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Review

Key physical processes and their model representation for projecting climate impacts on subarctic Atlantic net primary production: A synthesis

Mari S. Myksvoll [a,*], Anne Britt Sandø [a], Jerry Tjiputra [b], Annette Samuelsen [c], Veli Çağlar Yumruktepe [c], Camille Li [d], Erik A. Mousing [a], Joao P.H. Bettencourt [d], Geir Ottersen [e]

[a] Institute of Marine Research, and Bjerknes Center for Climate Research, Bergen, Norway
[b] NORCE Norwegian Research Centre, and Bjerknes Centre for Climate Research, Bergen, Norway
[c] Nansen Environmental and Remote Sensing Center, and Bjerknes Centre for Climate Research, Bergen, Norway
[d] Geophysical Institute, University of Bergen, and Bjerknes Centre for Climate Research, Bergen, Norway
[e] Institute of Marine Research, Bergen, Norway

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ABSTRACT

Oceanic net primary production forms the foundation of marine ecosystems. Understanding the impact of climate change on primary production is therefore critical and we rely on Earth System Models to project future changes. Stemming from their use of different physical dynamics and biogeochemical processes, these models yield a large spread in long-term projections of change on both the global and regional scale. Here we review the key physical processes and biogeochemical parameterizations that influence the estimation of primary production in Earth System Models and synthesize the available projections of productivity in the subarctic regions of the North Atlantic. The key processes and modelling issues we focus on are mixed layer depth dynamics, model resolution and the complexity and parameterization of biogeochemistry. From the model mean of five CMIP6 models, we found a large increase in PP in areas where the sea ice retreats throughout the 21st century. Stronger stratification and declining MLD in the Nordic Seas, caused by sea ice loss and regional freshening, reduce the vertical flux of nutrients into the photic zone. Following the synthesis of the primary production among the CMIP6 models, we recommend a number of measures: constraining model hindcasts through the assimilation of high-quality long-term observational records to improve physical and biogeochemical parameterizations in models, developing better parameterizations for the sub-grid scale processes, enhancing the model resolution, downscaling and multi-model comparison exercises for improved regional projections of primary production.

1. Introduction

The northern high-latitude spring bloom systems constitute a relatively small fraction of the world's ocean, but are nevertheless the most productive subregion considering fish catch (Hoegh-Guldberg et al., 2014). According to Hoegh-Guldberg et al. (2014), a total of approximately 20 million tons of fish are caught every year within a surface area of only 40 million km^2, meaning that 11% of the world's ocean generates 23% of the primary production and 29% of the fish catch (Table SM30-1 in Hoegh-Guldberg et al. (2014)). The Atlantic part of the unique subarctic ecosystem is the focus area in this synthesis paper, namely the Nordic Seas and the Barents Sea.

At high latitudes, seasonal primary production (PP) is marked by a spring bloom where productivity increases rapidly following stratification of the water column above the critical depth (Sverdrup, 1953) due to increasing temperature and irradiance (Zhao et al., 2013). Phytoplankton spring blooms are often dominated by large, colony-forming diatoms (Lochte et al., 1993) which can exhibit high growth rates under nutrient replete conditions. Following the initial bloom, nutrient concentrations decrease, giving smaller species a competitive advantage (Kiørboe, 1993) and smaller flagellates will often dominate during the summer period (Rey, 2004) when nutrient supply is restricted by strong stratification. As diatoms are typically opportunistic with blooms coming and going, the abundance of dinoflagellates and ciliates will increase towards summer (Sakshaug et al., 2009). In late fall and during the winter, decreasing light and upper ocean temperature combined with increasing wind-induced turbulence deepens the mixed layer, resulting in unfavorable conditions for phytoplankton growth

* Corresponding author at: PO Box 1870 Nordnes, 5817 Bergen, Norway.
E-mail address: mari.myksvoll@hi.no (M.S. Myksvoll).

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(Sakshaug et al., 2009). Temperature, light and nutrient availability are essential growth-limiting factors that, in turn, are regulated by physical processes related to ocean circulation, mixed-layer dynamics and the seasonal solar cycle (Behrenfeld et al., 2006).

The impacts of climate change on PP, are more pronounced in the Arctic and subarctic than almost anywhere else. The combination of sea ice loss, freshening, and changes in regional stratification directly affects the timing and distribution of PP, and indirectly through increased exposure of the surface ocean to atmospheric forcing (Meredith et al., 2019). *In situ* measurements (Stanley et al., 2015), modelling studies (Vancoppenolle et al., 2013, Jin et al., 2016) and satellite data (Arrigo & van Dijken 2011, 2015) all support that the decline in ice cover over recent decades has resulted in a pronounced increase in annual PP in now ice-free Arctic waters. Over the same period, Dalpadado et al. (2020) analyzed satellite derived PP estimates from 1998 to 2018 and found that the estimated PP in the Barents Sea more than doubled from around 40 to over 100 TgC yr^{-1}. While linked to sea ice loss, the authors underline that not only has the area available for phytoplankton production increased, but also the length of the growing season (Dalpadado et al., 2020). Regional studies also show a clear increase in production in the marginal ice zones of both hemispheres (Kulk et al., 2020). Thinner Arctic sea ice cover has led to the appearance of large and intense phytoplankton blooms that develop beneath first-year sea ice (Arrigo et al., 2012).

State-of-the-art coupled ocean biogeochemical general circulation models such that those included in Earth System Models (ESMs) are valuable tools to assess how PP would evolve under both historic times and future climate scenarios, complementing data from satellites in time and space. Nevertheless, these models vary in their physical dynamics and in the representation of biogeochemical process, yielding large spread in their long-term global and regional projected changes (Tagliabue et al., 2021). Despite this large spread, common large-scale features can be inferred from ESM simulations under future climate warming. Most ESMs project decreases in PP in low-latitude regions due to increased stratification and corresponding nutrient limitations (Bopp et al., 2013, Frölicher et al., 2016). PP is projected to decrease also in temperate regions with increase in stratification being the primary driver (Steinacher et al., 2010). At high latitudes, such as in the Arctic and the Southern Ocean, PP is projected to increase due to warming and increased light availability (Steinacher et al., 2010, Bindoff et al., 2019). In specific high-productive regions, like Eastern Boundary Upwelling Ecosystems (EBUE) and spring-bloom systems, the PP is expected to increase (Bakun et al., 2015). The balance between these regional changes will to a large extent determine the global PP trend (e.g., Nakamura and Oka (2019)).

There are large uncertainties in future projections of global PP. Laufkötter et al., (2015) estimate a change of between −15% and + 30% by the end of this century for the high-CO_2 emission scenario RCP8.5 projected by a subset of CMIP5 (Coupled Model Intercomparison Project phase 5) models. Under the same future scenario, the more recent IPCC special report on ocean and cryosphere reported that global PP is *very likely* to decline by 4–11% by 2081–2100 relative to 1850–1900 (Bindoff et al., 2019). However, there is a low confidence in this estimate due to the medium agreement among models and the limited evidence from observations (Bindoff et al., 2019). Uncertainties in the physical mechanisms as well as biogeochemical parameterizations further contribute to the large spread in PP projections (Laufkötter et al., 2015, Lee et al., 2016). Uncertainty in PP projections implies need for caution when extending the considerations to higher trophic levels (Chust et al., 2014).

The large-scale distribution of nutrients in models depends on aspects ranging from the simulated ocean circulation to the parameterizations of biogeochemical processes, such as sinking and remineralization of particulate organic matter (Schwinger et al., 2016). Furthermore, ESMs differ in the structure and parameterization of the ecosystem processes (Seferian et al., 2020), the impact of which has not

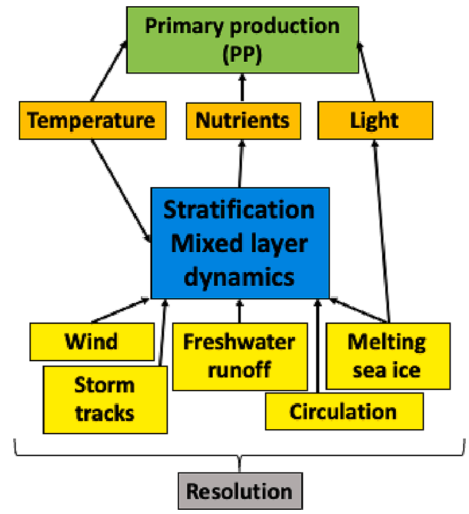

Fig. 1. Conceptual overview of the most important physical processes affecting primary production (PP) through temperature, nutrients, and light. Stratification and mixed layer dynamics influence the temperature and nutrient availability, and are themselves affected by physical factors like wind, storm tracks, freshwater runoff, melting of sea ice and circulation. How these physical factors including stratification and mixed layer dynamics are represented in ESM often depends on resolution.

been thoroughly assessed. Indeed, the biogeochemical formulations, parameterizations, and model physics do not operate independently, and this tight relation makes it a challenge to distinguish the source of uncertainties in the projections whether it is physics, biology, or a combination of both. It can also mask model shortcomings, such that, unresolved physical processes are to some degree compensated for by biogeochemical parameter tuning (Tjiputra et al., 2007). Therefore, one may not see an immediate improvement in realism in biogeochemical models with improved physics, and just as in physical models, a re-tuning of biogeochemical parameters is often needed. The major challenge in using ESMs to predict future PP is that they do not generally resolve the high productivity areas, like EBUE, which are related to small-scale dynamics near the coast. As biology and physics often interact at meso or smaller scales (Sinha et al., 2010, Mousing et al., 2016), local processes need to be realistically represented in ESMs to increase our confidence in model projections (Bopp et al., 2013). Therefore, a correct representation of the physics is particularly important, as biogeochemical models are only as good as the physical circulation framework in which they are coupled to (Doney 1999).

The objective of this study is to review the key physical processes and biogeochemical parameterizations that influence the estimates of primary production in ESMs and discuss these in relation with estimates from the recent CMIP6 (Coupled Model Intercomparison Project phase 6) models ensemble. The review also has a special focus on resolution issues since global primary production is modulated by small-scale physical processes that are not resolved in global models (Mahadevan 2019). We provide new estimates of future changes in primary production in the subarctic Atlantic region from five CMIP6 models and discuss recommendations on how to decrease uncertainty in future estimates of PP.

This is a synthesis paper, which aims to combine a literature review with recent results to provide new perspectives, and is organized correspondingly: in section 2 we review key physical processes affecting mixed layer dynamics, parameterizations of biogeochemistry and resolution issues related to PP; section 3 provides estimates of PP in the Nordic and Barents seas from CMIP6 models, and section 4 presents a synthesis in addition to discussion of uncertainties, challenges and future recommendations. A description of the methods applied in section 2.2 can be found in the supplementary material.

Table 1
Temperature dependence and nutrient acquisition parameters from various CMIP6 Earth System Models. Model specific temperature dependence parameters have been converted to the q_{10} equivalent (see supplementary material). Only the small/other phytoplankton groups have been extracted in models where multiple groups were present (*Models that only include one phytoplankton group).

#	Model	Ecosystem model	q_{10}	k_{NO3} (mmol m^{-3})	Reference (NPZD)
1	GFDL-ESM4.1	COBALTv2	1.89	0.49	Stock et al. (2020)
2	UKESM-1–0-LL	MEDUSA2.0	1.88	0.50	Yool et al. (2013)
3	CESM2	MARBL-BEC (METb)	2.00	0.50	Moore et al. (2004)
4	MIROC-ES2L	OECO2	1.89	0.50	Hajima et al. (2020)
5	CNRM-ESM2-1	PISCESv2-gas	1.88	0.13	Aumont et al. (2015)
6	CanESM5	CMOC*	1.62	0.10	Zahariev et al. (2008)
7	MPI-ESM1.2	HAMOCC6	1.88	0.16	Mauritsen et al. (2019)
8	NORESM2-LM	iHAMOCC*	1.88	0.64	Tjiputra et al. (2020)

2. Review of key physical processes and resolution issues

The key physical processes are those which affect the movement of the plankton themselves (sinking/retention/advection) and the growth of the phytoplankton, through the control of turbulent mixing and stratification, ultimately determining the availability of light and nutrients (Fig. 1). In polar regions, light availability is strongly limited by the presence of ice and snow. These processes are affected by changes in temperature and large-scale ocean circulation and will thus contribute to altering PP under global warming.

2.1. Factors affecting mixed layer dynamics

A proper understanding and representation of the upper water column, i.e., the mixed layer, are crucial for modeling PP. Surface warming, freshwater runoff, precipitation and melting of sea ice increase the stability of the water column, while wind mixing, surface cooling and evaporation contribute to destabilization. A realistic projection of light as a function of sea-ice thickness and extent (Yool et al., 2015), as well as a realistic ocean stratification and Mixed Layer Depth (MLD), are needed to get a good estimate of future PP, as changes in MLD during spring and summer might have large consequences for PP, e.g increased mixing during spring can delay the spring bloom (Vikebø et al., 2019).

Stratification can be defined as the density difference between the surface and 200 m depth (Fu et al., 2016). In a study by Fu et al. (2016), comparing nine CMIP5 models, the stratification was projected to increase in all models. In the Arctic Ocean and the subarctic Atlantic, the change was mainly caused by salinity changes. Consequently, all models display decreasing global trends for surface nitrate, phosphate, and silicic acid, while iron increases slightly. Two ESMs showed small changes in PP globally, while the others show large decreases (8–16%).

Huang et al. (2014) found a large spread in the MLD between 45 CMIP5 models. In general, most of the models have a MLD that is too shallow due to insufficient vertical mixing. Important physical processes for mixing in the upper ocean include surface waves, Langmuir circulation and wind-generated near-inertial waves, all of which are neglected in most models. Models that represent vertical mixing through a hybrid KPP (K-profile parameterization) and bulk mixed layer parametrization tend to produce a deeper MLD (Huang et al., 2014). However, Fox-Kemper et al. (2011) recommended mixed layer eddy parameterizations for general use in global climate models based on stability, minimal cost, and bias reduction, although the MLD is generally shallower when eddy parameterization is used. A model study using three phytoplankton functional types showed that deep MLD brought up more iron and phosphate, which favored the growth of diatoms and reduced production of calcifiers and the non-diatom phytoplankton groups (Sinha et al., 2010).

ESMs have some known biases in their representation of the atmospheric circulation in the subarctic Atlantic which could be of importance to the mixed layer dynamics. In general, the jet stream and storm tracks are too zonally oriented (i.e. do not have enough of a southwest-northeast tilt) and the cyclones are too weak (Zappa et al., 2013). CMIP6 models show reductions in the magnitude of these errors, particularly for the storm track, but the patterns of the errors remain (Harvey et al., 2020).

2.2. Complexity and parameterization of biogeochemistry

Biogeochemical models vary in complexity from simple nutrient models, over intermediate complexity nutrient-phytoplankton-zooplankton-detritus (NPZD) models (e.g., references in Table 1) to explicit size and trait-based models (Ward et al., 2012, Serra-Pompei et al., 2020). However, increasing complexity does not necessarily improve performance (Kriest et al., 2010), and the choice of model therefore depends on factors such as geographic area of interest, ecosystem complexity, research question and model purpose.

Seferian et al. (2020) provides an overview of the changes in complexity of the current generation of CMIP6 models compared to

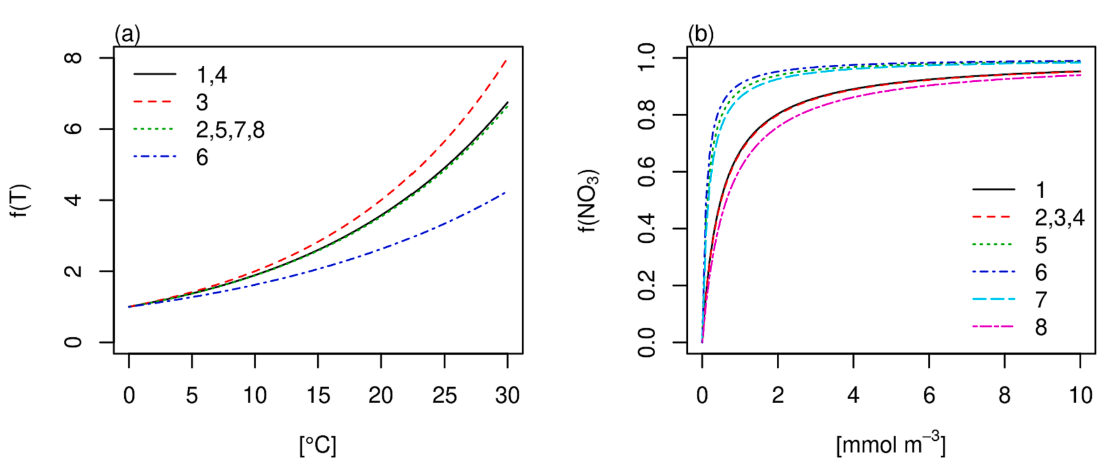

Fig. 2. Effects on the functional response of differences in parameterization between the ESMs listed in table 1 for a) temperature dependence on growth, b) nitrate uptake limitation. Most models include multiple functional groups, and, in these cases, we only include the smaller/other phytoplankton groups.

CMIP5 and concludes that the mean state of ocean biogeochemistry is more realistic, but that the causes of improvement are difficult to identify. In addition, it is also unclear how differences in the implementations and parameterization of the current generation of CMIP6 models impact the overall differences in model output (when compared to the impact of differences in ocean circulation). Here we focus on two parameters related to phytoplankton growth which are common among most models: temperature-dependent growth and nutrient uptake.

Fig. 2 and Table 1 summarize temperature dependence of growth (q_{10}) and the nitrate limitation term for a selection of CMIP6 models (see supplementary material). These models were chosen based on their ability to recalculate both variables into a general form. The temperature dependence varied between 1.62 and 2.00, with most models exhibiting a q_{10} of 1.88–1.89 which is the value originally suggested by Eppley (1972). Thus, while most models were similar, the CESM2 and CanESM5 differed by exhibiting a stronger vs. weaker response to increasing temperature (dashed red and dashed dotted blue lines, respectively in Fig. 2a). For the half-saturation constant, the models could be divided into two general groups: models with high affinity for nitrate uptake (<0.2) and models with lower affinity (>= 0.5). Fig. 2b, clearly exemplifies the differences, where the first group is virtually unlimited by external nutrient concentrations at ca. 2 mmol m^{-3} and greater, while the second group exhibit limitation at the entire range of nutrient presented, although with a considerable flattening of the curve at ca. 4–6 mmol m^{-3}.

The half-saturation constant for nutrient limitation, and to some degree temperature dependence, are often used as tuning parameters to achieve more realistic representations of specific phenomena. For example, adjustments were made to the half-saturation constant progressing from NorESM1 to NorESM2 to improve the representation of summer blooms in the Southern Ocean and total PP in high productivity areas like the Equatorial Pacific (Tjiputra et al., 2013, Tjiputra et al., 2020). Likewise, adjustments in the temperature dependence in MARBL-BEC (Moore et al., 2004), was done to improve production and biomass at high latitudes. Thus, mechanisms are added from the perspective of specific research questions, making it challenging to attribute any specific model improvements (e.g., primary productivity variability) to any particular model development.

The comparison of model output is further complicated when projecting change into the future. The half-saturation constants and temperature dependence are parameters representing the whole phytoplankton community and are based on observations of the present climate. However, phytoplankton species vary in the affinity for nutrient uptake which depends on size and acclimation processes (Lindemann et al., 2016). Given that the phytoplankton community structure is expected to change in the future (Acevedo-Trejos et al., 2014), using static parameters founded on present day observations are likely to be unrepresentative for the future. The PISCESv2-gas model is currently the only CMIP6 model that takes this into account (Aumont et al., 2015) by making the half-saturation constant dependent on the relative contribution of small vs. large phytoplankton, thus allowing the nutrient uptake dynamics to change with potential changes in the plankton community in a future ocean state.

2.3. Model resolution

While the biogeochemical model parameters strongly influence the vital biological processes, there is also a strong coupling between marine primary productivity and physical processes on different scales. With higher resolution, the modeled current field becomes much more energetic and eddying. There is also more vigorous vertical motion, though this does not always lead to more production. Both Lévy et al., (2012)(1/9° vs 1/54° resolution) and McKiver et al., (2015) (2° vs ¼° resolution) found that the location and extent of the subtropical gyres changed and that these were less productive when the resolution was increased. The higher-resolution simulations are in better agreement with ocean color observations in the subtropical gyres. Lévy et al. (2012) applied an idealized version of the subtropical/subpolar gyre in the North Atlantic and found a small reduction in the total primary production in the high-resolution model, despite a more vigorous vertical motion and increased production in the northern part of the domain. McKiver et al. (2015) compared a set of forced global ocean model simulations and found much higher production both at high latitudes and in coastal regions in their high-resolution simulation. The changes in coastal production were attributed to strengthened Ekman transport in the high-resolution model. Yool et al. (2015) compared a 1° and a ¼° model. In this case the models were fully coupled and were used to produce projections until 2100. They found that while changes in the Atlantic and Arctic were independent of resolution, the changes in the Pacific were different between the medium and fine resolution. The overall global trend is still the same at the two resolutions. Samuelsen et al. (2015) found that a forced 12 km (~1/8°) ocean model of the North Atlantic had improved nutrient distribution compared to a 30 km (~1/3°) resolution model when evaluated against in-situ observations. They attributed the change to improved circulation and placement of water masses.

Hansen and Samuelsen (2009) compared three simulations with different resolutions off the coast of Norway but found no large effect on the spring bloom timing. Nevertheless, they showed a large increase in new production in the eddy-resolving model simulation. McKiver et al. (2015) found the timing of the spring bloom was improved, but the magnitude overestimated in the high-resolution model. Based on these results it seems that some mixed-layer dynamics are resolved in high-resolution models but not sufficiently compensated for in low-resolution models through sub-grid scale parameterizations, which may lead to error in the timing of the spring bloom. Simulating the correct bloom timing is especially important if the results are used to force ecosystem models for higher trophic levels, where the life cycles are tightly linked to the changing of the seasons.

In another study targeting the resolution change only, Clayton et al. (2017) found that coupling the same ecological-biogeochemical model to a coarse-resolution (CR; 1°) and an eddy-permitting high-resolution (HR; 1/6°) global circulation model caused an overall decrease in annual mean PP and phytoplankton biomass at high latitudes in HR compared to CR. The global values of PP and phytoplankton biomass were similar between HR and CR. Zooplankton were less abundant in the northern subpolar gyres in HR. The differences were related to higher vertical nutrient supply in CR due to both advection and a deeper MLD. They also note that the onset of the spring bloom in the high latitudes is roughly 1 month earlier in the HR than in the CR.

Many early climate models (CMIP3) had the ice-edge in the subarctic Atlantic regions too far to the south (Arzel et al., 2006). And when the ice-edge retreats from this artificial position, the PP would increase. This was improved in the CMIP5 simulations (Sandø et al., 2014, Jin et al., 2016) and further in the CMIP6 simulations (Docquier et al., 2019). Comparing 5 different CMIP6 models with 12 different configurations, Docquier et al. (2019) conclude that with higher resolutions, models simulate stronger warm boundary currents and higher SST in the subarctic Atlantic resulting in an enhanced poleward ocean heat transport ultimately reducing sea ice area and volume. The Arctic sea-ice edge is also better represented with higher ocean resolution. The mean sea ice thickness among different models is either relatively similar or thinner with higher resolution. Hewitt et al. (2016), applying an eddy-resolving (1/12°) model compared to an eddy-permitting (1/4°) model, also report a reduced SST bias with increased poleward ocean heat transport, which reduces sea-ice extent. Likewise, Bindoff et al. (2019) report positive impacts of increased ocean resolution (~100 vs ~ 25 km) on Atlantic meridional overturning circulation, increased meridional ocean heat transport and more realistic sea-ice cover in ECMWF-IFS global circulation model.

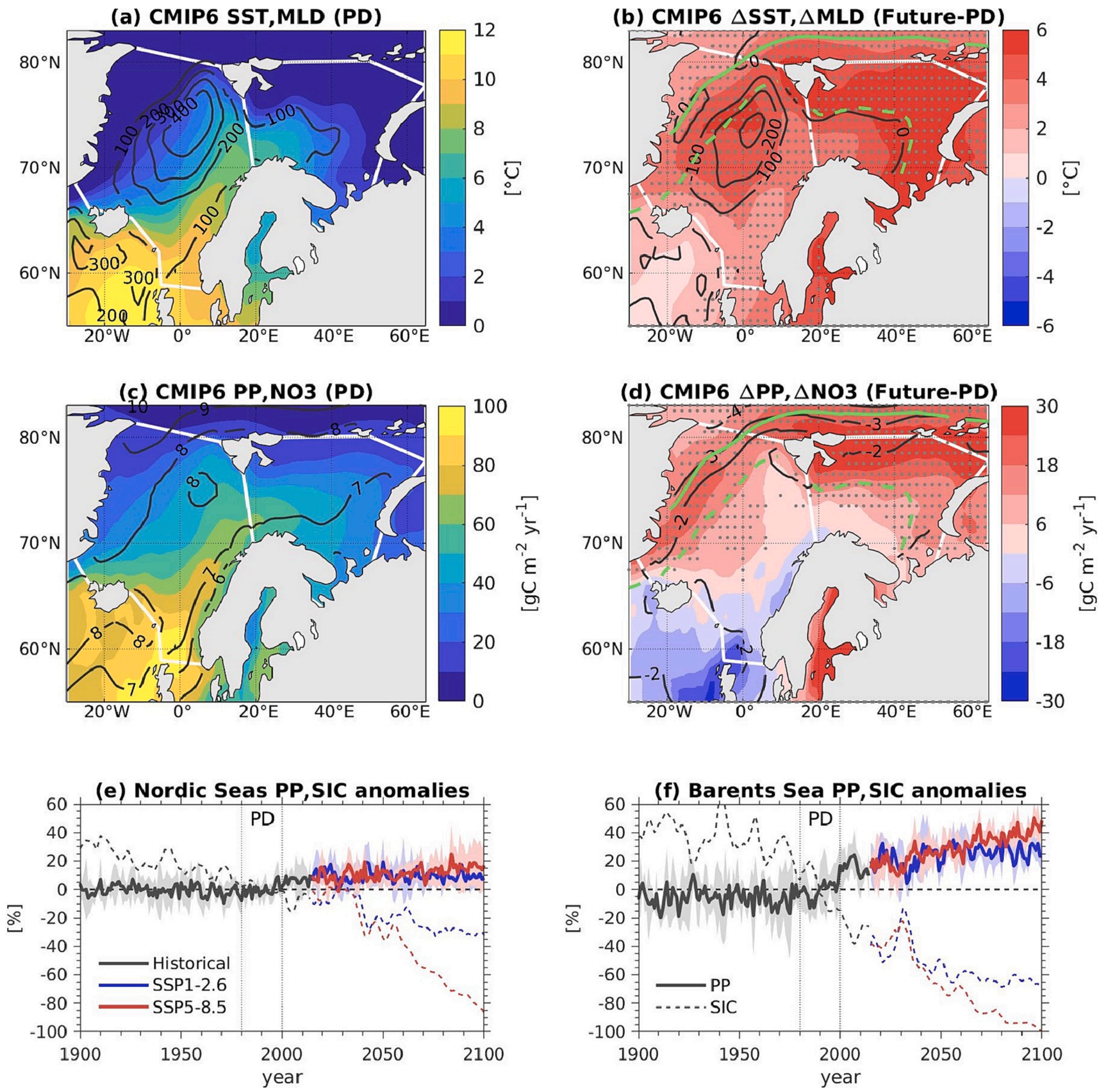

Fig. 3. Maps of simulated mean (a) sea surface temperature (color shading [°C]) and mixed layer depth (black contours [m]); (c) primary production (color shading [gC m^{-2} yr^{-1}]) and nitrate concentration (black contours [μmol L^{-1}]) under the present day period (1981–2000) together with the (b,d) respective mean changes by the end of the 21st century (2081–2100) under the business-as-usual SSP5-8.5 scenario. Solid and dashed green lines in (b,d) depict boundaries for sea-ice extent at 15% coverage under the future and present-day periods, respectively. Stipplings depicts grid points where all five ESMs agree in the sign of change. Panels (e,f) depict time-series of relative change (with respect to PD [%]) in the annual primary production (PP) and sea-ice extent (SIC) in the Nordic Seas and Barents Sea (see white outlines in panels a-d) under both historical as well as SSP1-2.6 and SSP5-8.5 future scenarios. Solid lines depict multi-model mean while color shadings (not shown for the SIC time-series) depict one-std multi-model spread. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Primary production in the Nordic Seas and the Barents sea from five CMIP6 models

The ESM simulations from CMIP6 have recently become available and the global projections of marine PP under different future scenarios have been assessed in Kwiatkowski et al. (2020). Here, we present projections of primary production in the Nordic Seas and the Barents Sea from five ESMs. We analyze simulations from historical and two contrasting future scenarios (i) the high-CO_2 SSP5-8.5 and (ii) the low-CO_2 SSP1-2.6. The latter was designed to simulate approximately 2 °C warming by 2100, while the former represents a business-as-usual non-mitigated scenario. The five ESMs are the (1) Commonwealth Scientific and Industrial Research Organisation ACCESS-ESM1.5 (Ziehn et al., 2020), (2) Institut Pierre Simon Laplace IPSL-CM6A-LR (Boucher et al., 2020), (3) Max Planck Institute for Meteorology MPI-ESM1.2-LR and (4) MPI-ESM1.2-HR (Mauritsen et al., 2019), and (5) Norwegian Climate Centre NorESM2-LM (Tjiputra et al., 2020). At the time of manuscript preparation, only these ESMs provide the necessary outputs for analysis, including PP, volume, and nutrient lateral transport fields.

For the present-day period (1981–2000; hereafter referred to as PD), the simulated annual PP rate in the Nordic Seas exhibits a wide range of estimates from 4.6 ± 0.6 to 18.2 ± 0.7 Tg C yr^{-1}, and similarly in the Barents Sea from 2.3 ± 0.3 to 6.0 ± 0.8 Tg C yr^{-1}. Nevertheless, all models display a consistent trend toward a more productive future by the end of the 21st century, ranging from 10% to 45% increase relative to PD (Fig. 3e,f). Higher increase is generally projected under the SSP5-8.5 than the SSP1-2.6.

Fig. 3a,b shows the distribution of PD sea surface temperature (SST) and mixed layer depth (MLD) from the CMIP6 multi-model mean as well as respective changes at the end of the 21st century (2081–2100) under the SSP5-8.5 scenario. In our study region, all models agree on the warming trend visible in all regions with the model-mean of warming as much as 6 °C in the Barents Sea. Consequently, in the Nordic Seas the CMIP6 ESMs project a relative stable and declining winter-spring mixed

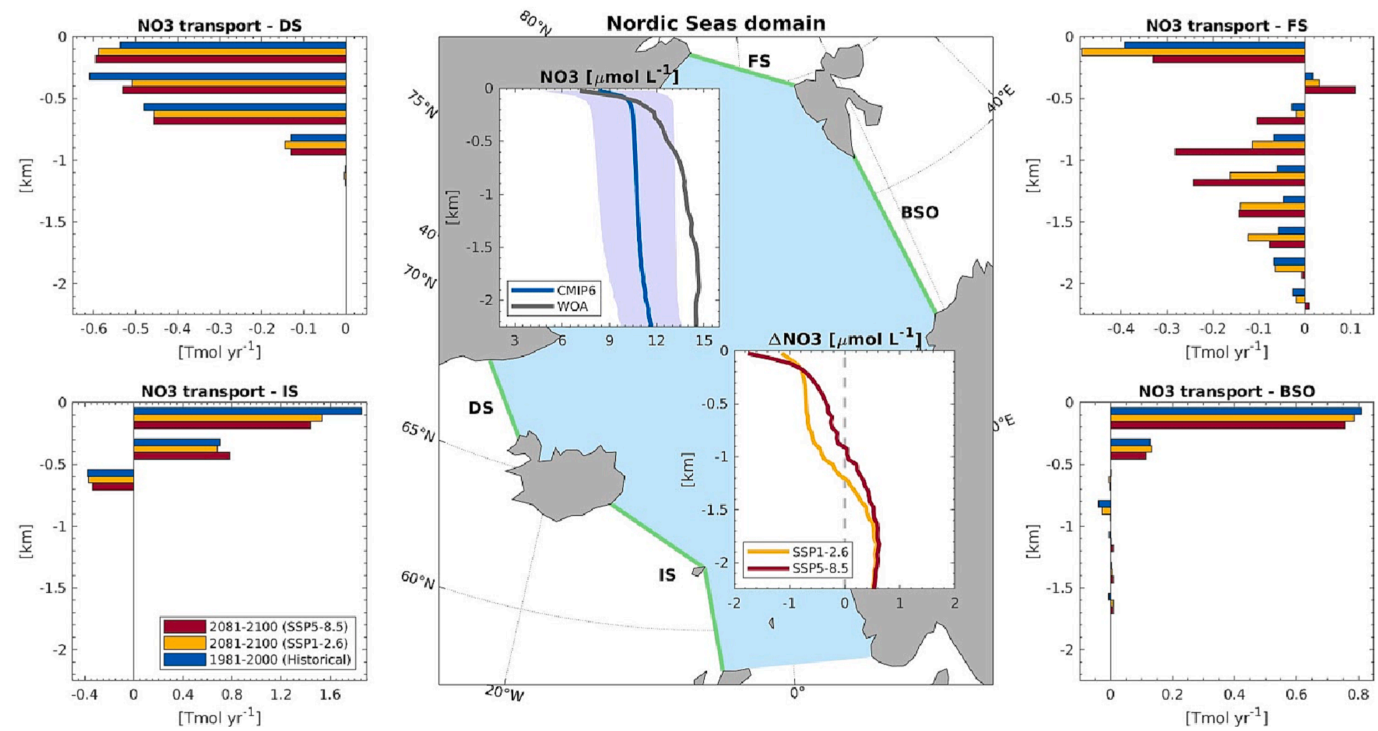

Fig. 4. Vertical profile of lateral nutrient (NO_3) transports across the boundaries of the Nordic Seas: DS - Denmark Strait, IS – Iceland-Scotland ridge, FS - Fram Strait, and BSO - Barents Sea Opening. Positive values depict north-eastward transport. Shown are multi-model mean from five CMIP6 ESMs, averaged over contemporary (1981–2000) and end of the 21st century (2081–2100; SSP1-2.6 and SSP5-8.5 scenarios). The middle panel illustrates the Nordic Seas domain and the NO_3 mean vertical profiles, averaged over the blue-shaded region, from model and climatological observations (WOA; (Garcia et al., 2013)) as well as the projected changes by the end of the 21st century. The lateral transports shown to the left and right are integrated at 250 m intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

layer depth (MLD) under the 21st century SSP1-2.6 and SSP5-8.5 scenarios, respectively. While a reduced MLD is often associated with a subsequent decline in primary production in many other parts of the world ocean, this is not the case in neither the Nordic Seas nor the Barents Sea.

In the Nordic Seas, the sea-ice area steadily declines under both future scenarios, with the multi-model annual mean indicates a sea-ice loss of $-84 \pm 16\%$ ($36 \pm 21\%$) by 2100 under the SSP5-8.5 (SSP1-2.6) scenario (Fig. 3e). In the Barents Sea, a strong decline in sea-ice extent is projected as early as 1970s, and by 2100 the annual mean sea-ice area is reduced by $-99 \pm 1\%$ ($-71 \pm 32\%$) under SSP5-8.5 (SSP1-2.6) (Fig. 3f). This suggests that the loss of sea-ice could be responsible for driving the higher primary productivity in both domains, for example by alleviating light and temperature limitation of phytoplankton growth rate, such as light or temperature. To illustrate this, Fig. 3d shows the map of projected changes in primary production from the multi model mean together with boundaries for sea-ice extent by the end of the 21st century (SSP5-8.5). Except for the southern Nordic Seas and western coast of Norway, an increase in annual productivity rates is simulated, with maximum increase situated in areas where the sea-ice has retreated. The PP increase is robust across all models, despite that the model-mean projection suggests a decline in surface nutrient (NO_3) concentration (Fig. 3d). The updated results from CMIP6 model are consistent with results from the previous CMIP5 model collection assessed by Vancoppenolle et al. (2013), even though they suggest a reduction in PP per unit area. This indicates that future environmental changes in the Nordic Seas and Barents Sea promote more efficient nutrient uptake and higher productivity.

Further, we assess the impact of climate change on the nutrient (specifically NO_3) budget in the Nordic Seas. Here, the observed vertical profile is characterized by low concentration at surface, increasing with depth, as shown in Fig. 4. The CMIP6 multi-model mean also exhibits a similar pattern but with lower and more uniform concentration below the MLD. As expected, warming-induced stratification, in both future scenarios, reduces the nutrient concentration in the upper ocean while increases it in the deeper layer. At the surface, NO_3 reduction of nearly 2 μmol L^{-1} under the SSP5-8.5 is comparable with estimates from CMIP5 models for the Arctic Ocean und RCP8.5 (Vancoppenolle et al., 2013). This enhanced vertical gradient suggests that less nutrients will be available for surface production in the future. Despite an altered vertical profile, there is no consensus among the models on the projected relative changes in the total nitrate budget in the Nordic Seas over the whole water column (blue shaded area in Fig. 4; i.e., ranges from -6% to $+6\%$ by the end of the 21st century relative to the present-day values). With respect to water column-integrated lateral transports of nutrients across the northeast (Fram Strait and Barents Sea Opening) and southwest (Denmark Strait and Iceland-Scotland Ridge) boundaries, there are generally little changes between present-day and future values, except for the Fram Strait, where the models simulate increasing transports in the future. Nevertheless, when looking at the near surface transports (0–250 m), there are noticeable changes between present and future SSP5-8.5 scenario across the Iceland-Scotland transect and the Fram Strait (IS and FS in Fig. 4). In these two sections, a reduction in the upper ocean NO_3 lateral influx under the SSP5-8.5 scenario is evident, reflecting the slowdown in the strength of the Atlantic Meridional overturning circulation (AMOC; Fig. 2 of Weijer et al. (2020)). This is also evident from the reduction in the volume transport. This influx reduction is consistent with the lower surface concentration. In addition to stratification, increased NO_3 at depth > 1 km can also be amplified by the higher primary production (hence higher export production) as well as the increase in lateral influxes across the Fram Strait.

Separating the time-series of relative change (with respect to PD) in the annual PP, MLD, and NO_3 into sea-ice covered and sea-ice free grid points, there is a clear difference between the positive trends in the

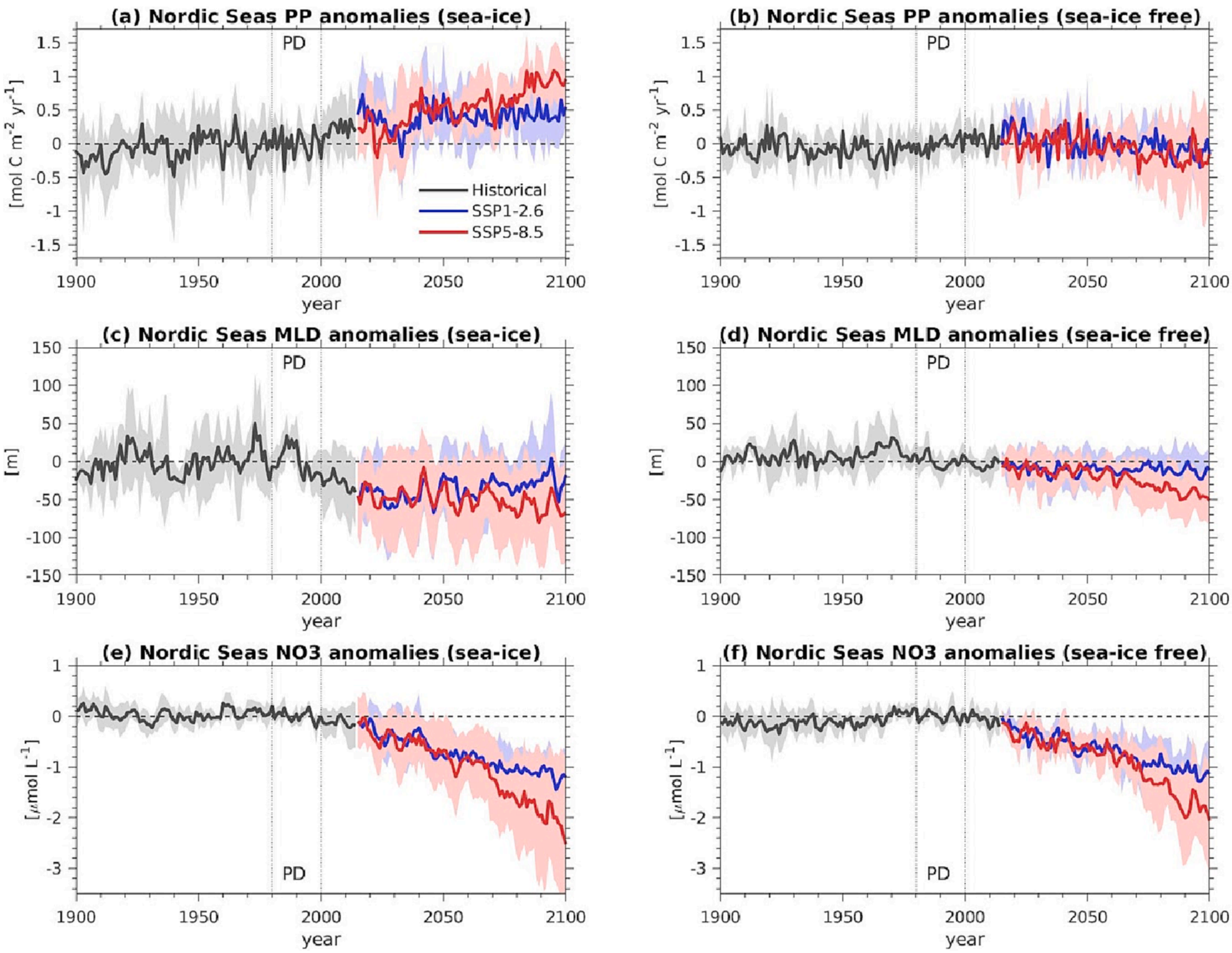

Fig. 5. Time-series of CMIP6 multi-model mean and (shading) one-std inter-model spread of (a,b) primary production, (c,d) mixed layer depth, and (e,f) surface nitrate anomalies. Panels (a,c,e) depict model values in model grid points where sea-ice exist in the first 50-yr of the historical experiment (1850–1999), whereas (b,d,f) depict only values from sea-ice free grid-points. NorESM2-LM is excluded in panel (c) due to its unexplained anomalous MLD increase in the 1990 s.

historically sea-ice covered grid points compared to those weak-to-no trends in the permanently sea-ice free grid points (Fig. 5a,b). Also, the reduction in the MLDs is greater at the beginning and middle of the 21st century in the sea-ice covered grid points, but these trends tend to stabilize towards the end of the century. For NO_3, there is no obvious difference between sea-ice covered and sea-ice free grid points, except for the model spread.

4. Discussion

4.1. Synthesis

Bopp et al. (2013) and Kwiatkowski et al. (2020) showed that the impacts of climate change on marine primary production are more pronounced in the Arctic and subarctic than almost anywhere else. Through our results we highlight the changes in the subarctic Atlantic, including a comparison of sea ice and sea ice free regions. Projections in the Nordic Seas and Barents Sea from the latest Earth System models illustrate the importance of key physical factors, like stratification and MLD, and biogeochemical parameterizations on future estimates of primary production.

Vancoppenolle et al. (2013) and Jin et al. (2016) reported that the largest increase in PP was found in areas where sea ice retreats throughout the 21st century. Also, in the Nordic Seas we found an increase in PP in the sea ice covered region (Fig. 5). As mentioned in section 2.3, the position of the Arctic sea-ice edge was non-realistic in previous ESMs for the historic period, however this has improved with higher resolution (Docquier et al., 2019). Since the impact on PP in the marginal ice-zone is so strong, it is of utmost importance to get the ice edge correct. In addition to higher resolution ESMs, dynamical downscaling has also been applied in the subarctic to improve the position of the ice-edge (Bindoff et al., 2019, Sandø et al., 2021, Hordoir et al., 2022). The large PP increase in the subarctic is also attributed by a strong warming, up to 6 °C in the Barents Sea.

Stronger stratification and declining MLD in the Nordic Seas, caused by sea ice loss and regional freshening, reduce the vertical flux of nutrients into the photic zone (Fig. 4). Changes in the circulation also affect the nutrient flux in the Fram strait specifically. Stronger stratification usually leads to a reduction in PP, as observed in the subtropics (Steinacher et al., 2010), however since nutrient availability is not the limiting factor in the subarctic, the increase in temperature and loss of sea ice cause an increase in PP (Nakamura & Oka 2019). Our results indicate that there will be higher productivity in the Nordic Seas and the Barents Sea with more efficient nutrient uptake. However, as pointed out in section 2.2, the half-saturation constants and temperature dependence are community parameters tuned to the present climate. As the phytoplankton community structure is expected to change in the future (Acevedo-Trejos et al., 2014), the CMIP6 models generally do not capture the dynamics of this transition since they do not include varying biogeochemical parameters for phytoplankton of different sizes.

As the northern high-latitude spring bloom system is among the most productive regions in the world, it is important to consider how future changes in PP will propagate to higher trophic levels. Our results indicate an increase in PP, which might be immediately perceived as positive also for zooplankton and fish recruitment. However, as pointed out in section 2.3, the uncertainty in the onset of the spring bloom (up to 1 month earlier in high resolution as compared to coarse resolution model) introduces also large uncertainty related to the impact on higher trophic levels. Fish recruitment is tightly linked to potential match/mismatch in zooplankton availability, which is controlled by the onset of spring bloom (Durant et al., 2007). Essential mechanisms for potential change in the subarctic Atlantic primary production in a future climate is the onset of the spring bloom and change in key variables as temperature, light and nutrient availability (Bindoff et al., 2019).

4.2. Uncertainties and challenges

The future hydrography and ocean circulation play key roles in terms of vertical stratification, poleward transports, and sea ice extent. Challenges in projecting these processes are related to uncertainties in global ESMs that do not resolve the high productivity areas. We summarize the uncertainties and challenges discussed in this synthesis within three research topics: PP historical trends and projections, parameterizations of biogeochemistry, and high (HR) and coarse (CR) resolution issues.

PP historical trends and projections

- Not straightforward to measure PP on regional to large scales, especially in the interior ocean, where earth observation systems are of very limited value and one depends on in situ measurements.
- ESMs do not generally resolve the known high productivity areas, which are relatively small and often located near the coast like EBUE.
- Low confidence in future projections (bias in amplitude and timing of seasonal productivity).
- Large differences in initial nutrient concentrations also contribute to the overall PP projection uncertainty.
- Large differences in representation of the sea-ice melting-induced freshwater budget in the subarctic Atlantic.
- CMIP6 models disagree on the sign of temperature changes south of the Greenland-Scotland Ridge and PP change in the Atlantic Water.

Parameterizations of biogeochemistry

- Biochemical models applied in the various CMIP6 models vary in complexity and parameterization, and there is considerable variation in the temperature and nutrient dependent performance.
- Uncertainty in physical forcing, which could either offset or amplify biases originated from the biogeochemical parameterizations.

High (HR) and coarse (CR) resolution issues

- Large uncertainty in position of ice-edge in CR CMIP5 models, partly improved in HR CMIP6 models due to improved poleward heat transport.
- CR CMIP5 models project increased stratification while observations and HR regional models show decreased stratification.
- Computational costs and needs for retuning of biogeochemical parameterizations.
- Unlikely to reach the stage where all the small-scale processes are resolved in global models or regional models.

As high-resolution global models are computationally expensive to run, dynamical downscaling can reduce the costs and improve the regional skill of global models thereby reducing biases resulting from unresolved regional processes through higher resolution (and improved parameterizations of smaller-scale physics and regional biogeochemistry; e.g., Skogen et al., 2018). For instance, using their regional model, Hordoir et al. (2022) showed that seasonal haline stratification will cease in an Arctic Ocean that is ice free throughout the year. This will have consequences for the mixed layer dynamics, especially in spring when the shoaling effect of melting sea ice on the surface mixed layer depth is no longer present. The model described by Hordoir et al. (2022) was able to represent the inter-annual variability of surface salinity observed during the last decades. This is of special importance for a realistic projection of Arctic primary production as the spring bloom depends on a stratification sufficient to keep the phytoplankton in the euphotic zone.

An important long-term goal is to enhance resolution to better represent coastal upwelling and mesoscale phenomena which support biological hot-spots (Godø et al., 2012, Bopp et al., 2013). This can be addressed through increased understanding of uncertainties that are related to model resolution by dedicated model experiments with the models where only the resolution is changed. It is therefore still a challenge that the most recent development in ESMs diverge more in future estimate of PP than previous versions in spite of some improvements in horizontal and vertical resolution (Kwiatkowski et al., 2020).

Also better parameterizations of unresolved processes that contribute to pronounced biases at regional scales should be in focus to improve simulations of biological production (Stock et al., 2011, Huang et al., 2014, Holt et al., 2017), keeping in mind that the Arctic amplification can lead to very different impacts of climate change on primary production in presently sea ice covered regions. Challenges reported from CMIP5, for the ocean specifically, was an overly deep tropical thermocline (Stouffer et al., 2017), and corresponding recommendations for CMIP6 were more focused on high resolution approaches to study influence of resolution on ocean circulation. Seferian et al. (2020) summarize the main improvements in CMIP6 compared to CMIP5 for simulated marine biogeochemistry, concluding that the latest development is more realistic since both horizontal and vertical resolution have increased and the new model versions have targeted missing processes. However, some CMIP6 models display larger model-data error than their predecessors suggesting that neither increasing resolution nor complexity automatically leads to model improvement in all metrics (Seferian et al., 2020). Response of marine biogeochemistry to variability in mesoscale and sub-mesoscale physics is still a missing factor. The projected decrease in primary production was reduced at the same time as inter-model spread increased, being consistently larger than scenario uncertainty. As the horizontal resolutions has increased in CMIP6, the representation of the physical environment has also improved (Davy & Outten 2020) while there has only been small changes in vertical resolution. It is interesting to note that even though the biogeochemical models have become more complex and realistic, the inter-model variability in PP has increased. Despite massive effort in development of the biogeochemical models, which has led to more consistent estimates of warming, acidification, deoxygenation and nitrate reduction, primary production is still an unresolved issue. The exception is at high latitudes, both in the Arctic and Southern Ocean, where changes in sea ice is such a strong driver and the projected increase in PP is mostly consistent across models and CMIPs. A recent prediction study also highlights the importance of air-sea interactions in regulating primary productivity in the stratified summer period, where atmospheric processes have stronger influence on surface productivity than ocean dynamics (Fransner et al., 2020).

4.3. Perspectives and future recommendations

Today, the state-of-the-art tool to project future climate change impact on regional marine ecosystem are ESMs. Even though these models have progressed tremendously over the past decades, outstanding limitations persist especially when applying them for regional scale impact assessment studies, as highlighted here. Incremental model developments through higher spatial resolutions and new process representations can be expected over the next few years. Nevertheless, an important objective of such global models is to capture

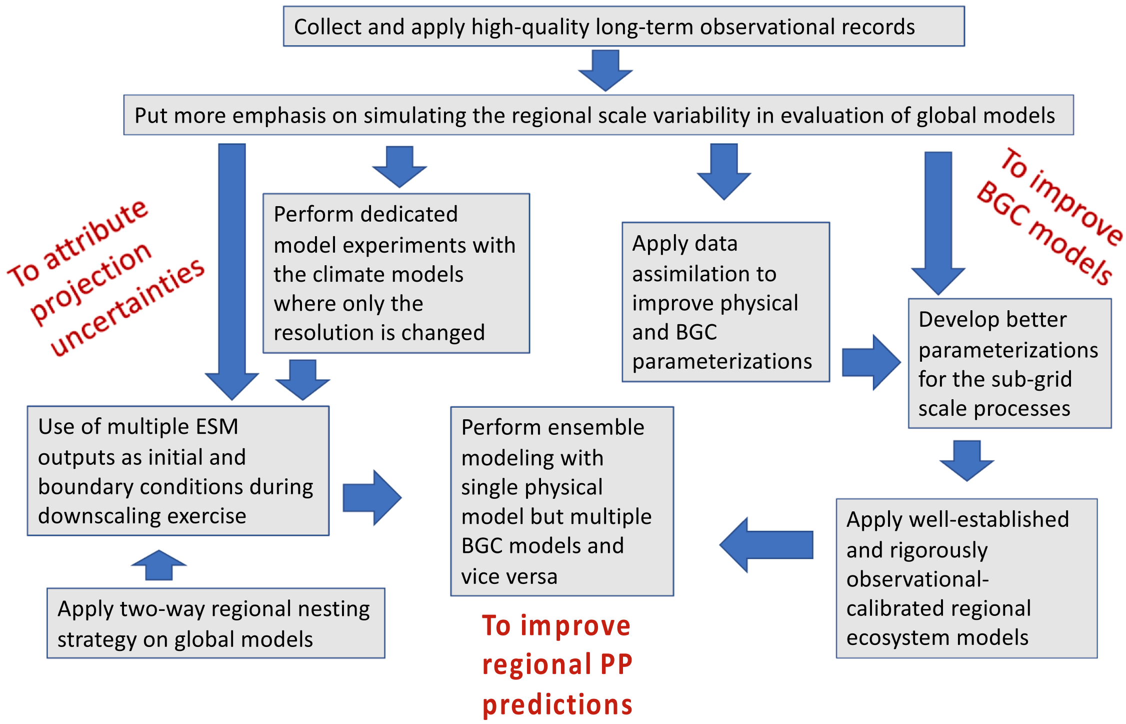

Fig. 6. Overview of recommendations to advance our understanding on the source of projection uncertainties and to constrain future PP projections on regional scale.

and study the observed large-scale climate variability and its interactions with the Earth's biosphere. Their large uncertainties on the regional scale are unlikely to be reduced substantially through conventional model developments.

To accelerate model improvement and increase credibility of future projections in dynamically complex regions such as the Arctic or subarctic, other approaches should be considered. Our recommendations for regional projections are illustrated in Fig. 6 and include chains of suggestions to improve the PP projections and attribute their uncertainties: (**1**) sustained and extended use of high-quality long-term observational records, particularly in regions with expected rapid climate change and (**2**) put more emphasis on simulation of the observed regional scale variability during global model developments. To improve BGC models for specific regions we suggest to (**3**) strengthen research in data assimilation with parameter estimation in biogeochemical models to obtain more consistent biogeochemical model estimates; (**4**) develop better parameterizations for the sub-grid scale processes; (**5**) perform community-motivated ensemble modeling exercise with single physical model but multiple biogeochemical models and vice versa to better attribute projection uncertainties. Furthermore, uncertainties that are related to model resolution in projections can be attributed by (**6**) dedicated model experiments with the climate models where only the resolution is changed; and (**7**) use of multiple ESM outputs as boundary conditions during downscaling exercise.

The Arctic Ocean and its neighboring seas represent the fastest-warming region of the world oceans (Meredith et al., 2019), but a large portion of this region remains lacking in long-term monitoring systems. This is especially true in the interior ocean, where earth observation systems are of very limited value and one depends on in situ measurements. While earth observation systems generally are well coordinated in large programs (like USA's NASA EOS and EU's Copernicus CMEMS), classic in situ observations, like research cruises, are to a large degree still organized at a local level.

Ideally, it would be useful to identify the optimal resolution that is needed at global scale to resolve the high productivity regions, specifically high-latitude spring bloom systems and eastern boundary upwelling systems. It is not necessary to apply high resolution globally, for instance, horizontally varying resolution or nested model systems are possible ways to move forward. Model resolution comparative studies cover a range of different resolutions from coarse resolution to eddy-permitting/resolving and sub-mesoscale resolutions, and they documented notable changes in primary production, circulation patterns, mixing and sea-ice coverage on the regional scale. The advantage of using sub-mesoscale resolutions is that models can resolve sub-mesoscale feedbacks on large scale fields, even with moderate changes.

In the subarctic Atlantic we are already experiencing fast climate change in a highly productive area (Hoegh-Guldberg et al., 2014). Even though the area considered here is relatively small, its contribution to the world ocean production on higher trophic levels is considerable. As PP forms the foundation for recruitment and biomass of commercial fish species, it is of utmost importance to evaluate the impacts of climate change on future PP and then evaluate the potential consequences for the existing fish stocks in this region as well as species that are migrating northwards due to climate change.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mari S. Myksvoll reports financial support was provided by Bjerknes Centre for Climate Research. Jerry Tjiputra reports financial support was provided by Research Council of Norway. Jerry Tjiputra reports financial support was provided by Trond Mohn Foundation.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pocean.2023.103084.

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