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Why do regional biogeochemical models produce contrasting future projections of primary production in the Barents Sea?

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A B S T R A C T

Projected future changes in primary production in the Barents Sea vary among different regional biogeochemical models, with some showing an increase, some a decrease, and some no change. This variability has been attributed to differences in the underlying physics, but little effort has been spent to understand the primary causal processes. In this study, we compare two extreme projections: one model (NORWECOM.E2E) projects a 36% increase and another model (SINMOD) projects a 9% decrease in primary production in a future warmer Barents Sea. Using structural equation modeling, we identify the direct and indirect effects of the major environmental variables on primary production. The results show that the two biogeochemical models agree on the directions of impacts, and that differences in the physical environment, specifically the factors controlling nutrient availability, are the main cause of the disparities. Both models agree that decreasing ice-coverage leads to increased primary production. However, the projection with a decrease in primary production was characterized by a decrease in winter nitrate concentrations and stronger temperature-induced stratification. By contrast, the projection with an increase in primary production was characterized by an increase in winter nitrate concentrations and weaker stratification due to a relatively smaller temperature increase which was offset by increasing wind stress. The results emphasize the need for accurate descriptions of the physical environments and inform discussions about the future of the Barents Sea ecosystem and the potential for Arctic blue growth.

1. Introduction

The Barents Sea is a seasonally ice-covered, highly productive, sub-Arctic shelf sea (Sakshaug, 2004). High primary production supports large populations of fish and marine mammals (Hunt Jr et al., 2013; Olsen et al., 2010) which in turn supports one of the largest fisheries in the world (ICES, 2021; Olsen et al., 2010). During recent decades, the Barents Sea has warmed extensively leading to decreasing ice-coverage (Arrigo and van Dijken, 2015), a pattern that is expected to continue in the future with the Barents Sea becoming completely ice-free during summer in the middle of the century (Onarheim and Årthun, 2017). This has already had clear implications for the Barents Sea ecosystem, leading to a substantial increase in primary- and secondary production (Dalpadado et al., 2020) and northwards shift in boreal fish stocks (Fossheim et al., 2015). While these changes are likely to impact the possibilities for human exploitation (Kjesbu et al., 2022), currently available regional climate projections show contrasting future changes in primary production, questioning if contemporary patterns of change can be extrapolated into an even warmer future.

Primary production in the Barents Sea is strongly affected by the summer ice-extent, which, in turn, is mainly controlled by the inflow of warm and saline water from the northern North Atlantic (Årthun et al., 2011; Sandø et al., 2021). Melting of sea-ice and inflow of warm water leads to the formation of the polar front, the position of which differs between years (Barton et al., 2018). Water masses north and east of the polar front are characterized as cold and dense with primary production light-limited due to the presence of ice (Wassmann et al., 2010). When the sea-ice melts in spring, strong haline stratification forms (Peralta-Ferriz and Woodgate, 2015) limiting vertical nutrient supply into the photic zone. South and west of the polar front, the mechanisms

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controlling primary production are more like the North Atlantic, where a strong pelagic spring bloom is followed by thermal stratification (Loeng and Drinkwater, 2007). In general, the Atlantic influenced region is more productive due to higher light availability and nutrient concentrations compared to the Arctic influenced region (Wassmann et al., 2010).

Global projections suggest an increase in primary production in the Arctic and sub-Arctic, primarily due to increased light availability following the loss of sea-ice (Jin et al., 2016). However, global models are not necessarily suitable for modeling regional scale processes as the circulation and bathymetry is not sufficiently resolved (Holt et al., 2017). For example, Huang et al. (2014) found that most CMIP5 models underestimated the summer mixed layer depth. In a recent study in the Nordic seas, including the Barents Sea, Skogen et al. (2018) compared a regional downscaling to the global model on which it was based and found that the regionally downscaled model performed better, both in terms of temperature and nutrient drawdown, when compared to observations. Thus, to resolve fine-scale physical-biological processes, it is necessary to downscale the global models using regional modeling systems.

Unfortunately, regionally downscaled models are not as available, and are usually only produced from a few global models and emission scenarios. For the Barents Sea, only a few published studies exist and, in contrast to the global models, they do not agree on the projected changes in primary production in a future warmer climate. Skaret et al. (2014) reported a 36% increase in primary production, Slagstad et al. (2015) reported a 9% decrease and Sandø et al. (2021) reported no long-term change. Holt et al. (2016) showed increases in primary production in the north and central Barents Sea and decreases along the Norwegian coast. It is currently not known why the existing projections differ and a qualitative comparison of the existing publications reveals little information on the major cause of disparity. The available projections have in common that they all conclude on how warming may impact primary production in the future, but they differ in their setup, simulations periods, emission scenarios, physical forcing, and ecological processes. As a result, the currently most objective conclusion is that primary production in a future Barents Sea will either increase, decrease or stay the same. Obviously, this conclusion, without proper context, is not informative from either a scientific or public point of view.

Therefore, in this study, we compare the model output of the two extreme scenarios, i.e., Skaret et al. (2014) using the NORWECOM.E2E and Slagstad et al. (2015) using SINMOD. Both models use the A1B emission scenario, are forced by regionally downscaled ocean physics, and apply ecosystem models of comparable complexity. We then apply a simple structural equation modeling framework to quantify the direct and indirect effects of changes in the environment on changes in primary production in order to identify the major causes of the contrasting conclusions.

2. Methods

2.1. Model descriptions

The two projections analyzed were based on two different ecosystem models: SINMOD and NORWECOM.E2E. The models and setups are described in the publications by Slagstad et al. (2015) and Skaret et al. (2014), as well as references within, and only a summary is provided below. For simplicity, we henceforth refer to the projections presented in these publications as their model names.

2.1.1. SINMOD

SINMOD is developed and maintained by the independent research institute SINTEF in Norway. The model is a coupled physical-biological modeling system consisting of a biogeochemical model for lower trophic levels and nutrient budgets. The phytoplankton includes flagellates and diatoms, whereas the zooplankton includes nano−/microzooplankton and two groups of mesozooplankton (*Calanus finmarchicus* and *C. glacialis*). The model was originally developed for the Barents Sea and validated against field observations (Wassmann et al., 2006). SINMOD has since then been used in several studies in the Arctic and the Barents Sea and has been continuously evaluated against observations (e.g., Lee et al., 2016).

In the study by Slagstad et al. (2015), a regional setup for the Nordic and Arctic seas was run for the present-day scenario (1979–2010) using forcing from the ERA INTERIM reanalysis whereas the future scenario (SRES A1B, 2001–2099) was forced by a regional downscaling (REMO; Keup-Thiel et al., 2006) of the global MPI-ECHAM5 model. The model was run with 25 vertical layers and 20 km horizontal resolution. In the current study, the initial period was averaged using output from the A1B simulation.

2.1.2. NORWECOM.E2E

The NORWegian ECOlogical Modeling system End-to-End (NORWECOM.E2E) is developed and maintained by the Institute of Marine Research (IMR) in Norway. The model is a fully coupled 3D modeling system with a biogeochemical model at its core, handling nutrient cycling and lower trophic levels. Several modules can be coupled, including individual-based models for several pelagic fish and *Calanus* species as well as modules for ocean acidification and contaminants. The model was developed for the Nordic seas and has been validated against field observations (Skaret et al., 2014; Skogen et al., 2007).

In the study by Skaret et al. (2014), the phytoplankton included flagellates and diatoms, whereas the zooplankton was represented by micro- and mesozooplankton fields in an NPZD model, as well as by an individual-based model for *C. finmarchicus*. The physical forcing was based on a regional downscaling (ROMS; Sandø et al., 2014) of the global GISS-AOM model. The initial (1981–2000) and future scenario (2046–2065) were simulated individually and were based on the IPCC 20C3M control run and SRES A1B emission scenario respectively. The model was run with 20 vertical layers and 10 km horizontal resolution.

2.2. Statistical analyses

All statistical analyses were performed in the free and open source statistical software R v3.6 (R Core Team, 2019). NetCDF files were read using the “ncdf4” package v1.19 (Pierce, 2021), and data wrangling was performed using the “tidyverse” package v1.3.1 (Wickham et al., 2019). Least square modeling was done using the “nlme” package v3.1.152 (Pinheiro et al., 2021) and VIF scores calculated using the “rms” package v5.1.4 (Harrell Jr, 2019). Plots were produced using the packages “pathdiagram” v0.1.9.1 (Sanchez, 2019), “ggplot2” v3.3.3 (Wickham, 2016) and “patchwork” v1.1.2 (Pedersen, 2022).

2.2.1. Variable extraction and preparation

The two models’ simulation periods differed, and the initial and future periods were therefore set to 2001–2010 and 2061–2070, respectively, for SINMOD, and 1990–1999 and 2050–2059, respectively, for NORWECOM.E2E. While the period definitions differ between the models, both represent a change of 60 years.

A detailed description of variable extraction and preparation is provided in the supplementary material. In summary, for each model and period, we extracted output of gross primary production, temperature, salinity, wind stress, fractional ice cover, mixed layer depth, and winter nitrate concentrations. Data from all variables except nitrate were subset to include only the productive months (April to September). For nitrate, which represents the nutrient conditions prior to the spring bloom, data from the winter months (November to February) were extracted. Gross primary production was integrated over the entire water column, whereas temperature, salinity and winter nitrate concentrations were averaged over the photic zone (defined as the upper 30 m). The mixed layer depth was calculated based on the density difference from the surface with a threshold of 0.125 kg m^{-3}. Ice-coverage was extracted directly from the physical forcing and represents the fractional ice-cover in each grid cell. Lastly, wind stress was calculated from input of wind speed at 10 m above the sea surface.

Variable layers were then averaged for the initial and future periods (see supplementary material) and the changes between the periods (deltas) calculated by subtracting the averaged fields for the initial period from the future periods. The resulting deltas were shifted to be zero centered and scaled to have unit variance to nullify the effect of different scales during the modeling exercise.

2.2.2. Structural equation modeling

Direct and indirect effects of the environmental variables were investigated using structural equation modeling (Fan et al., 2016). This method requires a conceptual causal diagram to be constructed which was done in the following manner. First, a potential path diagram was constructed where causal relationships were based on a priori knowledge about the internal model mechanics (Fig. 1A). This path diagram included direct effects of changes in temperature, ice-cover, mixed layer depth and winter nitrate concentrations on changes in gross primary production. In addition, changes in temperature were assumed to have indirect effects on changes in gross primary production through direct impacts on changes in ice-cover and mixed layer depth, whereas changes in salinity and wind stress was assumed to have indirect impacts through changes in the mixed layer depth.

Correlations for all single relationships were then investigated to identify co-variables for each sub-model in Fig. 1A that were highly correlated (Table 1). Based on these correlations, a modified path diagram was constructed in which highly correlated variables were avoided (Fig. 1B). In both SINMOD and NORWECOM.E2E, changes in temperature and ice-cover were highly correlated, leading to the exclusion of temperature as a direct effect on gross primary production. In addition, in SINMOD, changes in temperature, salinity and wind stress were highly correlated whereas for NORWECOM.E2E, changes in temperature and salinity were highly correlated. Therefore, for both models, changes in temperature, salinity and wind stress were reduced to a single variable by performing a principal component analysis and extracting the first axis (PC1). For both SINMOD and NORWECOM.E2E, all three variables were positively correlated with PC1 which explained 93% and 75% of the variation, respectively (Fig. S1). Thus, the final path diagram (Fig. 1B) included direct effects of changes in ice-cover, mixed layer depth and winter nitrate on gross primary production and indirect effects of temperature though changes in ice-cover. Finally, indirect effects of changes in temperature, salinity and wind stress, through changes in the mixed layer depth, on primary production was included as the combined effects via PC1.

Table 1
Correlation coefficients for single variable relationship. Upper triangle represents values from SINMOD and lower triangle represents values from NORWECOM.E2E. Values in bold are relationships that violate assumptions of colinearity in the structure proposed in the initial path diagram (Fig. 1A).

	SAL	TEMP	NO3	GPP	ICE	WSTR	MLD
SAL	–	**0.89**	0.67	0.64	−0.85	**0.90**	−0.63
TEMP	**0.84**	–	0.57	0.53	**−0.70**	**0.91**	−0.56
NO3	0.51	0.40	–	0.40	−0.55	0.49	−0.58
GPP	0.61	0.60	0.51	–	−0.74	0.57	−0.22
ICE	−0.58	**−0.73**	−0.36	−0.48	–	−0.81	0.47
WSTR	0.50	0.51	0.48	0.59	−0.80	–	−0.57
MLD	0.60	0.38	0.43	0.48	0.05	0.08	–

Based on the conceptual diagram (Fig. 1B), we estimated the coefficients in Eqs. (1–3) using generalized least squares and using maximum likelihood as the estimation method, assuming normal (Gaussian) errors. Since the data were centered and scaled, the resulting coefficients are β-coefficients, i.e., the response of the dependent variable for increasing the independent variable 1 standard deviation. The advantage of the β-coefficients is that the magnitude of the effects become directly comparable between variables.

$$\Delta GPP = \beta_{11}\Delta ICE + \beta_{12}\Delta MLD + \beta_{13}\Delta NO3 + \epsilon_1 \tag{1}$$

$$\Delta ICE = \beta_{21}\Delta TEMP + \epsilon_2 \tag{2}$$

$$\Delta MLD = \beta_{31}\Delta PC1 + \epsilon_3 \tag{3}$$

Where *GPP* is changes in gross primary production, *TEMP* is temperature, *NO*3 is the winter nitrate concentration, *MLD* is the mixed layer depth, *ICE* is ice-cover, *PC*1 is the combined changes in temperature, salinity, and wind stress, and ϵ are the residual errors.

Model assumptions were checked visually by examining the residual patterns (Fig. S2–3) and using variation inflation (VIF) scores. In general, VIF scores above 5 indicate that the predictor variables are highly correlated, compromising the underlying assumptions of the model and the resulting coefficient estimates. VIF scores were in the range of 1.2–1.8 for both models which is within an acceptable range (Table S1).

2.2.3. Spatial autocorrelation

The impact of spatial autocorrelation was investigated by repeating Eq. (1) while explicitly modeling the error-covariance matrix (*d* in Eq. (4)).

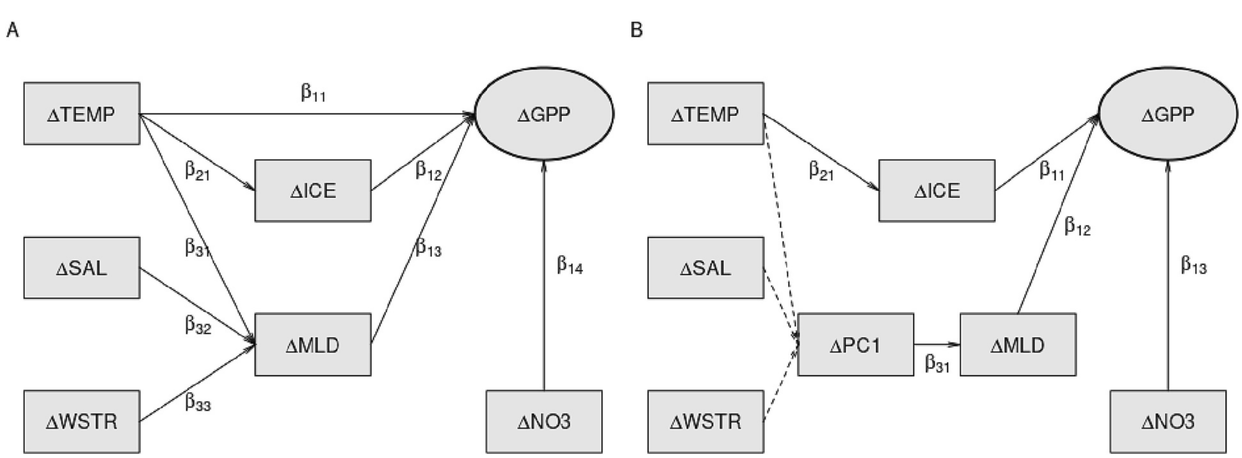

Fig. 1. Conceptual path diagrams with the proposed causal relationships between changes in gross primary production (GPP) and changes in the environment: temperature (TEMP), salinity (SAL), wind stress (WSTR), ice-cover (ICE), mixed layer depth (MLD) and the winter nitrate concentration (NO3). (A) represents the initial conceptual diagram with direct effects of temperature, salinity, and wind stress on the mixed layer depth. (B) represents the chosen conceptual diagram where the effect of temperature, salinity and wind stress is combined through the first axis of a principal components analysis (indicated as dashed lines).

$$\epsilon_1 \sim N(0, d) \quad (4)$$

Where 0 is the mean and d was assumed to be spatially dependent and modelled as a correlation structure where correlations decreased exponentially with increasing latitudinal separation. Due to computational limitations, the data from all grid cells could not be included and the results were therefore based on a sub-sample of approximately 500 evenly spaced grid cells (Fig. S4). The resulting β-coefficients were not significantly different from the models excluding the error-covariance matrix (Table S2) and we therefore chose not to account for spatial autocorrelation, and to include data from all grid cells in the final analyses.

3. Results and discussion

Changes in primary production from the initial to the future period for the two models are presented in Fig. 2A,B. In SINMOD (Fig. 2A), primary production was projected to increase in the northern and south-eastern part of the domain as well as the western part between Svalbard and Bear Island. However, in most of the central and southern part of the domain, primary production was projected to decrease. By contrast, in NORWECOM.E2E (Fig. 2B), primary production was projected to increase in most of the model domain, although with a west-east gradient with higher projected changes in the eastern part. Differences in the changes in temperature between the two models resembled the changes in gross primary production (Fig. 2C,D). Thus, for SINMOD, temperature showed the largest increase in the northern part (Fig. 2C) whereas changes in NORWECOM.E2E showed a west-east gradient with larger increases in the central and eastern part of the domain (Fig. 2D). In general, temperature increases were considerable higher in most of the domain for SINMOD compared to NORWECOM.E2E, with median increases of +2.7 and + 0.9 °C, respectively (Fig. 3).

Slagstad et al. (2015) discussed the differences between the projected changes in primary production from their model and the contrasting changes reported in Skaret et al. (2014). They noted that no explanation was given in Skaret et al. (2014) for "how additional nitrate can be added to the upper layers of the ice-free Barents Sea in times of warming". The differences are remarkable given that both projections are based on the same climate emission scenario (SRES A1B) and ecosystem models of comparable complexity. However, as also suggested by Slagstad et al., the results of the structural equation models (Fig. 3) indicate that the major differences arise from the underlying ocean physics. In both SINMOD (Fig. 3A) and NORWECOM.E2E (Fig. 3B), the direct effects of mixed layer depth and winter nitrate concentrations were positive. That is, increases in any of these variables would lead to increases in primary production in both models. Conversely, the direct effect of increasing ice-cover was negative, i.e., decreases in ice-cover leads to increasing primary production. In addition, increasing temperature had a negative effect on ice-cover, resulting in a net-positive effect of increasing temperature on primary production in both models. Thus, in terms of internal processes, the two ecosystem models agree on the direction of the included effects. These processes are consistent with the conclusions of other studies. For example, while the projection in Sandø et al. (2021) showed no long-term trend,

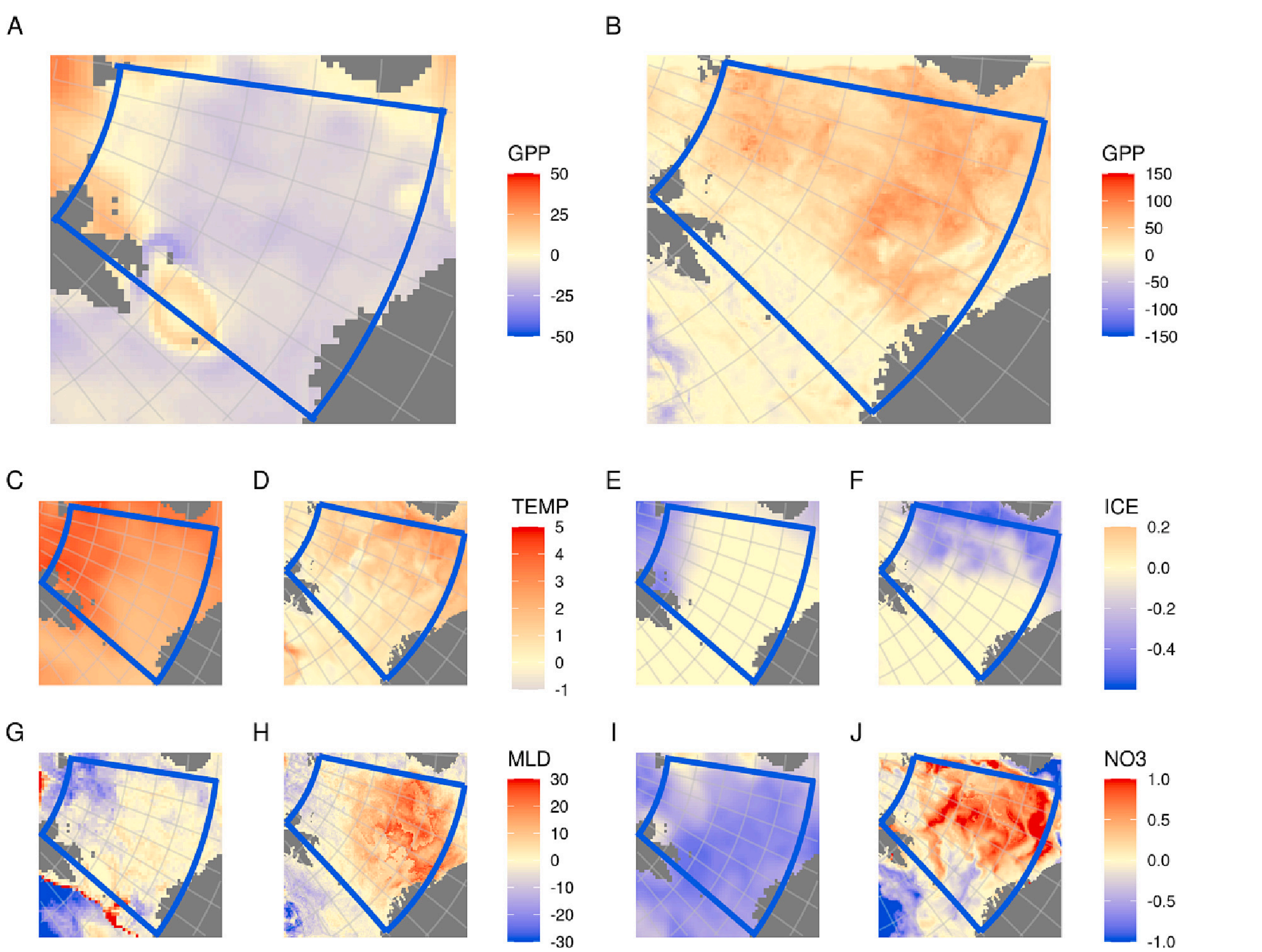

Fig. 2. Changes from the initial period to the future period in (**AB**) gross primary production (gC m^{-2}), (**CD**) temperature (°C), (**EF**) fractional sea-ice concentration, (**GH**) mixed layer depth (m) and (**IJ**) winter nitrate concentration (mmol m^{-2}) for SINMOD and NORWECOM.E2E, respectively. The blue box represents the study area where variables were extracted for structural equation modeling.

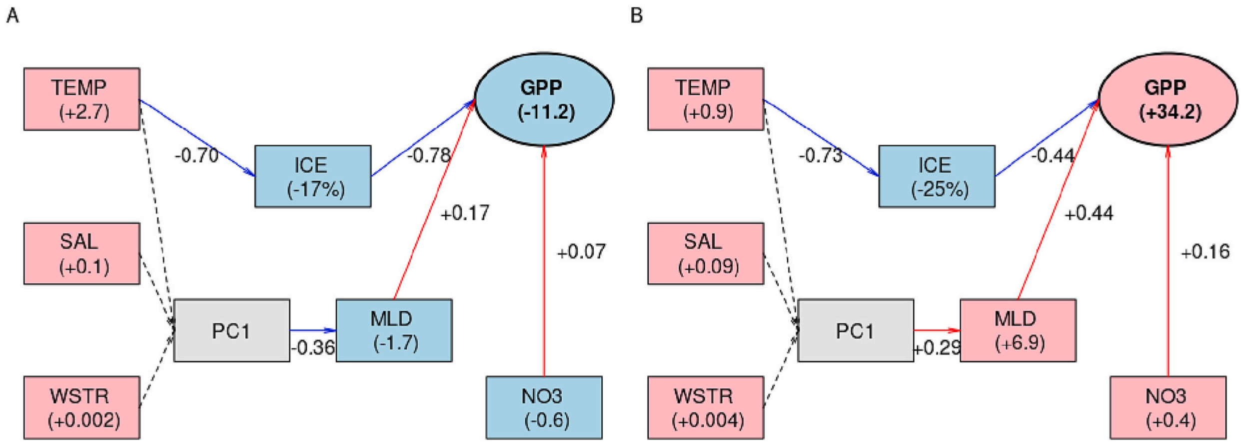

Fig. 3. Results of structural equation modeling for SINMOD (A) and NORWECOM.E2E (B). Arrow colors represents the direction of the effect increasing one variable (boxes) on another as estimated from the β-coefficients in Eqs. (1–3) (values on arrows). Colors of boxes represents the direction of change from the initial to the future period as estimated from the median difference (values in boxes). The change in ICE is presented as percentage change in the number of grid cells with more than 10% ice-coverage.

interannual changes in primary production in the Barents Sea were found to be primarily controlled by ice-coverage in the north, whereas the ice-free areas in the south were primarily controlled by wind-induced mixing energy. Similarly, Holt et al. (2016) concluded that the loss of sea-ice was the most important driver for increases in primary production in the Barents Sea, but also reported relatively higher increases in areas with negative changes in the potential energy anomaly (i.e., decreased strength of stratification).

However, while the two models exhibited similar internal mechanics, they differed in the direction and magnitude of the projected environmental changes, resulting in different net effects of the processes. The median changes across the whole domain for the mixed layer depth and winter nitrate concentration were positive in NORWECOM.E2E and negative in SINMOD (Fig. 3). Therefore, the net effect of changes in mixed layer depth and winter nitrate was to increase primary production in NORWECOM.E2E, and to decrease production in SINMOD. Coupled to the spatial change in the environment (Fig. 2C-J), we can deduce that for SINMOD, the increased primary production in the north-eastern area was controlled by decreasing ice-cover (Fig. 2E), whereas primary production in the remaining area decreased due a shallower mixing layer leading to less nutrients in the photic zone (Fig. 2G) as well as a decrease in the winter nitrate concentration (Fig. 2I). However, in NORWECOM.E2E, primary production increased in a much larger part of the Barents Sea as resource limitation (light and/or nutrients) was alleviated both in the northern and eastern parts due to decreasing ice-cover (Fig. 2F) as well as in the central part due an increase in the winter nitrate concentration (Fig. 2J) and an increase in the mixed layer depth (i.e., increased mixing in the production months; Fig. 2H).

On the global scale, increasing warming is generally associated with increasing thermal stratification limiting vertical nutrient supply (Fu et al., 2016) and leading to a decrease in primary production. However, changes in stratification at the regional scale may be different due to different combinations of stressors (Holt et al., 2017; Holt et al., 2016). As the summer sea-ice continues to retract in the coming decades, the direct impact of ice on light availability will eventually disappear (Onarheim and Årthun, 2017) and salinity-driven stratification from melting will be reduced. This process, also known as Atlantification (Barton et al., 2018), will result in a physical climate where local scale stratification and nutrient supply during the productive months, to a higher degree, is controlled by temperature and wind-induced mixing (Ardyna and Arrigo, 2020). The substantial increase in annual net primary production in the period 1998–2017 reported in Dalpadado et al. (2020) was primarily linked to temperature-induced decreases in ice-coverage. While this pattern is likely to continue as the ice melts, primary production in the Barents Sea will eventually become decoupled from the ice and instead be governed by the factors controlling the mixed layer dynamics.

In the current study, the individual direct effects of changes in temperature, salinity and wind stress on the mixed layer depth could not be quantified as the variables were highly correlated. However, the relationship between the combined effects of these variables and the mixed layer depth through the first principal component axis (PC1) still provide some information pointing to the underlying processes. For SINMOD (Fig. 3A) the impact of the combined effects on mixed layer depth was negative, indicating that processes leading to stabilization and shoaling of the mixed layer depth were stronger than the corresponding mixing processes, while the opposite was true for NORWECOM.E2E (Fig. 3B).

Median salinity increases were similar between both models (+0.1), indicating a larger influence of Atlantic water and a decrease in salinity-driven stratification (Holt et al., 2016; Sandø et al., 2021). The median temperature increase, however, was much greater in SINMOD (+2.7°C vs +0.9°C for NORWECOM.E2E), indicating that temperature-driven stratification was greater in SINMOD compared to NORWECOM.E2E. Lastly, the median change in wind stress was larger in NORWECOM.E2E (+0.004 m^2 s^{-2}) compared to SINMOD (+0.002 m^2 s^{-2}), which combined with similar salinity increases and relatively smaller increases in temperature for NORWECOM.E2E, led to a deepening of the mixed layer depth compared to SINMOD. Sakshaug and Slagstad (1992) reported that wind speeds above 8 m s^{-1} led to pulsed primary production events during summer. Using a coupled biophysical model, Le Fouest et al. (2011) used this threshold to quantify the relative importance of winds and found that wind-induced mixing events accounted for 9% and 4.5% of the summer production for the central Barents Sea and total Barents Sea, respectively. Future changes in wind speeds are highly uncertain but modeling studies have suggested an increase in the total number of extreme weather events in the Barents Sea (Myslenkov et al., 2018) and an increased occurrence and intensity of storms in the Arctic during the summer (Orsolini and Sorteberg, 2009). It is thus possible that thermal stratification following increased warming, to some extent, can be compensated by increasing wind stress.

The structural equation modeling framework was found to be a suitable approach to analyzing the output of the included ecosystem models. However, the approach is not without limitations. In this study, linear models were used to represent underlying non-linear processes and the absolute strength of the individual effects in Fig. 3 should therefore be evaluated with care. Thus, we deliberately do no emphasize the coefficients in this study, and instead focus on the directions. Given that the coefficients differ between SINMOD and NORWECOM.E2E they indicate that the two models do have different implementations of the biological mechanisms and that the magnitude of change in primary production is impacted differently by the combination of multiple stressors in the two models. In general, the impact of different implementations and parameterizations of ecosystem models remains largely unknown and to fully assess the impact of different ecosystem models vs. simulated ocean dynamics, it is probably necessary to make direct comparisons. One potentially valuable approach is the Framework for Aquatic Biological Models (FABM) which allows multiple ecosystem models to run simultaneously forced by the same physical model (Bruggeman and Bolding, 2014).

In summary, the two regional projections of primary production in a future Barents Sea we have explored differ because the physical processes controlling resources for phytoplankton growth are different. Both models predict an increase in areas where ice-cover decreases. However, in ice-free areas, primary producers in SINMOD are subject to a smaller inventory of nutrients and stronger thermal stratification whereas the opposite is found in NORWECOM.E2E. This also answers the question posed in Slagstad et al. (2015; See above) as nitrate can be added to the upper layer if thermal stratification is compensated and overcome by increasing wind exposure. The most plausible future scenario remains unknown as it is still highly uncertain how the factors controlling mixed layer dynamics will change in the future (Holt et al., 2016). Thus, as also stated by Slagstad et al. (2015), "future studies should ensure that the physics are as correct as possible" as it will be paramount for reliable projections of primary production.

Clearly, the outcome of climate change and warming in the Barents Sea has significant implications. In the past decades, warmer conditions have been linked to important transformations in the ecosystem, with increased advection of Atlantic zooplankton (Dalpadado et al., 2003), favorable recruitment, northward shifts of important commercial species (Kjesbu et al., 2014), habitat loss for Arctic communities and altered food-webs (Kortsch et al., 2015). In the future, global models project increases in biomass of commercial fish stocks and maximum revenues for fisheries in the Arctic and Sub-Arctic regions (Bryndum-Buchholz et al., 2019; Cheung et al., 2009, 2010). These projections are driving high expectations for the Arctic blue growth. The present study contributes to this discussion by shedding light on the uncertainties surrounding these possible outcomes, driven by regional characteristics and differences in the model projected environment (Niiranen et al., 2018).

4. Conclusions

In this study we have statistically analyzed the output of two climate projections to assess direct and indirect effects of changes in the environment on primary production. The two projections produce contrasting changes in primary production in the future, representing either a relatively large increase or a relatively large decrease. The analyses show that when the effects of the environmental variables are combined with their net change, the two ecosystem models represent consistent internal processes where the discrepancies between the resulting conclusions can be explained by the underlying physical models.

That ocean physics are important for the projected changes in primary production is not surprising as biogeochemical models are closely coupled to the underlying physical models (Skogen and Moll, 2005). Our results, however, add additional information by indicating the primary physical processes leading to the different outcomes. Changes in ice-cover had the strongest single effect of primary production. However, only part of the Barents Sea is seasonally ice-covered, and this impact thus becomes weaker when seen across the entire area. Therefore, the most important factors for controlling primary production in a future warmer (and ice-free) Barents Sea are changes in the nutrient supply either through changes in the mixed layer dynamics (here proxied as the mixed layer depth) or through changes in the bulk input advected into the region. In terms of the temperature impact, a relatively small increase in temperature (as projected in Skaret et al., 2014) will potentially result in an overall increase in primary production as thermal stratification can be compensated by increased wind exposure. However, a large increase in temperature (as projected in Slagstad et al., 2015) is more likely to result in an overall decrease in primary production as the temperature-induced stratification becomes too strong in relation to the mixing processes.

Author contributions

EAM, MDS and PW: conceptualization. IE and PW: Data curation, Investigation. EAM: Data curation, Investigation, formal analysis, writing - original draft. All authors: writing - review and editing.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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.seares.2023.102366.

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