantis experience. *Fish and Fisheries*, 12, 171–188. <https://doi.org/10.1111/j.1467-2979.2011.00412.x>
- Gjøsæter, H., Huserbråten, M., Vikebø, F., & Eriksen, E. (2020). Key processes regulating the early life history of Barents Sea polar cod. *Polar Biology*, 43, 1015–1027. <https://doi.org/10.1007/s00300-020-02656-9>

- Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S. K., Huse, G., Huth, A., Jepsen, J. U., Jørgensen, C., Mooij, W. M., Müller, B., Pe'er, G., Piou, C., Railsback, S. F., Robbins, A. M., ... DeAngelis, D. L. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, 198, 115–126. <https://doi.org/10.1016/j.ecolmodel.2006.04.023>
- Grimm, V., Railsback, S. F., Vincenot, C. E., Berger, U., Gallagher, C., DeAngelis, D. L., Edmonds, B., Ge, J., Giske, J., Groeneveld, J., Johnston, A. S. A., Milles, A., Nabe-Nielsen, J., Polhill, J. G., Radchuk, V., Rohwäder, M.-S., Stillman, R. A., Thiele, J. C., & Ayllón, D. (2020). The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. *JASSS*, 23, 7. <https://doi.org/10.18564/jasss.4259>
- Hansen, C., Drinkwater, K. F., Jähkel, A., Fulton, E. A., Gorton, R., & Skern-Mauritzen, M. (2019). Sensitivity of the Norwegian and Barents Sea Atlantis end-to-end ecosystem model to parameter perturbations of key species. *PLoS ONE*, 14, e0210419. <https://doi.org/10.1371/journal.pone.0210419>
- Hansen, C., Nash, R. D. M., Drinkwater, K. F., & Hjøllø, S. S. (2019). Management scenarios under climate change—A study of the Nordic and Barents Seas. *Frontiers in Marine Science*, 6, 668. <https://doi.org/10.3389/fmars.2019.00668>
- Hansen, C., & Samuelsen, A. (2009). Influence of horizontal model grid resolution on the simulated primary production in an embedded primary production model in the Norwegian Sea. *Journal of Marine Systems*, 75, 236–244. <https://doi.org/10.1016/j.jmarsys.2008.10.004>
- Hansen, C., Skern-Mauritzen, M., van der Meeren, G., Jähkel, A., & Drinkwater, K. (2016). Set-up of the Nordic and Barents Seas (NoBa) Atlantis model. <https://doi.org/10.13140/RG.2.1.3339.9929>
- Heneghan, R. F., Galbraith, E., Blanchard, J. L., Harrison, C., Barrier, N., Bulman, C., Cheung, W., Coll, M., Eddy, T. D., Erasquin-Extramiana, M., Everett, J. D., Fernandes-Salvador, J. A., Gascuel, D., Guiet, J., Maury, O., Palacios-Abrantes, J., Petrik, C. M., du Pontavice, H., Richardson, A. J., ... Tittensor, D. P. (2021). Disentangling diverse responses to climate change among global marine ecosystem models. *Progress in Oceanography*, 198, 102659. <https://doi.org/10.1016/j.pcean.2021.102659>
- Henson, S. A., Beaulieu, C., Ilyina, T., John, J. G., Long, M., Séférian, R., Tjiputra, J., & Sarmiento, J. L. (2017). Rapid emergence of climate change in environmental drivers of marine ecosystems. *Nature Communications*, 8, 14682. <https://doi.org/10.1038/ncomms14682>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., ... Thépaut, J.-N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049. <https://doi.org/10.1002/qj.3803>
- Höfle, H., Solemdal, P., Korsbrekke, K., Johannessen, M., Bakkeplass, K., & Kjesbu, O. S. (2014). Variability of northeast Arctic cod (*Gadus morhua*) distribution on the main spawning grounds in relation to biophysical factors. *ICES Journal of Marine Science*, 71, 1317–1331. <https://doi.org/10.1093/icesjms/fsu126>
- Hordoir, R., Skagseth, Ø., Ingvaldsen, R. B., Sandø, A. B., Löptien, U., Dietze, H., Gierisch, A. M. U., Assmann, K. M., Lundesgaard, Ø., & Lind, S. (2022). Changes in Arctic stratification and mixed layer depth cycle: A modeling analysis. *Journal of Geophysical Research, Oceans*, 127, 2021JC017270. <https://doi.org/10.1029/2021JC017270>
- International Council for the Exploration of the Sea. (2020). Working Group on Widely Distributed Stocks (WGWIDE). ICES Scientific Reports. 2:82, 1019 pp. <https://doi.org/10.17895/ices.pub.7475>
- International Council for the Exploration of the Sea. (2021). Arctic Fisheries Working Group (AFWG). ICES Scientific Reports. 3:58, 817 pp. <https://doi.org/10.17895/ices.pub.8196>
- Intergovernmental Panel on Climate Change. (2022). Climate Change 2022: Impacts, adaptation, and vulnerability. In *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Kearney, K. A., Alexander, M., Aydin, K., Cheng, W., Hermann, A. J., Hervieux, G., & Ortiz, I. (2021). Seasonal predictability of sea ice and bottom temperature across the eastern Bering Sea shelf. *Journal of Geophysical Research, Oceans*, 126, e2021JC017545. <https://doi.org/10.1029/2021JC017545>
- Kirtman, B. P., Bitz, C., Bryan, F., Collins, W., Dennis, J., Hearn, N., Kinter, J. L., Loft, R., Rousset, C., Siqueira, L., Stan, C., Tomas, R., & Vertenstein, M. (2012). Impact of ocean model resolution on CCSM climate simulations. *Climate Dynamics*, 39, 1303–1328. <https://doi.org/10.1007/s00382-012-1500-3>
- Kjesbu, O. S., Bogstad, B., Devine, J. A., Gjøsæter, H., Howell, D., Ingvaldsen, R. B., Nash, R. D. M., & Skjæraasen, J. E. (2014). Synergies between climate and management for Atlantic cod fisheries at high latitudes. *PNAS*, 111, 3478–3483. <https://doi.org/10.1073/pnas.1316342111>
- Kjesbu, O. S., Sundby, S., Sandø, A. B., Alix, M., Hjøllø, S. S., Tiedemann, M., Skern-Mauritzen, M., Junge, C., Fosshem, M., Thorsen Broms, C., Søvik, G., Zimmermann, F., Nedreaas, K., Eriksen, E., Höfle, H., Hjelset, A. M., Kvamme, C., Reecht, Y., Knutsen, H., ... Huse, G. (2022). Highly mixed impacts of near-future climate change on stock productivity proxies in the North East Atlantic. *Fish and Fisheries*, 23, 601–615. <https://doi.org/10.1111/faf.12635>
- Kovacs, K. M., & Lydersen, C. (2008). Climate change impacts on seals and whales in the North Atlantic Arctic and adjacent shelf seas. *Science Progress*, 91, 117–150. <https://doi.org/10.3184/003685008X324010>
- Kraft, B., Rivera, A.M., Mozfar, B., Skern, R., Dahle, G., Sundby, S., Thorsen, A., Asplin, L., & Wehde, H. (2021). Assessment of Fish Spawning in the North Sea; Final Project Report of KINO-2, 2017–2021. Havforskningssinstituttet nr 2021-17
- Langangen, Ø., Färber, L., Stige, L. C., Diekert, F. K., Barth, J. M. I., Matschner, M., Berg, P. R., Star, B., Stenseth, N. C., Jentoft, S., & Durant, J. M. (2019). Ticket to spawn: Combining economic and genetic data to evaluate the effect of climate and demographic structure on spawning distribution in Atlantic cod. *Global Change Biology*, 25, 134–143. <https://doi.org/10.1111/gcb.14474>
- Langehaug, H. R., Sandø, A. B., Årthun, M., & Ilıcak, M. (2019). Variability along the Atlantic water pathway in the forced Norwegian Earth System Model. *Climate Dynamics*, 52, 1211–1230. <https://doi.org/10.1007/s00382-018-4184-5>
- Lee, Y. J., Matrai, P. A., Friedrichs, M. A. M., Saba, V. S., Aumont, O., Babin, M., Buitenhuis, E. T., Chevallier, M., de Mora, L., Dessert, M., Dunne, J. P., Ellingsen, I. H., Feldman, D., Frouin, R., Gehlen, M., Gorgues, T., Ilyina, T., Jin, M., John, J. G., ... Zhang, J. (2016). Net primary productivity estimates and environmental variables in the Arctic Ocean: An assessment of coupled physical-biogeochemical models. *Journal of Geophysical Research, Oceans*, 121, 8635–8669. <https://doi.org/10.1002/2016JC011993>
- Lindstrøm, U., Smout, S., Howell, D., & Bogstad, B. (2009). Modelling multi-species interactions in the Barents Sea ecosystem with special emphasis on minke whales and their interactions with cod, herring and capelin. *Deep Sea Research Part II: Topical Studies in Oceanography, The Proceedings of the ECONORTH Symposium on Ecosystem Dynamics in the Norwegian Sea and Barents Sea*, 56, 2068–2079. <https://doi.org/10.1016/j.dsr2.2008.11.017>
- Lotze, H. K., Tittensor, D. P., Bryndum-Buchholz, A., Eddy, T. D., Cheung, W. W. L., Galbraith, E. D., Barange, M., Barrier, N., Bianchi, D., Blanchard, J. L., Bopp, L., Büchner, M., Bulman, C. M., Carozza, D. A., Christensen, V., Coll, M., Dunne, J. P., Fulton, E. A., Jennings, S., ... Worm, B. (2019). Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proceedings of the*

- National Academy of Sciences, 116, 12907–12912. <https://doi.org/10.1073/pnas.1900194116>
- Melsom, A., Lien, V. S., & Budgell, W. P. (2009). Using the Regional Ocean Modeling System (ROMS) to improve the ocean circulation from a GCM 20th century simulation. *Ocean Dynamics*, 59, 969–981. <https://doi.org/10.1007/s10236-009-0222-5>
- Mitchell, I., Daunt, F., Frederiksen, M., & Wade, K. (2020). *Impacts of climate change on seabirds, relevant to the coastal and marine environment around the UK* (pp. 382–399). Marine Climate Change Impacts Partnership.
- Mohr, S. H., Wang, J., Ellem, G., Ward, J., & Giurco, D. (2015). Projection of world fossil fuels by country. *Fuel*, 141, 120–135. <https://doi.org/10.1016/j.fuel.2014.10.030>
- Murray, A. G., & Parslow, J. S. (1997). *Port Phillip Bay integrated model: Final report*. CSIRO Environmental Projects Office. Technical Report No. 44. 201 pp. <https://doi.org/10.4225/08/585d683f7b126>
- Nielsen, I., Hansen, C., Kaplan, I., Holmes, E., & Langangen, Ø. (2022). Exploring the role of Northeast Atlantic cod in the Barents Sea food web using a multi-model approach. *Fish and Fisheries*, 23, 1083–1098. <https://doi.org/10.1111/faf.12671>
- Olsen, E., Hansen, C., Nilsen, I., Perryman, H., & Vikebø, F. (2019). Ecological effects and ecosystem shifts caused by mass mortality events on early life stages of fish. *Frontiers in Marine Science*, 6, 669. <https://doi.org/10.3389/fmars.2019.00669>
- O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, 9, 3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>
- Pantus, F. J. (2007). *Sensitivity analysis for complex ecosystem models* [PhD thesis, School of Physical Sciences, University of Queensland].
- Pauly, D., & Watson, R. (2005). Background and interpretation of the 'Marine Trophic Index' as a measure of biodiversity. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 360, 415–423. <https://doi.org/10.1098/rstb.2004.1597>
- Pedersen, T., Mikkelsen, N., Lindstrøm, U., Renaud, P. E., Nascimento, M. C., Blanchet, M.-A., Ellingsen, I. H., Jørgensen, L. L., & Blanchet, H. (2021). Overexploitation, recovery, and warming of the Barents Sea ecosystem during 1950–2013. *Frontiers in Marine Science*, 8, 732637. <https://doi.org/10.3389/fmars.2021.732637>
- Plagányi, É. E. (2007). *Models for an ecosystem approach to fisheries*. Food and Agricultural Organization. FAO Fisheries Technical Paper. 108 pp. <https://doi.org/10.25607/OBP-392>
- Planque, B., Favreau, A., Husson, B., Mousing, E. A., Hansen, C., Broms, C., Lindstrøm, U., & Sivel, E. (2022). Quantification of trophic interactions in the Norwegian Sea pelagic food-web over multiple decades. *ICES Journal of Marine Science*, 79, 1815–1830. <https://doi.org/10.1093/icesjms/fsac111>
- Planque, B., Lindstrøm, U., & Subbey, S. (2014). Non-deterministic modeling of food-web dynamics. *PLoS ONE*, 9, e108243. <https://doi.org/10.1371/journal.pone.0108243>
- Righton, D. A., Andersen, K. H., Neat, F., Thorsteinsson, V., Steingrund, P., Svedäng, H., Michalsen, K., Hinrichsen, H.-H., Bendall, V., Neuenfeldt, S., Wright, P., Jonsson, P., Huse, G., van der Kooij, J., Mosegaard, H., Hüsey, K., & Metcalfe, J. (2010). Thermal niche of Atlantic cod *Gadus morhua*: Limits, tolerance and optima. *Marine Ecology Progress Series*, 420, 1–13. <https://doi.org/10.3354/meps08889>
- RStudio Team. (2020). *RStudio: Integrated development for R* [WWW Document]. RStudio, PBC. <http://www.rstudio.com/>. Accessed 5.1.18
- Sandø, A. B., Johansen, G. O., Aglen, A., Stiansen, J. E., & Renner, A. H. H. (2020). Climate change and new potential spawning sites for Northeast Arctic cod. *Frontiers in Marine Science*, 7, 28. <https://doi.org/10.3389/fmars.2020.00028>
- Sandø, A. B., Melsom, A., & Budgell, W. P. (2014). Downscaling IPCC control run and future scenario with focus on the Barents Sea. *Ocean Dynamics*, 64, 927–949. <https://doi.org/10.1007/s10236-014-0731-8>
- Seland, Ø., Bentsen, M., Olivie, D., Toniazzo, T., Gjermundsen, A., Graff, L. S., Debernard, J. B., Gupta, A. K., He, Y.-C., Kirkevåg, A., Schwinger, J., Tjiputra, J., Aas, K. S., Bethke, I., Fan, Y., Griesfeller, J., Grini, A., Guo, C., Ilicak, M., ... Schulz, M. (2020). Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations. *Geoscientific Model Development*, 13, 6165–6200. <https://doi.org/10.5194/gmd-13-6165-2020>
- Skogen, M. D., Hjøllø, S. S., Sandø, A. B., & Tjiputra, J. (2018). Future ecosystem changes in the Northeast Atlantic: A comparison between a global and a regional model system. *ICES Journal of Marine Science*, 75, 2355–2369. <https://doi.org/10.1093/icesjms/fsy088>
- Small, R. J., Curchitser, E., Hedstrom, K., Kauffman, B., & Large, W. G. (2015). The Benguela upwelling system: Quantifying the sensitivity to resolution and coastal wind representation in a global climate model. *Journal of Climate*, 28, 9409–9432. <https://doi.org/10.1175/JCLI-D-15-0192.1>
- Smedsrud, L. H., Esau, I., Ingvaldsen, R. B., Eldevik, T., Haugan, P. M., Li, C., Lien, V. S., Olsen, A., Omar, A. M., Otterå, O. H., Risebrobakken, B., Sandø, A. B., Semenov, V. A., & Sorokina, S. A. (2013). The role of the Barents Sea in the Arctic climate system. *Reviews of Geophysics*, 51, 415–449. <https://doi.org/10.1002/rog.20017>
- Steinacher, M., Joos, F., Frölicher, T. L., Bopp, L., Cadule, P., Cocco, V., Doney, S. C., Gehlen, M., Lindsay, K., Moore, J. K., Schneider, B., & Segschneider, J. (2010). Projected 21st century decrease in marine productivity: A multi-model analysis. *Biogeosciences*, 7, 979–1005. <https://doi.org/10.5194/bg-7-979-2010>
- Stige, L. C., Eriksen, E., Dalpadado, P., & Ono, K. (2019). Direct and indirect effects of sea ice cover on major zooplankton groups and planktivorous fishes in the Barents Sea. *ICES Journal of Marine Science*, 76, i24–i36. <https://doi.org/10.1093/icesjms/fsz063>
- Tittensor, D. P., Novaglio, C., Harrison, C. S., Heneghan, R. F., Barrier, N., Bianchi, D., Bopp, L., Bryndum-Buchholz, A., Britten, G. L., Büchner, M., Cheung, W. W. L., Christensen, V., Coll, M., Dunne, J. P., Eddy, T. D., Everett, J. D., Fernandes-Salvador, J. A., Fulton, E. A., Galbraith, E. D., ... Blanchard, J. L. (2021). Next-generation ensemble projections reveal higher climate risks for marine ecosystems. *Nature Climate Change*, 11, 973–981. <https://doi.org/10.1038/s41558-021-01173-9>
- Tjiputra, J. F., Polzin, D., & Winguth, A. M. E. (2007). Assimilation of seasonal chlorophyll and nutrient data into an adjoint three-dimensional ocean carbon cycle model: Sensitivity analysis and ecosystem parameter optimization. *Global Biogeochemical Cycles*, 21, 1–13. <https://doi.org/10.1029/2006GB002745>
- Tjiputra, J. F., Roelandt, C., Bentsen, M., Lawrence, D. M., Lorentzen, T., Schwinger, J., Seland, Ø., & Heinze, C. (2013). Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM). *Geoscientific Model Development*, 6, 301–325. <https://doi.org/10.5194/gmd-6-301-2013>
- Tjiputra, J. F., Schwinger, J., Bentsen, M., Morée, A. L., Gao, S., Bethke, I., Heinze, C., Goris, N., Gupta, A., He, Y.-C., Olivie, D., Seland, Ø., & Schulz, M. (2020). Ocean biogeochemistry in the Norwegian Earth System Model version 2 (NorESM2). *Geoscientific Model Development*, 13, 2393–2431. <https://doi.org/10.5194/gmd-13-2393-2020>
- Vancoppenolle, M., Bopp, L., Madec, G., Dunne, J., Ilyina, T., Halloran, P. R., & Steiner, N. (2013). Future arctic ocean primary productivity from CMIP5 simulations: Uncertain outcome, but consistent mechanisms. *Global Biogeochemical Cycles*, 27, 605–619. <https://doi.org/10.1002/gbc.20055>

Wang, J., Feng, L., Tang, X., Bentley, Y., & Höök, M. (2017). The implications of fossil fuel supply constraints on climate change projections: A supply-side analysis. *Futures*, 86, 58–72. <https://doi.org/10.1016/j.futures.2016.04.007>

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How to cite this article: Nilsen, I., Fransner, F., Olsen, A., Tjiputra, J., Hordoir, R., & Hansen, C. (2023). Trivial gain of downscaling in future projections of higher trophic levels in the Nordic and Barents Seas. *Fisheries Oceanography*, 32(5), 479–493. <https://doi.org/10.1111/fog.12641>